BACKGROUND PAPER

INTERNATIONAL
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ADAPTING THE GLOBAL FOOD SYSTEM TO NEW CLIMATE REALITIES

GUIDING PRINCIPLES AND PRIORITIES

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Executive Summary

The **effects of climate change** are increasingly felt among **vulnerable populations** in many developing countries, particularly those relying on agriculture for their livelihoods, but also the urban poor. Adverse impacts include lower crop yields and crop nutritional values and ripple effects will be felt throughout the entire food value chain unless significant adaptation actions are taken.

This paper takes a broad **food system perspective** and connects the roles and actions of international organizations, national governments, local communities and farmers. After an extensive review of the likely effects of climate change and the available adaptation responses, the paper identifies a series of **guiding principles** to be considered by decision makers as they plan adaptation actions. These principles, which are expected to increase the uptake and the efficiency of climate change adaptation in agriculture are the following:

1. Publicly funded **agricultural research** is the underlying engine of all adaptation actions and requires increased investments. Particular emphasis should be given to the growing risks faced by vulnerable people;
2. Climate change generates multidimensional challenges and adaptation actions should be evaluated accounting for their economic, environmental and social costs and benefits. **Trade-offs** across alternative objectives should be made explicit;

About this paper

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3. **Coordination** across international, regional, national and local actors is not only necessary but essential to maximize the outcomes of adaptation actions. Sufficient resources should be dedicated to these efforts;

4. **Risk management** is an inherent component of climate change adaptation. Increased efforts are necessary to improve our understanding of how to deal with risk and uncertainty and to educate decision-makers on how to manage risks;

5. Adaptation actions should be deployed along the **entire food system** as actions in the areas of post-harvest, transportation, retail and food consumption work synergistically with efforts on the production side;

6. **Institutional capacity** enables change and transformation in the agriculture sector. Insufficient investments in institutional capacity slow down the pace of adaptation and reduce the efficiency of adaptation actions;

7. **New digital technologies** have the potential to transform the agriculture sector. Investments in these technologies and in building the capacity to use them must be facilitated. Particular attention should be given to preserving access to these technologies by poorer producers and consumers;

8. Climate change-induced **temporary and permanent migrations** have the potential to significantly disrupt the normal functioning even of established economies. Planning, coordination and adequate support are necessary to avoid catastrophic consequences; and

9. The adoption of certain adaptation measures could be significantly constrained because of the growing need to **abate greenhouse gases** (GHGs). Adaptation measures should also be evaluated according to their potential effects on GHG emissions.

With these guidelines in mind, the paper identifies key adaptation actions in different parts of the global food system that can accelerate current efforts and help avoid catastrophic outcomes including:

- **For food production:** Acceleration of agricultural research (such as investments in improved agricultural management practices, including breeding and agricultural water management; climate service provision, risk management, ICT) as well as migration;

- **For food supply and trade:** Adaptation of trade policies to rapid but uncertain climate change; the climate proofing of infrastructure; investments in improving the safety and efficiency of value chains as well as special support to small producers;

- **For food security, nutrition and health:** Improving availability and access to healthier diets; incentivizing healthier diet choices; and biofortified food and crop varieties;

- **For environmental sustainability:** Increased focus on resource use efficiency; direct actions to preserve, protect and enhance natural resources, ecosystems and biodiversity, improved governance of natural resources, efforts to reduce agricultural land expansion and more environmentally sustainable diets.

1. Introduction: Making the Case for Adaptation of Food Systems

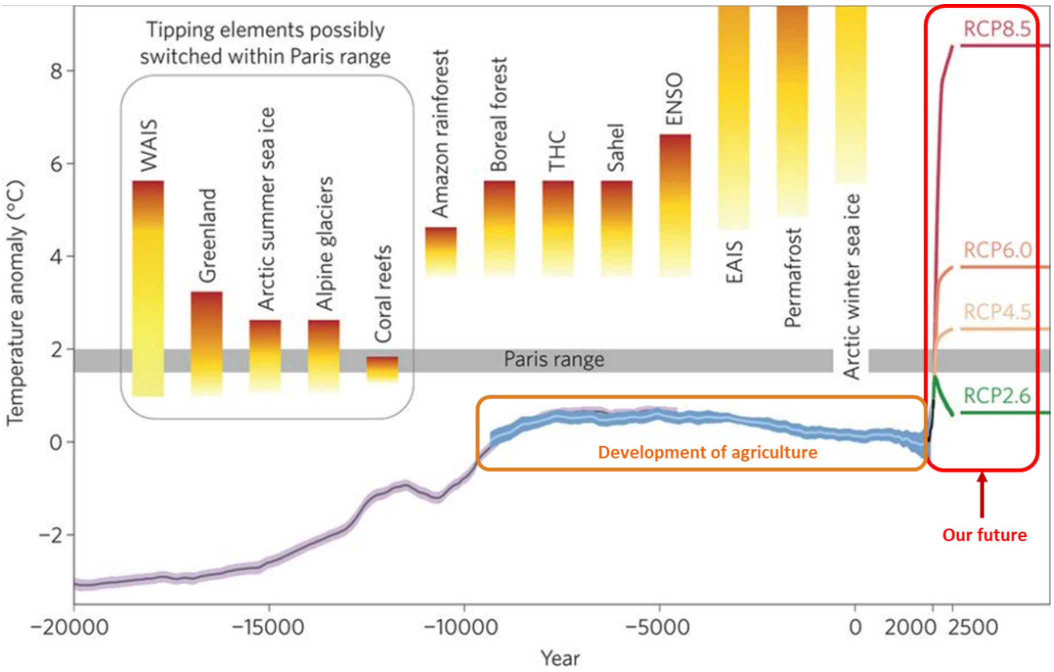
Climate change is a significant and growing threat to food supply and food security. It already directly affects vulnerable populations in many developing countries and is expected to affect many more people in more areas in the future, even if remedial actions are taken beginning today.[1] The worst-hit areas will be underdeveloped economic regions of the world, where food security already is problematic, and populations are highly vulnerable to climatic and other shocks.[2] However, climate change also is expected to have a substantial impact on food production in developed countries,[3] and the resulting impacts on global food prices also could adversely affect developing country outcomes. Without substantial measures that address the challenges caused by increasing temperatures and the increased frequency and intensity of extreme weather events, crop and livestock productivity losses are expected to reduce past rates of gains from technological and management improvements.[4] Furthermore, climate change will not only threaten the productivity of the world's agricultural systems and associated food security and nutrition outcomes but also have adverse consequences for other ecosystems and their services to humankind.[5]

Most troubling, albeit not often discussed, is the rate at which the climatic conditions underlying current food production systems are projected to change. To appreciate the gravity of the problem, it is useful to consider how mean temperatures have evolved during the past 10,000 years (Figure 1.1).

Human civilization as we know it—the locations of our cities, ports, and roads, the sites of our agricultural fields and forests—is the result of a stable environment: 10,000 years of global temperatures that have fluctuated minimally around the mean. Climate change and the resulting uncertainties have the potential to rapidly reshape the optimal location of production, the associated infrastructure connecting economic activities, and the very (often competing) forces that have led to the current market, resource, and price equilibria. However, the inertia in the system caused by sunk costs and learned behavior creates barriers to adaptation.

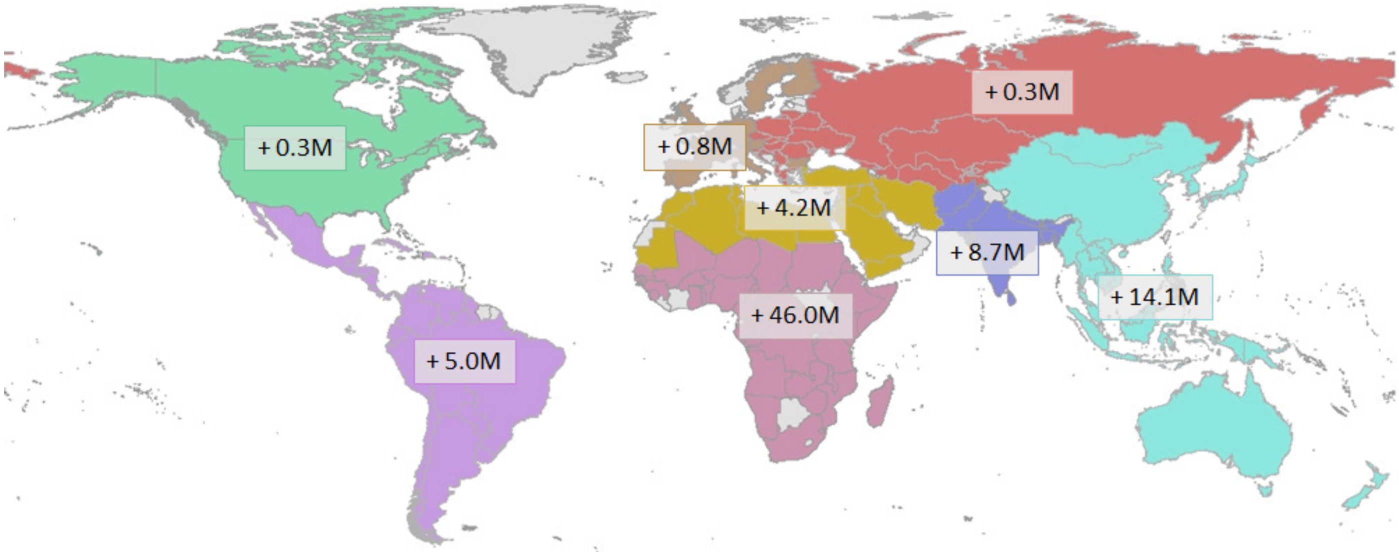
Uncertainties in climate change scenarios, particularly regarding precipitation, make it difficult to determine the precise impacts on future agricultural productivity, but total global supply is expected to decline. Warmer temperatures

FIGURE 1.1 Global mean temperature evolution and projections for the future



Source: Adapted from Schellnhuber et al. (2016).

FIGURE 1.2 Change in the number of people at risk of hunger in 2050, by region



Source: Authors, IMPACT model data

Notes: Figures show the difference in the estimated population at risk between a climate change scenario (HadGem GCM [general circulation model] run under [representative concentration pathway] RCP8.5) and a reference scenario without climate change (NoCC). Results are based on simulations, which do not include any explicit and specific adaptation strategy.

and longer growing seasons increase agricultural productivity in some high-latitude regions,[6] although expectations are mixed. This is due, among other reasons, to soil quality issues in the far north and emerging pest and disease breakouts that might constrain expansion and productivity. As an example, the 2000–2010 hot, dry seasons in northern Italy led to aflatoxin contamination of maize. Used as animal feed, this contaminated maize resulted in milk contamination.[7]

In low-lying regions, even a modest increase in maximum temperatures is expected to negatively affect agricultural production, and pest and disease outbreaks are much more severe. Studies have consistently found that under the most severe scenarios of climate change, significant losses should be expected worldwide (Figure 2.1).[8,9,10,11,12,13,14,15,16] No matter the severity, regional differences in agricultural production are expected to strengthen, risking a widening gap between the haves and have-nots, increases in food prices globally, and associated increased hunger among poorer nations.[17,18,19] The International Food Policy Research Institute (IFPRI) projects that without climate change, the total number of people at risk of hunger could decrease by approximately 425 million by 2050.[20]

Figure 1.2 shows a projection of how climate change can slow this progress. An additional 80 million people, approximately 1% of the projected world population in 2050, may be at risk of hunger because of the effects of climate change; definitively putting out of reach the goal of ending hunger by 2030 (Sustainable Development Goal [SDG] 2), and slowing progress toward global equality (SDG 10), with direct and indirect negative effects on the goal of ending poverty (SDG 1) and furthering economic growth (SDG 8). The regional differences are striking, and the global South—Sub-Saharan Africa in particular—appears to be particularly affected.

As a result of potentially great disparities in production and people at risk of hunger, interregional trade flows are expected to expand from mid- and high-latitude regions to low-latitude regions. Nevertheless, trade (including food aid) alone will not be able to buffer food shortages caused by climate change.[21,22,23] Moreover, the differential climate change effects on various components of the food system act on biophysical and socioeconomic processes with feedback mechanisms that at times are cumulative and self-reinforcing.

Developing countries are expected to receive the brunt of adverse impacts from climate change.[24] The Intergovernmental Panel on Climate Change (IPCC) *Fifth Assessment Report* (*AR5*) projects that under more optimistic scenarios, climate change could reduce food-crop yields in parts of Africa by 10% to 20%, a large drop for populations and regions already at-risk. The outlook for key food crops across Africa under climate change is mostly negative; low productivity, together with increasing global demand, will likely drive up food prices.[25,26,27] Moreover, localized weather shocks and emerging pest and disease outbreaks are already compromising the stability of crop production, highlighting the urgency for immediate and adaptive management responses.[28] Conflicts between pastoralists and crop farmers have been recorded during El Niño–Southern Oscillation (ENSO) events in sub-Saharan Africa and appear to be on the rise.[29] Unfortunately, government spending on agricultural research and development is in decline, and aid flows to agriculture in developing countries also are falling. These trends will make the challenge of adapting to the negative impacts of climate change more daunting.

Climate change impacts are long-ranging and affect many aspects of the global food system. Thus, climate change not only affects agricultural production but also has ripple effects throughout the food value chain and food systems. Storage, marketing, and retail systems will need to adapt to agricultural commodities that are more susceptible to aflatoxins. As certain areas become hotter, greater investments in cold-storage options will be needed. Transportation infrastructure will need to adapt to a more variable climate that will increase the likelihood of damages to the transportation network, such as flooded roads and port infrastructure or retail shops that lose power when hydroelectric dams run dry and the electrical grid fails. Finally, food security and nutritional outcomes can be affected directly by climate change, or indirectly as shocks move through the value chain.

Importantly, the ways in which the food system adapts to climate change will also affect broader ecosystems and the environment, and the ways in which the environment and ecosystems adapt will in turn affect agriculture and food systems. It is thus highly desirable that food system adaptations both support food security and nutrition outcomes and improve environmental outcomes. In addition, agricultural production contributes substantially to climate change, with yearly greenhouse gas (GHG) emissions that range from 5.0 to 5.8 gigatons of carbon dioxide equivalents (Gt CO_2 e), or about 11% of total anthropogenic GHG emissions, not including land-use change.[30] Combined with forestry and other land uses, anthropogenic land activities contribute about a quarter of annual GHG emissions, the equivalent of 10 to 12 Gt CO_2 e per year—and three-fourths of this amount is estimated to originate in the developing world.[31] Therefore, adaptive responses will have to be tailored to local agroecological conditions, environmental challenges, and social objectives, while also contributing to keep emissions in check. In other words, we will have to prioritize adaptation options that work synergistically with environmental sustainability and GHG mitigation goals.

Two main types of adaptation are possible: autonomous and planned. Autonomous adaptation is generally thought to occur “organically” due to changes in operating conditions experienced by individuals or companies. It is facilitated by access to information but can occur based on personal experience, such as when farmers shift crops or planting/harvest dates in response to changing precipitation patterns. Such adaptations tend to be short term, driven by small adjustments to existing practices. Planned adaptation is generally thought to involve larger structural changes and to be based on long-term strategies and novel policy options. Planned adaptation strategies can and often do span multiple sectors, consciously aiming to change the adaptive capacity of the food system and facilitating the uptake of adaptive actions. Forms of maladaptation are also possible. Maladaptation has been defined as “action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups”.[32] Livelihood diversification issues, such as selling firewood, charcoal production, or government programs for biofuel development, could be considered as maladaptation.

From an economic perspective, it is important to adapt to climate change to reduce negative impacts on the economy and livelihoods of small producers and to enable farmers and entrepreneurs to take advantage of new opportunities in new markets and services. From an environmental perspective, it is important to consider the possible irreversible damage that changes in the climate regime and unsustainable agricultural practices can cause for natural resource stocks, biodiversity, and the flow of ecosystem services. Given the contribution of agriculture to GHG emissions, adaptation options that provide mitigating co-benefits also increase the environmental sustainability of agricultural production under climate change. From a social perspective, adaptation options that increase equity in agricultural livelihoods, food distribution, food security, and nutrition outcomes are preferred. Moreover, climate change is just one of many drivers affecting global food production and food security. Adaptation efforts must operate in the context of global economic and political trends. For example, trends in economic growth, trade projections, anti-globalization sentiment, conflict and migration, urbanization, and changing food preferences and demands all have implications for the types of adaptation options that are both needed and feasible.[33]

The objective of this paper is to take stock of our current knowledge of climate change impacts and adaptation options in four key areas of the food system: (1) global food production, (2) global food supply chains and trade, (3) nutrition and food security, and (4) the environmental sustainability of food production. We address these issues with a focus on policy measures and investments that support smallholder producers of crops and livestock and poor consumers. We also incorporate insights and conclusions on the extent to which climate change impacts in the Global North affect poor producers and consumers. To identify key problems and potential opportunities in each area, evaluate our current understanding of the potential for adaptation, and identify the future actions needed to increase resilience to climate change across different geographies and populations, we have conducted an extensive literature review.[34]

2. Global Food Production

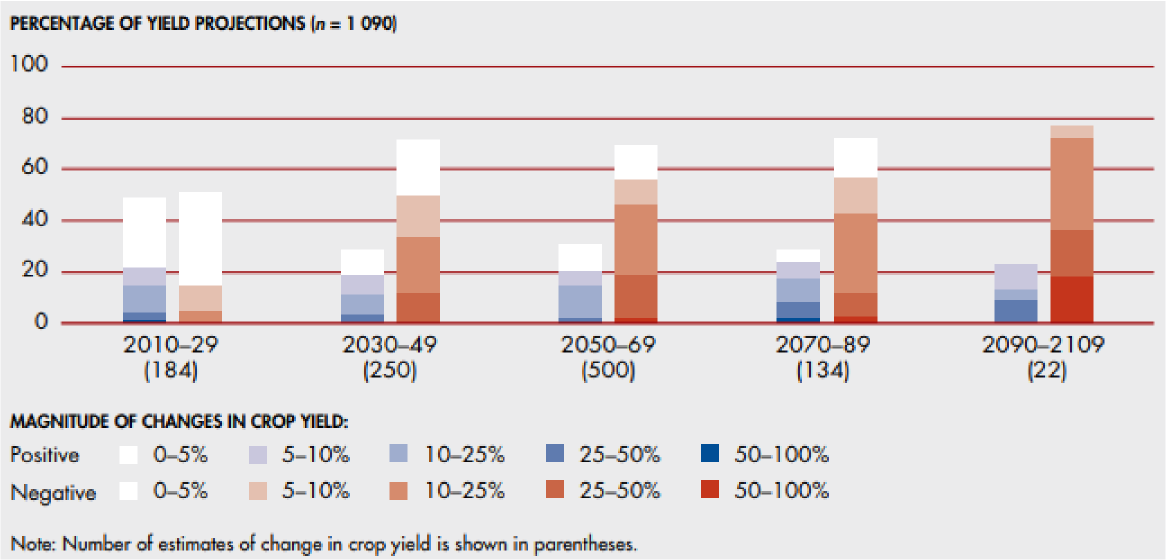
2.1 Climate Change Risks to Global Food Production

The effects of climate change on agriculture are multifaceted, but the consensus is that over time, those effects could make it increasingly difficult to grow crops, raise animals, and catch fish as people have traditionally done. Food crops need specific conditions to thrive, including the right temperature and sufficient water. Changing conditions may present some geographical trade-offs, such as increases in yields and greater productivity at higher latitudes as the growing season in these areas lengthen. However, higher temperatures, more variability in water availability, and the increased frequency of extreme events (especially floods and droughts) are expected to generate losses that are greater than possible gains. Furthermore, many weeds, pests, and fungi thrive under warmer temperatures, wetter climates, and increased CO_2 levels.[35]

Livestock, particularly in the Global South, are directly threatened by heat waves, which are projected to become more common under climate change. Over time, heat stress can increase animals' vulnerability to disease, thereby reducing fertility and meat and milk production. Climate change may also increase the prevalence of parasites and diseases that affect livestock. In areas where rainfall increases, moisture-reliant pathogens could thrive and affect production.[36] Likewise, many fisheries already face multiple stresses, including overfishing and water pollution. Climate change may exacerbate these stresses. Warmer water temperatures are likely to cause a shift in the habitat ranges of many fish and shellfish species, which could disrupt ecosystems, generating larger feedback effects on environmental and human systems.[37]

The precise impacts on agriculture are extremely difficult to predict because they will depend on local conditions and the magnitude and speed of the onset of climate change effects. Most studies indicate that climate change impacts will change over time and differ across locations. The IPCC's *Fifth Assessment Report*[38] which reviewed projected changes in crop yields owing to climate change over the 21st century, found that in the medium term (that is, until about 2030) the positive and negative effects on yields could offset each other (Figure 2.1). After that, as climate change accelerates, the balance increasingly would be negative.

FIGURE 2.1 Projected changes in crop yields caused by climate change over the 21st century



Source: Reproduced from FAO (2016).

Notes: Percentage change between 2010–29, 2030–49, 2050–69, 2070–89, and 2090–2109. The number of estimates of change in crop yield is shown in parentheses.

Estimates of the overall effects of climate change on yields, production, and other variables are qualitatively consistent across studies, although the magnitude of the impacts can vary, as they are sensitive to the assumptions underlying the different models.[39] This report takes a conservative approach and presents the results of model simulations that assume no additional benefits from atmospheric carbon (CO_2) by 2050. The response of crops to CO_2 concentration is complex, and there is still significant uncertainty as to whether CO_2 may increase crop productivity via carbon fertilization (Box 2.1).

Nelson et al. [40] compared nine economic models, based on a common combination of assumptions regarding socioeconomic (SSP2) and climate-forcing (RCP8.5) parameters. They estimated an average reduction in yields of 11% (Figure 2.2, YTOT). Decreases in yields are compensated by an expansion in cultivated areas (+11%). The combined effect is estimated to lead to an average decline in production of only 2%, whereas consumption is projected to decrease on average by 3%.[41]

Most models also estimate large changes in price (average increase of 20%). On one hand, higher prices trigger more intensive management practices (i.e., creating incentives for investments that promote increased yields), expansion in area, and reallocation of production through trade. On the other hand, price hikes significantly increase the share of income that the poor will have to spend on food; this will compound the blow to the poor in rural areas, who will also see reduced income from climate change impacts on production.

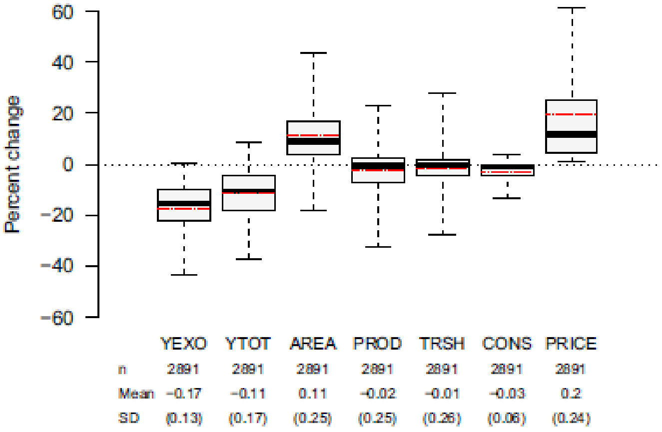
An analysis that integrates more combinations of socioeconomic and climate-forcing assumptions[42] shows a similar pattern of effects with a somewhat smaller magnitude of impacts (Figure 2.3).[43]

BOX 2.1 CO_2 Concentrations and the Uncertainty around Carbon Fertilization Effects

The extent to which elevated CO_2 concentrations may benefit crop yields and offset the negative impacts of mean temperature and precipitation changes is still debated.[44,45,46,47] The general expectation is that CO_2 may provide a larger photosynthetic benefit to C3 crops (e.g., wheat, rice, soy) than to C4 crops (e.g., maize, millet, sorghum, sugar cane, but both C3 and C4 appear to achieve higher water-use efficiency at higher CO_2 concentrations.[48] A recent multi-ensemble crop model analysis found that higher CO_2 concentrations (specifically under RCP8.5) may lead to an increase in wheat yields and protein content (although the results varies by region), but most of the actual gains may be negated by the increase in temperature and changes in precipitation.[49] A 2014 review of available FACE (Free air CO_2 enrichment) experiments also found "equivocal increases in net primary productivity (NPP) from [elevated] CO_2 studies".[50] Overall, there is still significant uncertainty in the response of crops to CO_2 especially in the long term. The uncertainty stems mainly from a lack of field experiments and observations.[51,52] As a consequence, crop models treat the CO_2 effects in very different manners and the results can be seen in the high level of uncertainty in crop responses to CO_2 fertilization across the full suite of crop models, included in the Global Gridded Crop Model Intercomparison (GGCMI) project (part of the Agricultural Model Intercomparison and Improvement Project (AgMIP)).[53]

Crops response to CO_2 in GGCMI models has been shown to produce optimistic results, as ozone concentrations, which are expected to increase, can have an opposite and potentially larger effect than elevated CO_2 on plant productivity.[54,55,56] The degree to which CO_2-enhanced photosynthesis may result in higher crop yields is also unclear, considering the effects of competing plant physiological processes that down-regulate photosynthesis, confounding effects from nutrient limitation, and growth in plant tissues/organs other than the storage parts that are harvested,[57] as well as the possibility of higher susceptibility to herbivory from invasive pests.[58] In addition, there is mounting evidence that higher CO_2 concentrations have negative effects on the nutrient content of crops, with potentially dire effects on global food and nutrition security.[59,60]

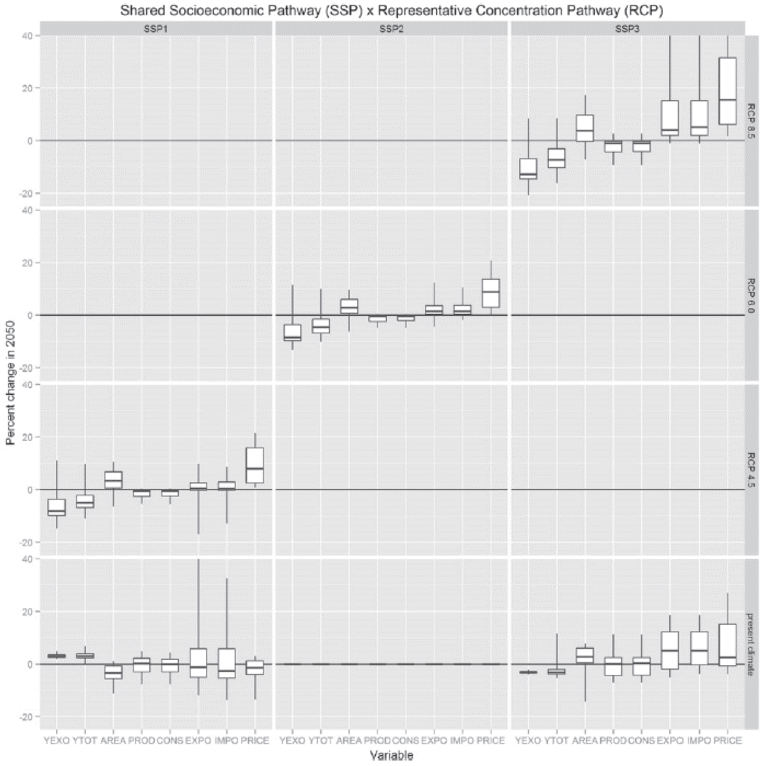
FIGURE 2.2 Change in agricultural variables across climate scenarios, geographies and crops



Source: Reproduced from Nelson et al. (2014b).

Note: Range of outputs across 9 models, 7 climate scenarios, 13 world regions, and 4 crops (coarse grains, oilseeds, wheat, and rice), relative to a reference scenario with constant climate (i.e., a NoCC scenario), in the year 2050. Changes in biophysical yields (YEXO), final yields from the economic models (YTOT), crop area (AREA), production (PROD), net imports (TRSH), consumption (CONS), and market price effects (PRICE) are shown. The black line shows the median value, and the thin red dotted line the mean.

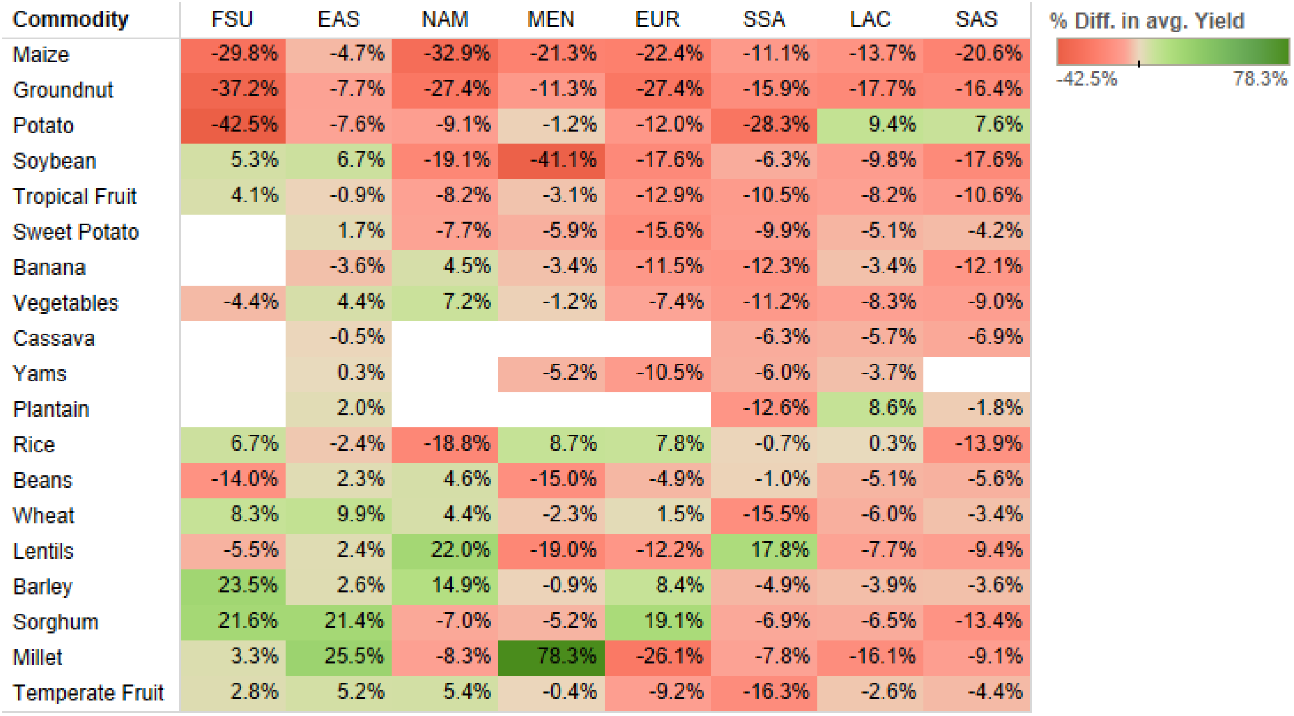
FIGURE 2.3 Range of impacts of climate change. Multiple RCPs and SSPs



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

Note: Range of impacts of climate change on global yields (YEXO biophysical yields and YTOT final yields), area, production, consumption (CONS), exports, imports, and prices of coarse grains, rice, wheat, oilseeds, and sugar across 3 GCMs, 5 economic models, and 13 regions, under different SSP × RCP/GCM combinations (% change from respective baseline in 2050 without climate change). The final row compares SSP1 and SSP3 results to SSP2.

FIGURE 2.4 Change in projected yields for selected crops and regions



Commodity	FSU	EAS	NAM	MEN	EUR	SSA	LAC	SAS
Maize	-29.8%	-4.7%	-32.9%	-21.3%	-22.4%	-11.1%	-13.7%	-20.6%
Groundnut	-37.2%	-7.7%	-27.4%	-11.3%	-27.4%	-15.9%	-17.7%	-16.4%
Potato	-42.5%	-7.6%	-9.1%	-1.2%	-12.0%	-28.3%	9.4%	7.6%
Soybean	5.3%	6.7%	-19.1%	-41.1%	-17.6%	-6.3%	-9.8%	-17.6%
Tropical Fruit	4.1%	-0.9%	-8.2%	-3.1%	-12.9%	-10.5%	-8.2%	-10.6%
Sweet Potato		1.7%	-7.7%	-5.9%	-15.6%	-9.9%	-5.1%	-4.2%
Banana		-3.6%	4.5%	-3.4%	-11.5%	-12.3%	-3.4%	-12.1%
Vegetables	-4.4%	4.4%	7.2%	-1.2%	-7.4%	-11.2%	-8.3%	-9.0%
Cassava		-0.5%				-6.3%	-5.7%	-6.9%
Yams		0.3%		-5.2%	-10.5%	-6.0%	-3.7%	
Plantain		2.0%				-12.6%	8.6%	-1.8%
Rice	6.7%	-2.4%	-18.8%	8.7%	7.8%	-0.7%	0.3%	-13.9%
Beans	-14.0%	2.3%	4.6%	-15.0%	-4.9%	-1.0%	-5.1%	-5.6%
Wheat	8.3%	9.9%	4.4%	-2.3%	1.5%	-15.5%	-6.0%	-3.4%
Lentils	-5.5%	2.4%	22.0%	-19.0%	-12.2%	17.8%	-7.7%	-9.4%
Barley	23.5%	2.6%	14.9%	-0.9%	8.4%	-4.9%	-3.9%	-3.6%
Sorghum	21.6%	21.4%	-7.0%	-5.2%	19.1%	-6.9%	-6.5%	-13.4%
Millet	3.3%	25.5%	-8.3%	78.3%	-26.1%	-7.8%	-16.1%	-9.1%
Temperate Fruit	2.8%	5.2%	5.4%	-0.4%	-9.2%	-16.3%	-2.6%	-4.4%

Source: Authors, data from Rosegrant et al. (2017, IMPACT simulations).

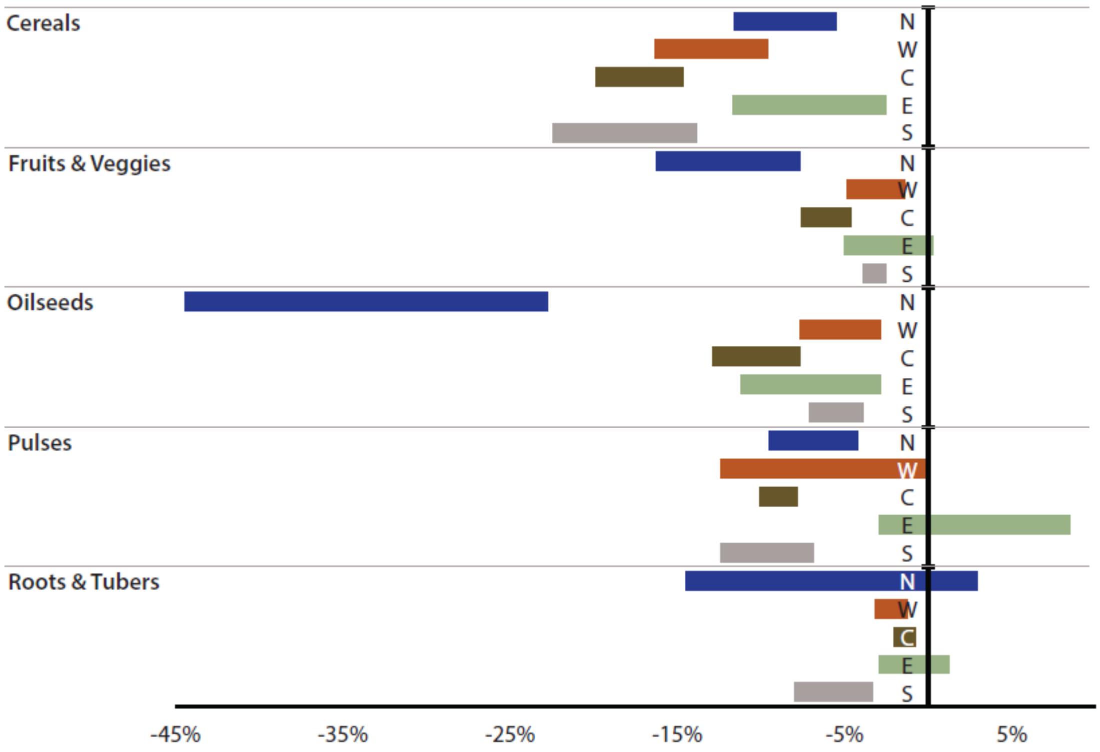
Notes: Change between a 2050 climate change versus a no-climate-change scenario. FSU: Former Soviet Union; EAS: East Asia Pacific region, with the exclusion of the Organization for Economic Cooperation and Development (OECD) countries (Japan, Australia, and New Zealand). NAM: North America; MEN: Middle East and North Africa; EUR: Europe; SSA: Sub Saharan Africa; LAC: Latin American countries; SAS: South East Asia.

Impacts are expected to vary strongly across crops and regions. IFPRI results show this variability in cereal yields projected for 2050 under different pathways of global warming assuming a "middle of the road" pathway for economic and population growth. Using combined biophysical and economic modeling, maize, groundnut, potato, and soybean are projected to suffer some of the largest negative impacts, whereas wheat and to some degree sorghum may experience a positive effect in some regions (Figure 2.4).

Figure 2.5 shows how yield impacts of climate change (relative to a no-climate-change baseline in 2050) vary across crops and subregions within Africa, even for a single socioeconomic and emissions pathway (SSP2 and RCP8.5).[61] Yield reductions of 5% to 15% are seen for most crops and subregions, with more severe impacts on oilseeds in North Africa and with modest gains for pulses in East Africa. Further disaggregation within national subregions would show further heterogeneity of locale-specific impacts. For example, many coastal areas are experiencing sea level rise and saline intrusion in freshwater aquifers. Countries with large coastal areas, like Bangladesh and Vietnam, are already experiencing problems related to increased soil salinity, reduced water for dry-season irrigation, a decline in yields of key crops like rice, and changes in the composition of capture fishery.[62,63] Hence, potential adaptation solutions must keep local realities and local impacts in mind. At the same time, global and regional collaborations offer opportunities for risk-sharing and the substantial transfer of technologies and local know-how.

Much less research has been conducted on climate change impacts on livestock. Climate change affects livestock production in multiple ways, both directly and indirectly. Most impacts are assessed through changes in feed costs, and resulting changes and substitution in feed inputs, that affect livestock yields and product quality. Other livestock impacts from climate change include changes in intensity and geographic extension of livestock disease, reproductive health, and direct impacts on livestock from heat stress and chang-

FIGURE 2.5 Impact of climate change on crop yields in Africa



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

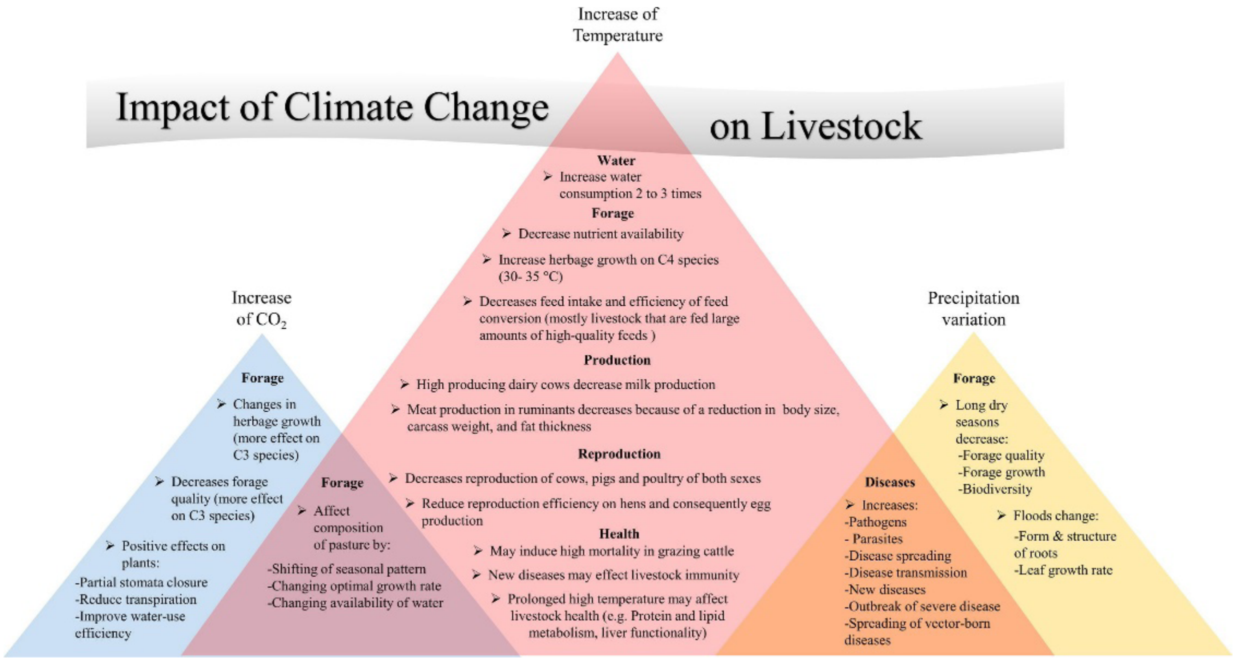
Note: change is estimated for the year 2050, by subregion. N = North, W = West, C = Central, E = East, and S = Southern.

es in the availability of watering points, particularly during drought events. Increases in temperature affect water availability for livestock production, yield, reproduction, and health. Changes in temperature and the variability of precipitation and CO_2 levels affect forage quantity and quality, and changes in precipitation patterns and temperature increases affect the potential for and spread of livestock disease.[64,65,66] Vector borne diseases (e.g., West Nile virus, schistosomiasis, bluetongue, Lyme) are projected to expand into new areas with effects on animal health. Increased temperatures, reduced precipitation, and increased precipitation variability have direct negative impacts on feed crops, forages, and grasslands, thereby reducing yields and forage production, reducing fodder quality, and increasing mold infestations and contaminations of feed resources.[67] Seo and Mendelson[68] find that net revenues from livestock production, the number of livestock per farm, and the earnings per livestock are all highly sensitive to climate. Small livestock farms, for instance, can more easily shift to heat-tolerant animals and adjust their animal holdings; as a result, they tend to be more resilient to temperature increases, whereas large farms that specialize in cattle production find it more difficult to substitute animal species and can only reduce their herd sizes in response to rising temperatures.[69] Figure 2.6 summarizes climate change impacts on livestock.

2.2 Uncertainty, Variability, and Risk

Most modeling projections, including those presented in the previous section, are based on estimates of changing temperature and precipitation averages to 2050. This paper will focus mainly (but not exclusively) on ways to adapt to a quick evolution of these averages. However, the main messages from the physics of climate change research have always been about increasing average global temperatures and heightened weather unpredictability caused by greater climate variability. The signature of climate change is already visible, and “each of the last three decades has been successively warmer at the Earth’s surface than any

FIGURE 2.6 Impact of climate change on livestock



Source: Rojas-Downing et al. (2018).

preceding decade since 1850".[70] The IPCC also reports that the frequency of heat waves has risen, and with it, the likelihood of an increase in the number of heavy precipitations over several land regions (IPCC 2014, 8).[71]

Climate change, in addition to natural variability (natural decadal and interannual variabilities), is expected to affect the incidence of climate extremes in the future. However, current modeling tools are still inadequate in the way they treat uncertainty and do not provide sufficient confidence in their estimation of the future magnitude and direction of changes in variability, at least globally (IPCC 2012).[72] However, the IPCC *AR5* expresses high confidence in three factors: (1) the intensification of variability for regional precipitation related to El Niño–Southern Oscillation (ENSO) events, (2) the intensification of monsoon precipitation, and (3) an increase in intensity and frequency of extreme precipitation events over most midlatitude land masses (IPCC 2013).[73] It also expects that in the future, "warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform".[74] Heat waves presents some of the most difficult challenges to public health and food production, and there is evidence that tropical countries in particular will face increasing temperature variability in the coming decades, especially in the Amazonia region, southern Africa, the Sahel, India, and Southeast Asia.[75] For some regions, there are large differences among global climate models in predicting future precipitation trends in terms of both the direction (wetter or drier) and magnitude of the effects, especially for parts of the developing world.

Global models that evaluate the effects of climate change on economic growth still are based mostly on precipitation and temperature trends. In fact, most of the literature on climate change considers the effects of variability a secondary effect, even though the implications of variability can compound with long-term impacts and should be considered in greater depth.[76] The effects of a change in the distribution of precipitation and temperature and the incidence of extreme events are not only biophysical, and there is extensive economic literature that evaluates the effects of risk on production choices and investments. However, as of today, global economic models that study the effects of climate change do not include extreme events and volatility in their projections and have not internalized the potential compounding effect of more unpredictable and unfavorable weather with standard risk-averse behavior.

The literature about the costs of extreme events is vast but spatially variable in availability.[77] We are beginning to have a better understanding of the impacts of specific weather anomalies and ways to cope with these (Box 2.2; Box 2.3), but there is less knowledge about the impacts of weather variability in general. Despite this uncertainty, weather variability certainly affects smallholder systems, and precipitation anomalies (interannual variability) can have a strong effect on the gross domestic product (GDP) of countries that rely heavily on agriculture.[78] Changes in the mean and variability of temperatures and rainfall can impact overall yields as well as the quality of the seeds (e.g., protein content in wheat), while rainfall variability and intra- and inter-seasonal changes in temperature appear to strongly affect year-to-year changes in yields,[79,80] Variability is already causing shifts in the growing seasons,[81] and it will affect feed production in livestock systems (especially if drought frequency were to increase) and drive substantial changes on the prevalence and distribution of pests and diseases—although the resulting effects on agricultural production are not yet well understood.[82]

The literature suggests a number of adaptation options aimed at reducing vulnerability to increased seasonality and weather events triggered by climate variability. The list includes supplementary irrigation; adoption of crops tolerant to both abiotic and biotic stresses; adoption of entirely different crops; shifting crop calendars; and the use of weather and climate services and early warning services, as well as insurance, including weather-index insurance (as tested both in South Asia and sub-Saharan Africa).[83] However, several questions remain unresolved. What decisions will farmers make once they start feeling the impact of climate variability on their bottom line? Will they decide to adapt or not adapt? In either case, what may be the best adaptation options when taking into consideration their response? Farmers' behavior, and their decision to adapt to climate variability, may be related to any number of factors, including (1) previous exposure to variability, (2) the magnitude of the effects experienced (e.g., rainfall changes), (3) the availability of support through extension services,[84] (4) their perceptions of the changing climate combined with socioeconomic and cultural factors,[85] and (5) the type and quality of climate information available.

One approach argues that the best first step to ensuring our preparedness for future climate variability is reducing our exposure and vulnerability to the current "natural" variability.[86] A series of Adaptation Gap Reports has focused on the considerable gap between countries' preparedness for climate change and the actual measures that should be put in place to prepare communities for a future of increasing climate risks (see, for example, UNEP 2018).[87] Long-term damages depend on how adaptive capacity evolves, and the impacts of recent extremes such as droughts, floods, heat waves, and wildfires on human systems reveal high levels of vulnerability. Trade and a strongly interconnected global food market are expected to help buffer some of the impacts of climate change, provided that the right policies are in place (Box 2.4).[88,89]

BOX 2.2 ENSO Effects in the Philippines

Historically, ENSO events have had a large impact on the Philippine agricultural sector and on the country's entire economy. ENSO events are naturally occurring fluctuations in ocean and atmospheric temperatures that disrupt weather patterns and most commonly lead to either a decrease (El Niño) or an increase (La Niña) in average rainfall. El Niño events have sizable effects on the size of planting area and the planting calendar, usually resulting in lower yields. The last El Niño, recorded in 2015–16, lasted 18 months and caused an estimated US$327 million in agricultural losses. A shock of this magnitude, hitting a sector that employs more than a quarter of the country's workforce, had lasting repercussions on the entire Philippine economy. A modeling exercise estimated that a strong El Niño could generate losses of up to US$3.3 billion across the Philippine economy (US$1.8 billion in the agriculture sector alone) and showed that policy interventions that include supplemental irrigation and the removal of rice import quotas can help reduce welfare losses and slow the increase in poverty rates.[90]

BOX 2.3 Ethiopia: Coping with ENSO Events[91]

Vulnerability to extreme weather events is a long-standing concern, especially for people who rely on agriculture for their livelihood. The 2015–16 ENSO event in Ethiopia caused both a severe drought and flooding, and it brought to the forefront the remarkable improvements in the country's resilience as well as the remaining challenges in ensuring that everyone recovers as swiftly as possible from adverse climatic shocks. Compared to a similarly severe 1984 event (in terms of climatic impacts) with a massive human toll—approximately 1.2 million people died, and more than 65 million people were internally displaced—Ethiopia "weathered" the 2015–16 event remarkably well. More than 10 million people were supplied with food relief in addition to the 7.9 million people already under the country's Productive Safety Net Programme; approximately 450,000 children were expected to be treated for severe acute malnutrition, and a further 2.2 million children and pregnant and lactating women for moderate acute malnutrition; and humanitarian relief expenditures amounted to more than US$1.3 billion in 2016 alone, more than double Ethiopia's average annual humanitarian aid contribution. The lower impacts and stronger response were due, in part, to the country's rapid agricultural and economic growth, its strong "resilience"-type programs, and the rapid donor reaction and support at the start of the crisis. An analysis of the 2015–16 ENSO event finds that yield losses were concentrated in several subregions, with impacts greatest in the drier, less-populated lowlands, where cereal production dropped by an estimated 10% and livestock herd size shrank by almost a quarter. At the national level, grain production fell by 5% and herd declines were small, owing to increases in size and production in more favorable areas. The overall adverse impacts on crop and livestock production lowered national GDP by 1.6% (or US$438 million in 2010/11 prices), and those economic losses were similarly concentrated in specific sectors and regions. Agricultural GDP fell by 3.6%, and the GDP of the drought-prone lowlands fell by a significant 11.1%.

More than a decade of increased investment in agriculture in Ethiopia clearly paid off. In the past decade, cereal production growth in the country accelerated to 7.4% annually, up from 3.9% per year during 1996–2006. Key programs that support resilience to climatic shocks include the Productive Safety Net Programme, the Program of Adaptation to Climate Change, the Agricultural Growth Program, and a series of irrigation investment programs. Several donors also used a crisis modifier (a funding mechanism to provide timely responses to crises by development partners already operating on the ground) to redirect or increase already funded aid programs.

Although the 2015–16 ENSO events had a marked impact—affecting several regions severely and particularly the lowland, pastoralist areas—strong agricultural and economic growth, existing resilience programs, and rapid donor support to address the adverse impacts helped avoid outright disaster. However, similar resilience programs either do not yet exist or are not equally strong in the lowland areas and are not as strong for pastoralist and livestock systems, where recovery of agricultural assets also takes much longer. Moreover, to further strengthen resilience, larger investments in rural services (such as access to education, healthcare, and credit) and rural infrastructure are urgently needed, particularly in the lowlands but also in more remote highland areas. Finally, to strengthen nutrition security, rapid growth in cereals needs to be accompanied by equally rapid growth in the horticultural, livestock, and fisheries sectors.[92]

BOX 2.4 Multiple Shocks on the Food System—A Dire Scenario

In 2015, Lloyds of London commissioned an exercise simulating the development and plausible effects of multiple shocks on the food market triggered, during a single year, by a strong El Niño event in the central equatorial Pacific Ocean. The scenario estimates that production of key global crop commodities (maize, soybean, wheat, and rice) would be significantly reduced due to a combination of flooding and droughts affecting the United States, South Asia, Australia, and large producers in Southeast Asia and Latin America. In addition, the scenario hypothesizes that strong winds would help the spread of stem rust pathogens, which would further affect production in Russia, Kazakhstan, and Ukraine. Despite the uncertainties surrounding exactly how shocks propagate through our vastly interconnected economies, the consequences of this dire scenario were estimated in a fourfold increase in commodity prices, fluctuations in commodity stocks, civil unrest, humanitarian crises, and major worldwide financial losses.[93] The main picture is that of a systemic shock that produces a cascade of economic, political, and social challenges.

2.3 Adaptive Responses

2.3.1 THE ROLE OF IMPROVED AGRICULTURAL MANAGEMENT PRACTICES

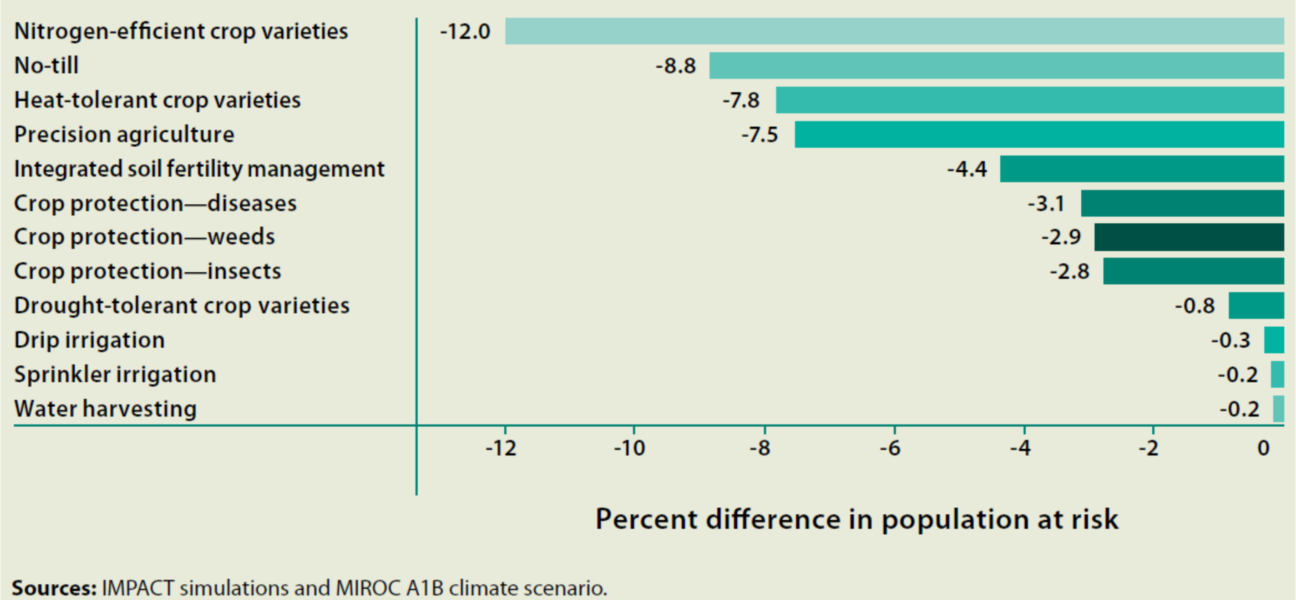
Recent IFPRI research has examined the potential of improved agricultural management practices to increase food security.[94] The analysis focused on three key staple crops—maize, rice, and wheat—and compared the effects of different management practices as well as breeding efforts (see section 2.3.2) on crop yields and the use of resources, such as harvested area, water use, and fertilizers. Among the management practices, no-till farming, which involves minimum or no soil disturbance, is the best option for wheat under one of the climate scenarios considered (MIROC A1B).

Adopting these management practices could have a significant positive impact on food security: the number of food-insecure people in developing countries in 2050 could be reduced by 9% (91 million people) if no-till farming were more widely adopted; and by 8% (close to 80 million people) if precision agriculture (a set of practices that includes more-precise, and sometimes Global Positioning System (GPS)-assisted, delivery of agricultural inputs) were adopted (Figure 2.7). The literature also documents how changing the planting dates have positive effects on yields and yield volatility. Positive results are shown for several crops.[95,96,97,98,99] To exploit this relatively simple form of adaptation, farmers would need information about the new weather patterns and the onset of the rainy season.

Changes in pest management has been a key proposed strategy to fight back the fall armyworm infestation in Africa and South Asia, but improved crop management practices, such as intercropping maize with drought-tolerant *desmodium* and planting of a third crop (*Brachiaria cv Mulato II*) as a border crop, can also help control the pest, particularly in areas where adequate pesticides are unavailable or expensive. An initial study in pilot areas of Kenya, Tanzania, and Uganda showed that the chemicals emitted by the intercrop repel stemborer moths of the same family as fall armyworm away from maize crops, while the border crop attracts the moths.[100] Fall armyworm likely may spread to these regions through the importation of infected crops or fruits, and the weather in these regions was already conducive to its spread; however, it is also expected to spread further north into Canada or Europe with climate change, as it cannot survive freezing winters.

Some experts summarize agricultural practices and technologies under the term *climate-smart agriculture* (CSA). CSA proposes a framework that supports decisionmaking in the agriculture sector by considering three foundational outcomes and by fully accounting for the trade-offs and synergies among them. The framework is composed of agricultural systems that contribute to (1) sustainable and equitable increases in agricultural productivity and incomes, (2) greater adaptation and resilience to climate change of food systems from the farm to the national level, and (3) the reduction or removal of GHG emissions where possible (Box 2.5).

FIGURE 2.7 Change in the global number of people at risk of hunger



Source: Reproduced from Rosegrant et al. (2014).

Note: change in 2050 relative to the baseline scenario, under alternative agricultural management practices and crop breeding strategies.

Importantly, similar to many other agricultural technologies and practices promoted in recent decades, the adoption of seemingly beneficial practices is not assured because of the large heterogeneity in factors influencing and determining the adoption process. For example, improved access to information on climate change and the appropriate technologies and practices for adaptation can increase adoption rates. Other factors influencing adoption include farm size, labor availability, level of risk aversion, access to financial services, and social capital.[101,102]

Strong governance institutions are also needed on multiple scales to encourage adoption of CSA practices. Institutions including national and regional governments, formal and informal community organizations, and market institutions play an important role in promoting inclusivity; providing information; encouraging innovation and investment; and managing risk to enable smallholders, women, and poor resource-dependent communities to adopt and benefit from CSA. Better policies and increased investments are needed to address the key structural, technological, and institutional weaknesses that constrain transformative adaptation.[103] In particular, investments in institutional capacity are required to improve the ability of governments and local organizations to provide effective leadership, allocate resources efficiently, and improve collaboration and coordination of adaptation efforts across scales and sectors.[104]

The economic, social, and environmental implications of improved agricultural management practices depend greatly on the choice of practice and geography. Again, strong governance is essential to avoid and address any potential tradeoffs. Decisionmakers should select from a set of available options the most promising approaches that address the challenge of climate change and maximize the economic, social, and environmental objectives based on their priorities. At the farm level, some agricultural practices may be profitable and contribute to livelihood improvements for farmers; others may increase the environmental sustainability of production but have limited economic benefits, at least in the short term. Finally, the selection of agricultural technologies and practices has implications for which social groups benefit (see Box 2.6 on youth in agriculture and Box 2.7 on the gender dimensions of adaptation). Moreover, there may be unintended negative effects on women and youth in terms of the nutrition outcomes of particular adaptation investments and technologies. For example, the commercialization of the dairy sector in Kenya has had documented negative impacts for women.[105]

BOX 2.5 The Case for Climate-Smart Agriculture

Recent developments in the United Nations Framework Convention on Climate Change (UNFCCC) negotiations (i.e., the 2015 Paris Agreement[106] and the Koronivia joint work on agriculture) and the recent Intergovernmental Panel on Climate Change special report have reinvigorated calls for incentives to reduce GHG emissions, including carbon pricing and the levy of a carbon tax. However, the latest analyses on the subject indicate that a tax on GHG emissions may lead to significant trade-offs between emissions abatement and food security. It is in this environment that the CSA concept has become increasingly relevant.

Many operational aspects of CSA are still under investigation, as local contexts determine the enabling environment as well as the trade-offs and synergies of productivity, adaptation, and mitigation. Farmers must identify climate-smart practices for their biophysical, agricultural, and socioeconomic contexts. Short-term tradeoffs, such as increased cost to farmers, are possible. However, in the long run, widescale adoption of a few CSA practices used in the production of maize, wheat, and rice can lead to increased food production, reduced food prices, and lower GHG emissions.[107] Further, by 2050, CSA practices are projected to increase global production of maize by an estimated 1.4% to 8.8% and of wheat by 0.5% to 8.5%, compared with a business-as-usual scenario. CSA practices appear to have the largest effect on rice, for which production is approximately 4% to 16% larger than under a business-as-usual scenario. As a result of these changes, prices for the three crops decrease, and the population at risk of hunger is projected to drop by 13 million people to 69 million by 2050, with the greatest improvements in sub-Saharan Africa, Southeast Asia, and South Asia. At the same time, farmers' adoption of CSA practices leads to a reduction in emissions of between 9 to 124 Mt CO_2 e per year, depending on how the practices are implemented. This result should alleviate existing concerns regarding the feasibility of reducing emissions while increasing the food-security conditions of many populations.

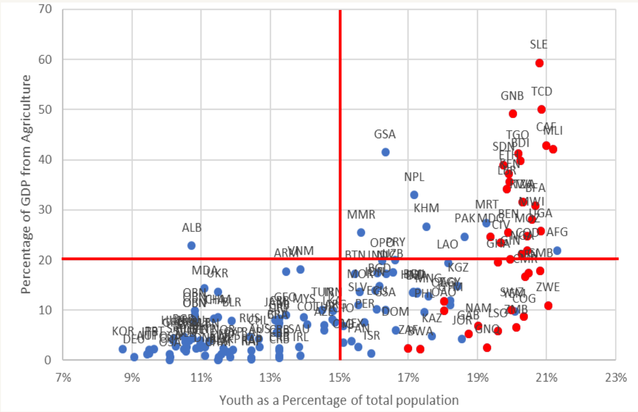
What is required and how can countries effectively transition to CSA? Transitioning from current policies and practices to those following CSA criteria will require that decisionmakers have accurate and current information to make effective decisions. Several broad areas for intervention at the country and regional levels include the following:

1. Establish the human and institutional capacity necessary to deal with a range of outcomes and empower decision- and policymakers with the tools to develop a range of response options. Develop and support governments, the private sector, farmer organizations, and civil society organizations to look across the range of challenges facing a country and work together to identify solutions.
2. Acknowledge the interaction between crop production and other land uses and the broad-based mitigation and adaptation potential of landscape systems. Policies that aim at promoting CSA should not consider agriculture in isolation.
3. Explore avenues to reduce and remove barriers that prevent the adoption of CSA practices. Barriers exist at all levels among stakeholders (i.e., lack of sufficient knowledge, or imperfect and fragmented markets that prevent farmers from engaging in more entrepreneurial activities) and need to be addressed at the local, regional, and national levels.
4. Improve data collection and access to spatially disaggregated weather data, prices, land-use information, and other important topics, such as gender-disaggregated data, in order to develop integrated metrics that are meaningful and useful for decisionmakers and the affected communities.[108]

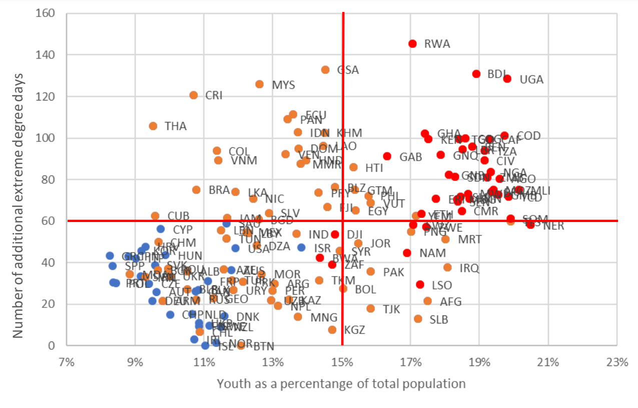
BOX 2.6 Youth in Agriculture in sub-Saharan Africa[109]

Countries with a high share of agriculture in GDP also tend to have high shares of youth (15–24 years old) in the total population (Box Figure 1). By 2030, two-thirds of the projected 500 million rural young people will be in sub-Saharan Africa (red dots in Box Figure 1), where farming still employs more than half of the labor force and the absolute number of agricultural workers continues to grow (although the share of employment in agriculture as a portion of total employment is declining). There is also a strong correlation between the share of youth in rural areas and the increase in additional heat days, a signal of climate change, with sub-Saharan Africa again being singled out (Box Figure 2).

Box Figure 1: Share of GDP from agriculture in 2016 vs. youth as a share of the population projected for 2030



Box Figure 2: Proportion of youth and additional extreme heat days by country, 2050



Achieving both food and job security in this region will thus be particularly challenging under climate change and variability. A wide range of technologies and practices have been identified that can help young people adapt to climate change in sub-Saharan Africa and elsewhere; these include improved climate information and extension services (through mobile phones), adoption of irrigation and other mechanization services (although not all mechanization will generate new jobs, it will increase competitiveness of agriculture over time), and adoption of low-cost precision agricultural tools such as soil moisture sensors or wetting front detectors in irrigated environments. In addition to the greater number of children and youth finishing secondary degrees, more on-the-job training opportunities and jobs need to be created for agricultural scientists, both men and women, in Africa and elsewhere. The AWARD program (https://awardfellowships.org/) is one such initiative focused on bridging the science gap in agriculture in Africa. In addition, the enabling environment needs to be enhanced to ensure job security for youth under climate change. This includes improved access to land, information, and financing sources to establish viable agricultural enterprises.

BOX 2.7 Gender Dimensions of Adaptation to Climate Change

The growing literature on the gender dimensions of climate change suggests that men and women have different capacities to adapt to climate shocks and stressors and different bargaining power to choose adaptation options that meet their own needs and preferences, and also are affected differently by chosen adaptation options.[110,111] These differences require careful consideration of the gender implications of improved agricultural management practices, technologies, policies, and investments, as well as program implementation that monitors differential well-being outcomes by gender and other social distinctions such as age, marital status, and ethnicity. For example, to address the gender gap in information access, climate information services should ensure that both men and women receive information that meets their needs.[112,113,114] Project implementers should consider the labor implications of practices that they promote because some practices, like conservation agriculture, have been shown to increase the burden on women's time.[115] Other measures are needed to ensure that women have equal access to productive assets, like land, and financial capital, such as credit, given that the gender gap in access to these resources limits women's adaptive capacity in ways that are detrimental to achieving other development outcomes, including better nutrition and health.[116,117,118,119,120]

2.3.2 CROP BREEDING FOR HIGHER YIELDS AND CLIMATE TOLERANCE

Climate change is recognized as one of the most serious challenges to the future health of ecosystems worldwide.[121] Increasing temperatures already have modified the phenology of biological processes, which can disrupt ecosystem functioning,[122,123] lead to changes in species' distributions,[124] and lead to increased extinction risk through decreases in population size.[125] If climate continues to change as predicted,[126] many populations will fall outside of their habitat niche. In the absence of migration or adaptation, these populations will be extirpated. Adaptation requiring new mutations will be unlikely for species with long generation times, so evolutionary success will depend on standing genetic variation.[127]

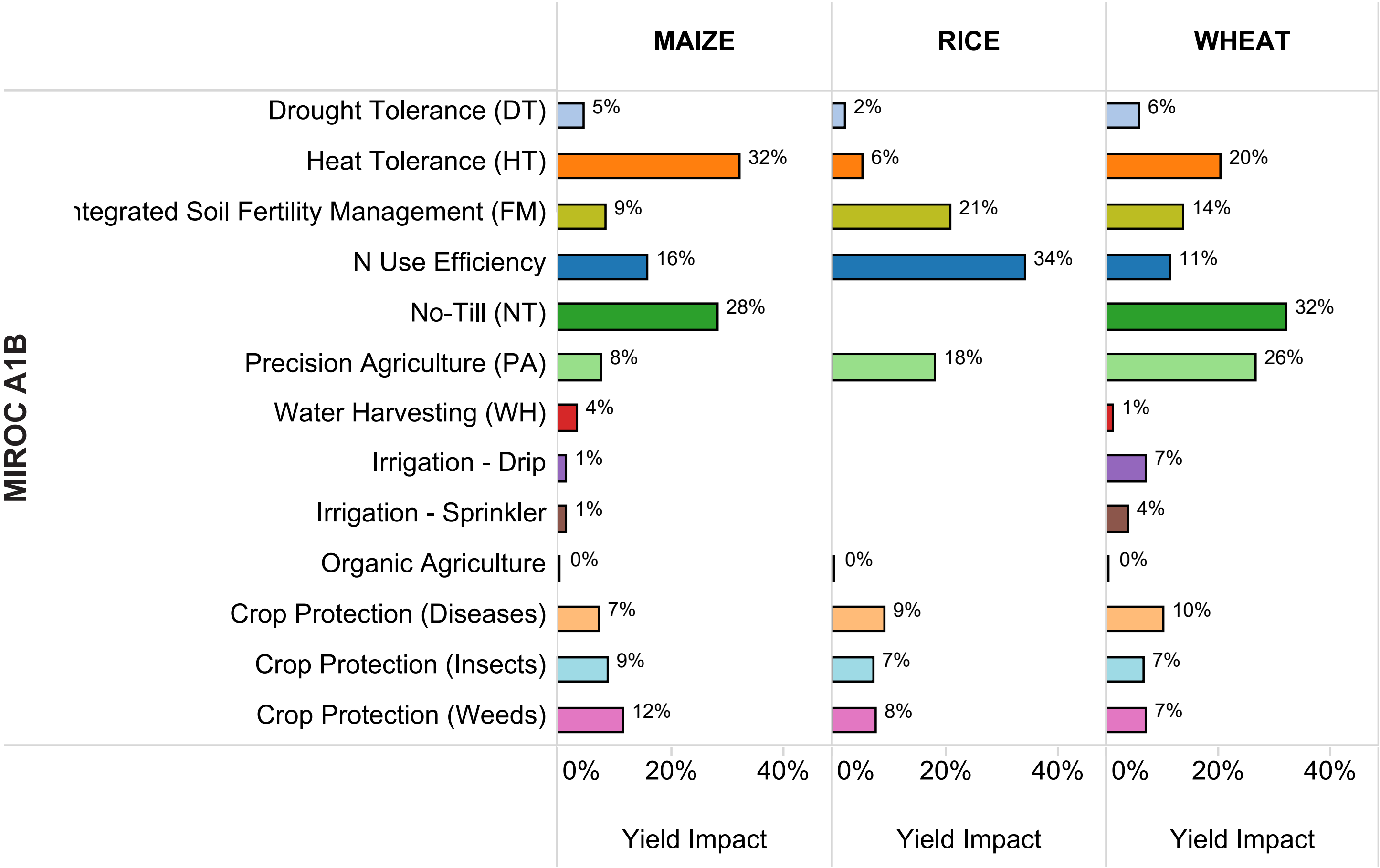
Genetic diversity has traditionally been used to fight many challenges to food security. Breeding methods have been used to select new crop varieties that provide better yields, resist pests and diseases, and are better suited to unfavorable climate and growing conditions. Access to improved crop varieties with characteristics suitable for different locations and new growing conditions (including prolonged droughts, heatwaves, and even more frequent and longer flooding) will be necessary to successfully adapt and maintain agricultural production and yields. Yet given the projected speed and magnitude at which climate change is advancing, it is unlikely that autonomous adaptation—the combination of adoption of new crops, some crop breeding, and changes in the planting period that farmers have relied on for centuries—will be enough.[128]

Recent IFPRI research has examined the potential of selected breeding strategies to increase food production under climate change.[129] Globally, across the three key staple crops of maize, wheat, and rice, heat-tolerant crop varieties generated the highest adaptation potential for maize; and breeding of nitrogen use efficiency had the best outcomes globally for rice. For wheat, heat tolerance was found to be particularly beneficial (Figures 2.8, 2.9).

Results varied considerably by region and to some extent, by climate change scenario. As an example, for heat-tolerant maize, adaptation benefits were highest in North America and South Asia, followed by East Asia and western Asia. Benefits of drought tolerance in maize, by contrast, were smaller and more evenly spread. Benefits from crop protection to diseases (managing pests, plant diseases, weeds, and other pest organisms that damage agricultural crops) were also spread somewhat evenly but slightly higher in West Africa, Central Africa, and South Asia. Results for drought tolerance varied if the climate scenarios included variability or only long-term means (see Box 2.8).

If investments in nitrogen-efficient crop varieties could be accelerated, the number of food-insecure people in developing countries in 2050 could be reduced by 12% (almost 124 million people); and by 8% (80 million people) if heat-tolerant crop varieties were adopted (Figure 2.6).

FIGURE 2.8 Changes in crop yields due to technology adoption



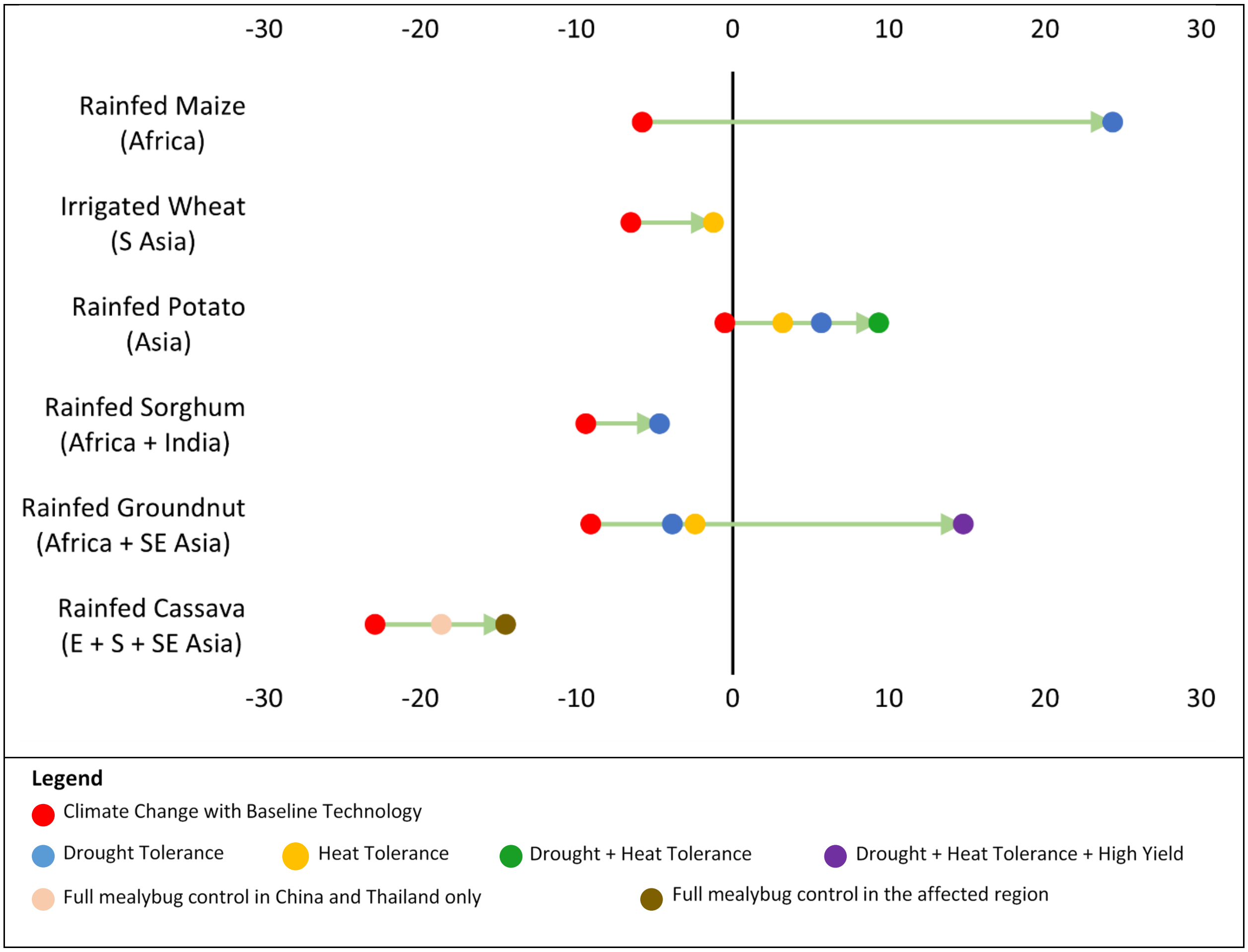
Source: Reproduced from Rosegrant et al. (2014).

Note: yield response to accelerated adoption of alternative breeding strategies and management practices. Percentage change in 2050 over a scenario without technology adoption. Biophysical results only (i.e., only from scenarios run through the DSSAT crop model).

BOX 2.8 Drought Tolerance: More Valuable Under Scenarios of Climate VariabilityClimate Change

Drought tolerance is a desirable trait that allows agricultural producers to manage risk. It is of greatest concern during drought conditions. However, as a technology that influences risk, drought tolerance may not show large ex ante yield benefits when considering mean effects on productivity. Rosegrant et al. (2014) assessed, ex-ante, the yield benefit of a drought tolerance trait of roots with improved access to soil moisture for maize using DSSAT with a stochastic weather generator. They find that the benefit of the technology depends on the original variety into which the drought tolerance, as well as on local conditions. At the regional level, improvements in the neighborhood of 9–13% could be achieved when drought conditions occur under both historical and future climate conditions. A more holistic bundle of traits would increase the envelope of yield improvements under drought conditions to well above 10%.

FIGURE 2.9 Impacts of selected crop improvements in offsetting yield losses to climate change



Source: Reproduced from Robinson, Mason D'Croz, Islam, Cenacchi et al. (2015).

Note: impacts are estimated for the year 2050. Red dot shows the impacts of climate change on yields when none of the improved technologies tested were adopted. The other colored dots show how adoption of improved varieties and technologies helps reduce the effects of climate change.

The Global Futures & Strategic Foresight program, led by IFPRI in collaboration with 14 other CGIAR Centers, has assessed the potential of new drought- and heat-tolerant crop varieties in greater detail for a select number of crops and regions. Similar to Rosegrant et al.,[130] results show that biophysical yield gains from accelerated investment in the development, dissemination, and adoption of selected technologies differ by technology and region but generally are able to reduce and sometime completely offset the adverse effects of long-term climate change (Figure 2.8). Ortiz-Bobea and Tack[131] suggest that yield gains in the order of those achieved during the period of rapid adoption of genetically engineered seeds will be needed to avoid yield reductions as a result of climate change. However, an "antiscience zealotry"[132] might well slow or even derail efforts toward accelerating agricultural productivity growth through the development of new technologies, from biotechnologies or other methods of agricultural science.

New and promising genome editing systems enable targeted, precise modifications of the genome at a previously unachievable degree. They present a great opportunity for molecular ecologists to achieve the target-specific manipulation of genes of interest. CRISPR/Cas gene editing[133,134] is a new technology with promising potential, given that it is capable of introducing precise genomic changes in a wide range of organisms and given its robustness, affordability, design flexibility, and high efficiency. Some selected traits have already been modified by genome editing in plants and animals. Soon these modified plants will reach the market, and some crop plant varieties are already being commercially produced in the United States and a few other countries. Gene editing examples include blight-resistant rice, powdery mildew–resistant wheat, herbicide-resistant canola, soybean with reduced trans fats, high-yielding rice, and high-yielding wax corn.[135] In addition, genome editing can be used to aid classical breeding strategies by revealing the genetic basis underlying contrasting phenotypic groups.[136] Genome editing is particularly promising to address food security issues in developing countries where local crop plant varieties are the mainstay, as it helps to minimize dependency on a shrinking list of major crops, which are associated with nutrition deficiency, limited genetic diversity, and lower crop resilience.[137]

A globally harmonized regulatory approach must still be developed and should be considered of high importance to avoid trade issues and unnecessary inefficiencies and barriers related to the use of this technology. Edits at the DNA level are considered equivalent to those that take place naturally or in mutagenesis and that have a long history of safe use. Therefore, these edits should be considered at least as safe as conventional breeding.[138]

Although genome editing of staple crops is particularly promising to address food security issues and micronutrient deficiencies in developing countries and to increase economic returns to small producers, care must be taken to avoid losing biodiversity or displacing crop varieties or types that are important for particular social groups, such as women. To address these concerns, new research programs focus on joint trait and seed system development and analysis with women and marginal farmers, such as the new gender and seed system program supported by the CGIAR Gender Platform.[139,140]

Developing countries currently are investing only limited amounts of funding into plant breeding. Given the promise of breeding for yield stability and climate tolerance, funding efforts in this area would need to be increased (Box 2.9).

2.3.3 THE ROLE OF IMPROVED AGRICULTURAL WATER MANAGEMENT AND IRRIGATION

Improved agricultural water management and expansion of irrigation are key climate change adaptation strategies, particularly in countries and regions affected by growing intra- and interannual variability. In the dryland areas of Africa, for example, irrigated areas account for less than 5% of the farmed area (5.2 million hectares) but support a much larger population proportionally than pastoral and rainfed systems.[141]

BOX 2.9 Examples on Breeding for Climate Change Adaptation in the Developing World

In the early 1990s, CIMMYT (International Maize and Wheat Improvement Center) scientists selected maize lines that survive and yield grain under controlled drought or low soil nitrogen on experimental plots. This initiative morphed into the Drought Tolerant Maize for Africa (DTMA) project (http://dtma.cimmyt.org/), which also included IITA (International Institute of Tropical Agriculture) from 2007 to 2015. Through work with dozens of national partners and private companies, DTMA was responsible for developing and releasing more than 200 drought-tolerant varieties. In 2014, 54,000 metric tons of certified drought-tolerant maize seed was produced across the 13 DTMA countries.

In 2011, the Indian Government established the National Innovations on Climate Resilient Agriculture (NICRA) network under the Indian Council of Agricultural Research (ICAR). The goal of the network was to enhance resilience of Indian agriculture to climate change and climate vulnerability through strategic research and technology demonstration. Breeding is one of several components of this initiative. Early results include the development of early-maturing drought-tolerant varieties and paddy varieties tolerant to submergence in flood-prone districts. Other efforts include identifying temperature-tolerant rice and maize varieties for the northeast, understanding relationships between high temperature and pest and disease on tomato and mango, and understanding disease-resistant traits in key livestock products. From 2011 to 2016, the program spent about US$100 million, accounting for approximately 4% of ICAR's total expenditures.

Governments, particularly those in Africa, have elevated the importance of investments in irrigation both to meet national food security goals and increasingly to address climate change adaptation needs.[142] Devajaran,[143] for example, suggests that whereas tripling irrigated area in the Zambezi River basin in southern Africa would be a break-even investment, the overall benefits would be double the cost of investment if avoided damages from climate change and more frequent droughts were considered. Ringler et al.[144] also find that without additional irrigation investment, the share of people at risk of hunger in sub-Saharan Africa would be 5% higher by 2030 and 12% higher by 2050.

The Permanent Interstate Committee for Drought Control in the Sahel (CILLS; Comité Permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel) has an ambitious strategy to accelerate irrigation development in West Africa. Given the water scarcity in the region, it focuses on large-scale irrigation supported by reservoir development. Other regions and countries focus on combinations of large-scale and smaller-scale irrigation development. Ethiopia, for example, is aggressively pursuing a household irrigation strategy, which contributed to an increase in irrigated area of 0.5 million hectares in the country during 2004–15.

In Morocco, a highly water scarce country in North Africa, the focus has been the switch from traditional irrigation methods, such as gravity irrigation, to drip irrigation. From 2008 to 2014, close to 0.5 million hectares of gravity irrigation areas were converted to drip irrigation. At the same time, there was a partial switch from groundwater sources to surface reservoirs. Drip systems increase the efficiency of the applied water for crops, can reduce the overall volume of water used in irrigation, and can improve the quality of the produce (particularly for horticultural crops). However, drip irrigation relies on the daily application of small amounts of water to plants, and therefore requires particularly high levels of water control, which might be challenging during climate extreme events and in light of increasing competition with non-irrigation water demands. Analyses suggest that irrigation development and modernization to date has made important contributions to the resilience of Morocco's economy. During the 2015–16 drought, agricultural GDP fell by only 7%, rather than the 40% that might have occurred without the large investment in irrigation development.[145]

Households themselves often list irrigation as their top preferred—but not implemented—adaptation strategy. As an example, among farmers in a household survey of various agroecological regions in Kenya, almost half (49%) of all farmers interviewed listed irrigation investment as their preferred adaptation strategy, followed by investment in agroforestry (39%). This desire was confirmed by gendered focus-group discussions, in which irrigation and water-harvesting schemes were ranked as the key priority adaptations regardless of gender and agroecological zone. Farmers mentioned lack of access to financial resources and, in the case of irrigation, lack of access to water, as key barriers to adaptation.[146]

The future of irrigation in Africa will likely be threefold. Most smallholders will continue to rely on rainfed agriculture. Here, water-harvesting schemes and integrated soil and water management are important and typically are farm-led investments. In regions where farmers can access water at low costs and where markets are developed, small-scale irrigation can provide opportunities for large numbers of poor households to increase their income and reduce production variability. In some instances, small-scale irrigation systems, such as those that rely on small reservoirs or ponds or weirs diverting irrigation water from rivers or streams, require support from national or local governments and development partners. In areas where large-scale irrigated agriculture is feasible, commercial value chains could emerge, propelled by economies of scale, which will provide producers with higher and more stable cash incomes that will considerably reduce their vulnerability to shocks. Spillover effects from small-scale and large-scale irrigation to rainfed systems can increase the resilience of rainfed farming systems.[147,148,149]

Xie et al.[150] find that accelerated irrigation development in the dryland areas of sub-Saharan Africa—with a particular focus on small-scale irrigation—can reduce net cereal imports to the region by as much as 68%, or 90 million metric tons, from a baseline net import volume of 133 million metric tons in 2050. The dramatic production increases achieved under the accelerated irrigation scenarios can also drastically reverse the region's growing net food import dependency, from 54% by 2050 under a business-as-usual scenario to between 17% and 40%—that is, as low as today's import dependency levels. National economic growth and rural income gains could substantially reduce the region's population at risk of hunger, even beyond the calculated reductions from increased access provided by lower food prices from accelerated growth. Successful development of irrigation can have a further transformative impact on rural livelihoods because of the multiplier effect on local economies. Yet the benefits of irrigation extend beyond the African continent. Rosegrant et al.[151] find that globally, irrigated environments provide a yield multiplier effect and improve the overall outcomes for most, if not all, agricultural management practices and technologies studied, including no-till, crop protection, and heat stress technologies.

Africa and parts of Asia have great potential for the development of renewable energy technologies and systems.[152] This would provide an opportunity for irrigation development on the continent to follow a greener path than the case of South Asia, for example. The overall increased availability of low-cost pumps to draw water from ground and surface water sources—human-powered, diesel, electric, and increasingly solar (see Box 2.10)—has been a game changer in South Asia's and parts of Southeast Asia's agricultural and economic development. Such pumps might well be the key factor accelerating irrigation development in Africa. Small-scale irrigation is expanding particularly rapidly in countries that have established favorable environments for pumps, such as by eliminating import charges for pumps (Ethiopia, Zambia) or providing credit access.

However, as the case of South Asia demonstrates, without adequate institutions and knowledge to manage water for irrigation, water resources can quickly be depleted or deteriorate in quality. Opportunities exist to maximize resource use efficiency in irrigated and even rainfed systems through infrastructure improvements, adoption of water-saving technologies (such as low-cost soil water measurement devices or sensors), and improved monitoring of water quantity and quality. The social implications of irrigation also need to be strengthened. Irrigation offers great potential to increase the availability and quality of nutritious foods, such as fruits and vegetables, and economic access to diverse diets, through income gains. However, access to water for irrigation is not always equally distributed among members of the community. Moreover, the costs and benefits of small-scale irrigation technologies adopted at the household level do not always benefit men and women within the same household equally.[153]

In addition to agricultural water management, enhanced management of water resources using a catchment, watershed, and basin-level approach will be essential for climate change adaptation. For example, protection of upstream watersheds from deforestation is essential to avoid soil erosion, degradation, and associated sedimentation of water bodies. Payment for Ecosystem Services have been used to achieve this important adaptation mechanism, supporting both agricultural and urban areas. Other, so-called nature-based solutions that can support agricultural water management (water quality and quantity) include the concepts of sponge cities, more general wetland restoration, and joint management with reservoirs and other water infrastructure, as well as managed aquifer recharge. All of these methods can reduce rural (and urban) infrastructure risks posed by floods and droughts.[154]

2.3.4 LIVESTOCK MANAGEMENT PRACTICES AND BREEDING STRATEGIES

Currently, livestock production employs at least 1.3 billion people worldwide. About 600 million of the world's poorest households keep livestock as an essential source of income.[155] Livestock contribute 40% of the global value of agricultural output and are one of the fastest-growing agricultural subsectors in developing countries.[156] The rapidly increasing demand for livestock products is being driven by population growth, urbanization, and increasing incomes in developing countries.[157] Economic growth is expected to have a considerable impact on food consumption patterns, particularly on the demand for livestock products. This demand is projected to grow particularly fast in sub-Saharan Africa and South Asia (by 317% and 315% by 2050, respectively), while growth is expected to be moderate in industrialized countries (30% by 2050) (Valin et al. 2014).[158] Over the coming decades, livestock production systems will need to meet the substantial increases in demand for food products. Climate change will make it more difficult to meet this demand.

BOX 2.10 Solar-powered Irrigation: A Game Changer?

Solar groundwater irrigation is considered a game changer for agricultural intensification, particularly in the more remote areas of South Asia and sub-Saharan Africa that are not yet connected to the public grid. But on-grid models (where farmers can sell solar power back to the grid in addition to obtaining increased farm income) are also being developed (IWMI 2017). Solar-powered irrigation has only recently become a viable option for better-off small-scale producers as the cost of solar panels has fallen dramatically.[159] Yet high subsidy levels for solar operations have contributed to the overpricing and more limited availability of solar pumps in the market in countries like India. Solar pumps remain an expensive capital investment for individual smallholders and increased access will depend on innovative financing mechanisms.

If access challenges can be overcome, solar irrigation could help address many of the challenges of underinvestment in irrigation. Groundwater can be accessed at a much larger scale than surface water, which is limited to surface water bodies such as rivers, streams, and lakes or must be collected through harvesting of rainwater. As an alternative to hand-lifting devices or diesel and electric pumps, solar-powered water pumping systems reduce labor costs and drudgery. They also can reach more remote areas and those not served by electric grids; in Africa south of the Sahara, less than 40% of the population has access to electricity, and access in rural areas is even lower. In places without electric grid access, solar-irrigation systems can be used for lighting and cooling, for charging mobile phones, and for operating televisions and radios.

Whereas diesel and electric pumps carry variable costs, potentially providing a signal for their efficient use, the only limit to extraction is availability of solar radiation. To ensure that solar irrigation does not deplete groundwater resources, solar irrigation introduction needs to be accompanied by groundwater governance institutions. The development of strong institutions takes a long time, but in the interim collective-action mechanisms can increase groundwater stewardship.[160,161]

Adaptation to climate change in the livestock sector includes addressing the threats to animal nutrition and animal health, with the goal of improving animal productivity. For instance, novel feeds may provide alternative sources of protein and energy, although the potential of such feeds is largely unknown.[162] A closer integration of crops and livestock systems is expected to increase productivity and stover quality and promote soil fertility.[163,164] The use of mixed systems (including silvopastoral systems), together with methods to reduce the tannin content of tree and shrub material, can have beneficial effects on livestock performance. One other area that offers significant promise, particularly for tropical ruminant nutrition, is microbial genomics of the rumen, for breaking down lignocellulose.[165] Finally, there are ample opportunities to address emissions through improved manure management, avoided land use change, and changes to diets.[166] It is particularly difficult to addressing livestock productivity in semiarid regions; the most likely way to improve in this area will involve disseminating information from early warning systems and drought predictions, allowing herders to better manage the complex interactions between herd size, feed availability, and rainfall.[167] Changes in the abundance, seasonality, and spatial spread of vector borne diseases raise the need for improved diagnosis and early detection of livestock parasitic disease, along with greater awareness and preparedness to deal with changing disease patterns.

There are also considerable opportunities to increase productivity in developing countries using “within-breed” selection and breed substitution or breed crossing. However, these approaches need to be tailored to specific and at times constrained production systems.[168] Molecular genetics and genome editing (CRISPR/Cas) are likely to have considerable future impacts. Existing genome maps for poultry and cattle open opportunities for advances in evolutionary biology, animal breeding, and animal models for human diseases.[169] Genomic selection likely will revolutionize the future of animal breeding. Furthermore, multipurpose and nanosized sensors to report on the physiological status of animals are being developed, and advances can be expected in drug delivery methods. Nanoparticles can induce a more efficient use of nutrients for milk production and improve animal waste management by enhancing biogas production from anaerobic digesters.[170]

Although the pressure for increasing livestock production will increase, it is important to keep in mind that livestock, and related food chains, are among the major contributors to GHG emissions, accounting for about 18% of total emissions.[171,172] Limits on emissions will be one of the main factors that determine the future of this sector. Improved feeding practices (such as increased amounts of concentrates and improved pasture quality), or selection of breeds with lower feed intake[173] can reduce methane (CH_4) emissions per kilogram of product. Many specific agents and dietary additives have been proposed to reduce CH_4 emissions, including certain antibiotics; compounds that inhibit methanogenic bacteria; probiotics, such as yeast cultures; and propionate precursors, such as fumarate and malate, that reduce CH_4 formation.[174] Some adaptation options also have mitigation benefits, among them growing agroforestry species that can sequester carbon and also provide high-quality dietary supplements for cattle.

Finally, artificial meat and plant-based meat alternatives, which are already widely available in restaurants and food chains, can truly disrupt the sector (Box 2.11). The uptake of these alternatives on a large scale would raise critical issues regarding livestock keeping and the livelihoods of the resource-poor in many developing countries. Massive reductions in livestock numbers could reduce GHGs substantially, the net effects would depend on the resources needed to produce alternative forms of artificial meat and plant-based alternatives to meat.

Livestock management practices, such as improved feeding, breeding, and breed selection; expansion of veterinary care; and expansion of mixed crop-livestock systems are important for the livelihood sustainability of small livestock producers as well as the nutrition security of the rural and urban poor in developing countries, where protein deficiencies are common. However, overconsumption of animal-source foods in developed countries and growing demand for meat in middle-income countries and urban areas in developing countries are unsustainable from an environmental perspective. Different strategies are required to increase the sustainability of livestock production for small producers in developing countries and larger producers in the developed world. The distribution of economic and social costs and benefits of alternative options should be considered carefully to ensure that the needs of most vulnerable groups are met.

2.3.5 CLIMATE SERVICES

Climate services are crucial for successful adaptation to occur.[175] Climate services play a crucial role in developing and disseminating standards as well as customized climate information and products to stakeholders. These products include climate change impacts, vulnerability, risks, and uncertainties. In 2009, the World Climate Conference-3 (WCC-3) convened by the World Meteorological Organization (WMO) established the Global Framework for Climate Services (GFCS) “to strengthen the provision and use of climate predictions, products, and information worldwide”.[176] These services are essential to monitor natural weather hazards and alert countries and people in order to facilitate preparedness (e.g., ENSO), improve long-range forecasts, and develop responses related to evolving or foreseen climate anomalies and extremes at the regional and national levels. The importance of these data for economic modeling and policy formulation should not be underestimated. Up to now, the effects of changes in mean temperatures and precipitation have been the main focus of discussions on climate change impacts on agriculture and the related quantitative modeling. The effects of climate change on the volatility of agricultural production, crop and livestock prices, and longer-term producer responses to the associated increased risk have received much less attention. However, other analyses[177,178,179,180] suggest that impacts will include increases in the frequency of droughts, shifts in the timing of optimal planting and harvesting periods, increased variability in growing conditions, and greater uncertainty in predicting short-term weather events, like the onset of rain and dry seasons, complicating smallholder farmers’ production decisions. To provide these services, stronger data network collection, quality, and standards are necessary. Local governments also will need increased capacity to develop and disseminate climate information at local and regional scales, given discrepancies in global models and the need to develop appropriate adaptation actions at the local level.[181] Research and capacity building may help strengthen local forecasting of future climate risks and better account for the costs and benefits of alternative locally-relevant adaptation options.[182]

BOX 2.11 Alternatives to the Conventional Production of Animal-Source Foods (ASFs)

Three types of alternatives to farm-based production are being considered in future food supply-and-demand analyses: (1) plant-based alternatives to meat, (2) cultured ASFs (also called clean or cultured meat, clean seafood, or cultured eggs and dairy), and (3) edible insects.

Demand for plant-based alternatives to meat and dairy has been growing rapidly in the Global North, with an annual growth of 8% for meat alternatives, and much faster growth in selected markets (GFI 2018). The introduction of a plant-based meat-like burger (“Impossible Whopper”) by the fast food chain Burger King[183] likely will help propel plant-based meat alternatives into mainstream eating culture. These products have large GHG mitigation benefits, and also conserve water and land resources compared with conventional production of meat products such as beef. However, the quality of the plant-based protein differs from that of ASF, and evidence is growing that ASFs are important for child linear growth, particularly for children from ages of 6 to 24 months.[184] This still leaves a large share of the population that could be served by these meat alternatives. Cultured ASF include cell cultures from animals, and are or have been developed for meat and seafood, as well as those produced through fermentation processes including milk and egg proteins. These products include higher-quality protein than their plant-based alternatives, as reflected in the concentration of essential amino acids needed for human growth. ASF also have higher concentrations of important micronutrients linked with both growth and cognitive development. Cow milk similarly has important growth characteristics.[185] Cultured ASFs are being developed to preserve these important properties of ASF. Similarly, to plant-based ASF alternatives, cultured ASF can support food security and nutrition goals and should be considered a long-term adaptation strategy of agriculture and food systems. Although cultured ASFs generally have substantially lower environmental footprints than farm-raised ASFs, including lower GHG emissions, there are mixed assessments regarding energy use of cultured ASFs.[186,187] More research is needed once these options become available at scale.

A third alternative to conventional ASF that continues to grow is edible insects. Edible insects can be produced much more efficiently than conventional livestock. They have a smaller environmental footprint than plant-based alternatives and thus also support both climate change adaptation and mitigation goals.[188]

Conventional ASF alternatives have other desirable properties. For example, cultured and plant-based alternatives generally have a longer shelf life than conventional fresh ASFs, and factory processes are also considered to reduce a series of risks, such as exposure to antibiotics and hormones. One important concern, however, is the potential displacement of a large number of livestock farmers and fishers once such products enter mainstream agriculture.

Rodrigues et al.[189] assessed the potential economic impact of farmers using seasonal weather forecasts that draw on improved climate services. Using economy-wide models for Kenya, Malawi, Mozambique, Tanzania, and Zambia, they find that a timely and accurate forecast adopted by all farmers could generate average regional income gains of US$113 million per year. Gains are much higher during extreme climate events and are generally pro-poor. The forecast value falls when forecast skill and farm coverage decline (value is also dependent on national economic and trading structures).

Although climate information services are essential for adaptation to climate change, some climate information may be too granular for practical use at the local level. Furthermore, difficulties may arise when communicating scientific results and the level of uncertainty in these results to farmers. Furthermore, information services often do not reach those that need them most, including poor smallholder producers in remote areas. Among households that are reached, not all household members may receive the information. For example, women often are not targeted with information through formal channels, like extension agents, even in contexts where they are involved heavily in agricultural production.

2.3.6 INSURANCE AS A FORM OF RISK MANAGEMENT

Understanding and managing risk is an essential component of climate change adaptation in agriculture. In the past, the discussion on risk management related to adaptation has concentrated narrowly on the use of a small set of risk management instruments, such as crop insurance and index-based insurance. More recently, several initiatives have started to take a more holistic approach to risk management. Among these are the multi-stakeholder Platform on Agricultural Risk Management,[190] the World Bank's Forum for Agricultural Risk Management in Development,[191,192] and programs in the Center for Resilience by the U.S. Agency for International Development. Although financial instruments like insurance may be able to address some of the risks faced by farmers, a number of unresolved questions should be answered before significant amounts of resources are allocated to large insurance schemes. Some of these questions are technical, others are political, and others are social, but all have important fiscal implications particularly for developing economies. Technical shortcomings are related to the changing of the fundamental distribution of weather outcomes caused by climate change. These changes are still mainly unknown.[193] Therefore, insurance in the traditional sense (the charging of actuarially fair premiums to offset a risk) is likely to be highly problematic. Furthermore, while farmers regularly cope with multiple sources of risk—from weather variability to price spikes,[194,195] and from poor market access and policy vagaries[196] to health risks[197] and the death of a spouse[198]—a recent review of the risk literature[199] demonstrates how the economic discipline is technically unprepared to support a broader approach to risk management. Empirical studies have focused overwhelmingly on one source of risk at a time, typically production risks or to a lesser extent market risks, and have also disregarded the jointness of the risks faced by farmers. The relative importance of the different sources of risk is basically unknown and it will be impossible to prioritize which source of risk should be addressed first.

Second, observations indicate that crop insurance is widely adopted only when heavily subsidized, and insurance schemes can become a sizable burden for taxpayers. In the United States, where more than 80% of the major grains area is insured, the average farmer can expect to receive more than US$2 for every dollar they spend buying federal crop insurance.[200] Babcock and Hart[201] have estimated that taxpayers have at times paid upward of US$3 for every dollar disbursed to farmers. In Europe, where policymakers are looking carefully at the American experience, the uptake of insurance varies significantly from nation to nation, and recent literature stresses the need for further research on multiple topics such as portfolio management at farm level and the role of advisory services,[202,203,204] the degree to which various indices are an accurate measure of farm or sector risk,[205] the assessment of the impact of insurance on farm efficiency[206] and improve knowledge on the market distortions with respect to agricultural insurance.[207] The problem of distortions, their implications for the environment, and the effects of subsidized insurance on the adoption of other adaptation practices also should receive due consideration. Smith et al.[208] discuss how heavily subsidized crop insurance affects crop choices and production practices and can lead to shifting highly erodible lands from pasture and grazing to crop production. Lubowski et al.[209,210] report that the increase in crop insurance subsidies changed land use measurably in the United States, and that changes in premium subsidies in the mid-1990s led to an increase in cultivated cropland, most of which came from uncultivated cropland and pasture. Claassen et al.[211] and Miao et al.[212] found qualitatively similar effects on land use. Additionally, some studies[213,214,215] find that insurance encourages farmers to change crop mix and tend to concentrate on monocropping and also find an increase in soil erosion and chemical use. However, other studies refute both the land erosion claim[216] and the increase in fertilizer application.[217] Hill et al.[218] find that the use of insurance in Bangladesh leads to crop diversification and to higher levels of rice production through a more intensive use of both irrigation and fertilizers. And Clarke and Kumar[219] find that gendered differences in literacy and numeracy might well result in poor insurance choices by women farmers. Another gendered assessment by Delavallade et al.[220] found that while men in Burkina Faso and Senegal were interested in insurance, women were more concerned with shocks to health and other issues affecting income levels and thus favored savings-based instruments over index insurance.

In recent years, index insurance has surfaced as an important alternative to traditional crop insurance. Index insurance is an alternative approach to conventional indemnity-based crop insurance which pays benefits on the basis of a specific predetermined index (for example, rainfall) for loss of assets and investments resulting from unfavorable weather events. Because index insurance reduces or eliminates the traditional services of claims assessors, it potentially allows for the claim settlement processes to be less costly. However, so far the uptake of index insurance generally has been low[221] because of basis risk—farmers experiencing losses when a payout is not triggered or receiving a payout when losses are not experienced—and because of other factors such as constraints in cash funds, scarce familiarity with the functioning of the insurance, and lack of trust in the providers[222,223,224,225,226] in a recent empirical study demonstrate how highly price-sensitive the demand for insurance is and find that without financial incentives there would be no demand for their proposed insurance product “even at actuarially-favorable prices.” Therefore, notwithstanding the potential advantages of index insurance before this instrument becomes fully viable, more work will be needed to reduce basis risk and rigorous impact analyses of ongoing programs and experiments must continue.[227,228] More generally, more work is needed to explore the possibility to combine insurance, credit, savings, and risk-reducing investments to optimally address different categories of risk.[229] Moreover, resources must be devoted to understanding the determinants of behavior toward risk and insurance. Besides index insurance, additional forms of risk sharing mechanisms should be explored such as the use of microfinance institutions, local banks or cooperatives that can enroll small farmers in group insurance programs, the pooling of risks within a country’s region and transfer the pool tail risk to the reinsurance market, and layering risk to facilitate risk transfer.[230,231]

Sumner et al.[232] state that designing and implementing a widely adopted crop insurance scheme without potential production distortions would prove very difficult. Governments are rarely swayed by subtle economic arguments, and more often than not they choose to subsidize agricultural insurance for political and social purposes. Therefore, insurance schemes should be promoted with extreme caution: not only they can lead to a long-term unsustainable fiscal exposure, but their distortions can have undesirable environmental outcomes and lead to forgoing alternative forms of risk management.

2.3.7 NEW CROSS-CUTTING TECHNOLOGIES

Portable technologies like mobile phones are transforming the delivery of information about market finance; weather; and agricultural, health, and educational services for farmers.[233] This technology will be used to collect highly disaggregated information for researchers and private enterprises—seen, for instance, in recent pilot projects in India of picture-based weather insurance using smartphones, which may help reduce the cost of weather-based index insurance for small farmers.

Forms of portable technologies are also behind the idea of precision agriculture. This is an area that holds significant promise, as it can provide farmers with the detailed information necessary to optimize field management practices and input usage, resulting in improved yields and profits as well as in environmentally less burdensome production.[234,235] Variable-rate seed applications and nutrients based on inherent soil properties can increase yield in high-producing areas, maintain yield in low-producing areas, and reduce the use of costly inputs. Likewise, precision nitrogen management can balance soil nutrient content, preventing unwanted nitrate leaching and thereby protecting surface water and groundwater quality.[236] Geolocated weather data, precise sensors for soil water and nutrient availability, and a detailed field-level understanding of crop variability support improved decision making and lead to higher productivity. However, the advantage of implementing location-specific cropland management is seen not only in higher yields but also in a less volatile output, and consequently in increased resilience.[237,238,239,240,241] Furthermore, as the use of digital technologies and mobile telephones expands, farmers can become a cost-efficient source of highly disaggregated information for researchers and possible a way of sharing useful adaptation measures among their peers via mobile phone.[242,243] Although precision farming could include simple practices, the concept implies complex and intensely managed production systems that rely on the use of GPS and substantial spatially referenced information on soils, water, and yield potentials.[244] As such, precision agriculture also requires mastering relatively knowledge-intensive technologies, and small farmers should receive sufficient support to ensure that they can take advantage of these technologies. Remote sensing will be essential for implementing precision agriculture and for collecting global data on soil carbon, soil and water quality, and crop health, as well as for monitoring land use and land-use change in general.[245]

2.3.8 MIGRATION OUT OF AGRICULTURE

Depending on the severity of climate change, farming may become increasingly less viable in large areas owing to a combination of physical and social factors (e.g., extreme temperatures, soil depletion, sea-level rise and salinization, migration). Mobility and temporary migration already appear as resilience-increasing strategies, but with climate change it is possible that the only solution available to communities is to abandon agriculture altogether and find other sources of livelihood. Although proper measures and international agreements could help manage a gradual transition out of these areas, a sudden unplanned transition could be troublesome.[246] A few global initiatives acknowledge that climate change acts as a threat multiplier and that migration contributes to climate resilience by increasing food security, reducing reduction, and promoting economic growth (e.g., The Sendai Framework for Disaster Risk Reduction,[247] the Paris Agreement,[248] the 2030 Agenda for Sustainable Development[249]). More work is necessary to favor a nondisruptive unfolding of new migration patterns: building and supporting institutional capacities to manage large movements of migrants; promoting and facilitating policy dialogues to enhance the positive contribution of migration to the economy; and gathering data to assess the location of high-risk areas, the likely migration flows, and the best opportunities to integrate migrant labor into agricultural activities.

3. Trade and Food Supply Chains

3.1 Climate Change Risks to Trade and Food Supply Chains

3.1.1 TRADE

Even as low-income countries become increasingly integrated in the global economy, antitrade and protectionist agendas are on the rise in Europe and the United States.[250] This is particularly problematic because several studies find that climate change could cause a substantial decline in the food self-sufficiency ratio of developing countries (see, for example, Valenzuela and Anderson,[251] who find a decline of about 12% by 2050), and collective economic and climate-related shocks and stressors can increase overall vulnerability.[252] Climate change will alter temperatures and precipitation patterns along with producers' responses to changing constraints and opportunities and, ultimately, countries' comparative advantages in agricultural production.

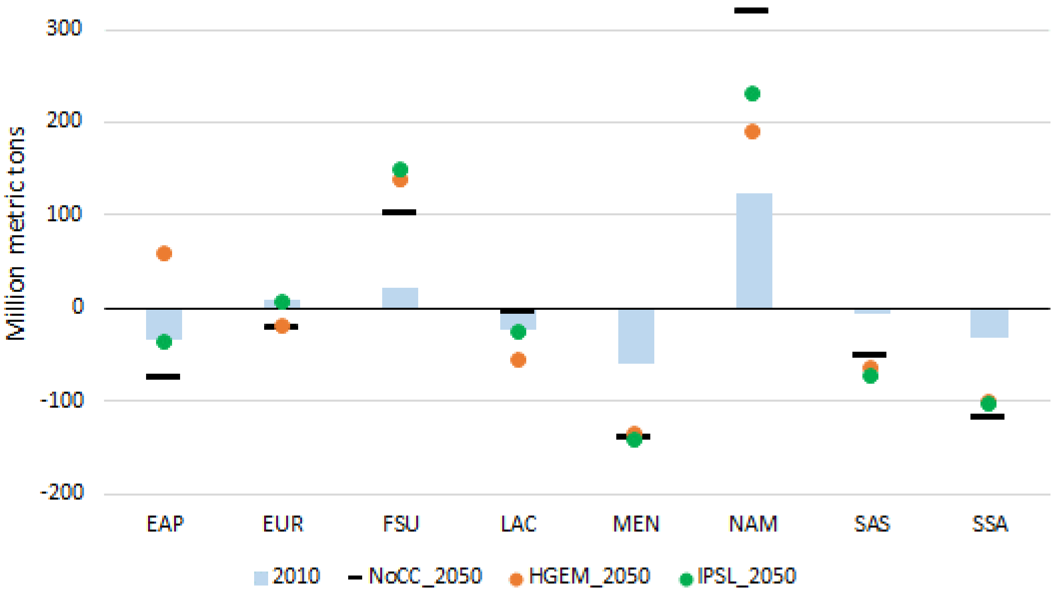
Liberalized international trade allows comparative advantages to be fully exploited and changing trade flows can be an important mechanism to offset, at least in part, the negative productivity effects of climate change.[253] The globalization of the food system has enabled the diffusion of new technologies and regional agricultural specialization and intensification, resulting in a calorie production that potentially would be sufficient for everyone on the planet.[254,255,256] The global food system connects producers and consumers and facilitates investments in agricultural production and transportation infrastructure that increase the movement of food from producers to consumers,[257] resulting in lower food costs and higher producer prices through the reduction of necessary transportation and storage costs. Trade can also contribute to more sustainable use of scarce natural resources (e.g., land, water) by allowing countries that are comparatively less endowed to focus on producing goods that rely less on those resources (e.g., water in the Middle East and North Africa).[258] Overall, these changes are thought to provide most people within this food system with greater access to trade.[259] Hence, restrictions on trade may worsen the effects of climate change by reducing the ability of producers and consumers to adjust to the new conditions or take advantage of new opportunities. Several studies show that trade improves household food access by moderating price increases under climate change.[260,261] Wiebe et al.[262] show that more liberalized trade, with the removal of tariffs and export subsidies for agricultural products, may trigger smaller price increases by 2050, on average, whereas trade restrictions caused by substantial tariff increases may raise prices by an average of over 25% by 2050. Most results show that when trade is restricted, options to adapt to shocks are limited, with negative implications for food security.[263]

Regional results show important differences in the effects of climate change on trade flows as well as the stark differential effects between different scenarios. For example, South Asia was a small net importer of cereals in 2010, but is projected to transition to a large net importer of cereals by 2050, a trend further aggravated by climate change (Figure 3.1). Latin America and the Caribbean was a net importing region of cereals in 2010; net imports would decline to almost nil without climate change but grow further with climate change. Similar changes can be observed when all crops are considered (Figure 3.2). Under climate change, the East Asia and Pacific region increases its net export position in the presence of climate change, replacing lost exports from North America and Latin America. Globally, these changes in trade flows (driven by changes in productivity and prices) will reduce the number of people at risk of hunger and in the number of malnourished children. Impeding these rearrangements of production and the ensuing movement of agricultural commodities could lead to a higher number of people at risk of hunger.

3.1.2 VALUE CHAINS

Climate change directly affects agricultural production and productivity in general, and also affects all dimensions of food and nutrition security: availability, access, utilization, and (through its impacts on production) the stability of food supplies and food prices. Climate change will directly affect food availability through its increasingly adverse impacts on crop yields, animal health, and fish stocks, especially in sub-Saharan Africa and South Asia, where most of today's food-insecure populations live. Projections provide some insights into how climate change will likely worsen economic access to food through negative impacts on production and commodity prices (Figure 3.3).

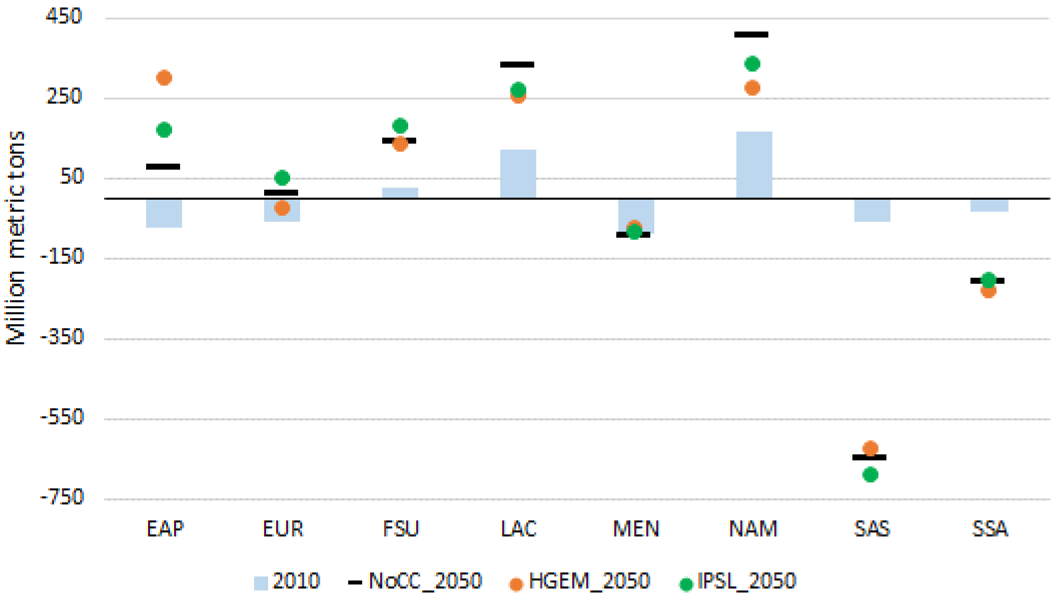
FIGURE 3.1 Net trade of cereals by region



Source: Reproduced from Rosegrant et al. (2017).

Note: The blue bars show the net trade in the year 2010. Black lines show the estimated net trade in 2050 under assumptions of no climate change. Colored dots show the estimated net trade in 2050 under RCP8.5 and two different GCMs (HGEM and IPSL). EAP: East Asia and Pacific; EUR: Europe; FSU: Former Soviet Union; LAC: Latin American Countries; MEN: Middle East and North Africa; NAM: North America; SAS: Southeast Asia; SSA: Sub Saharan Africa.

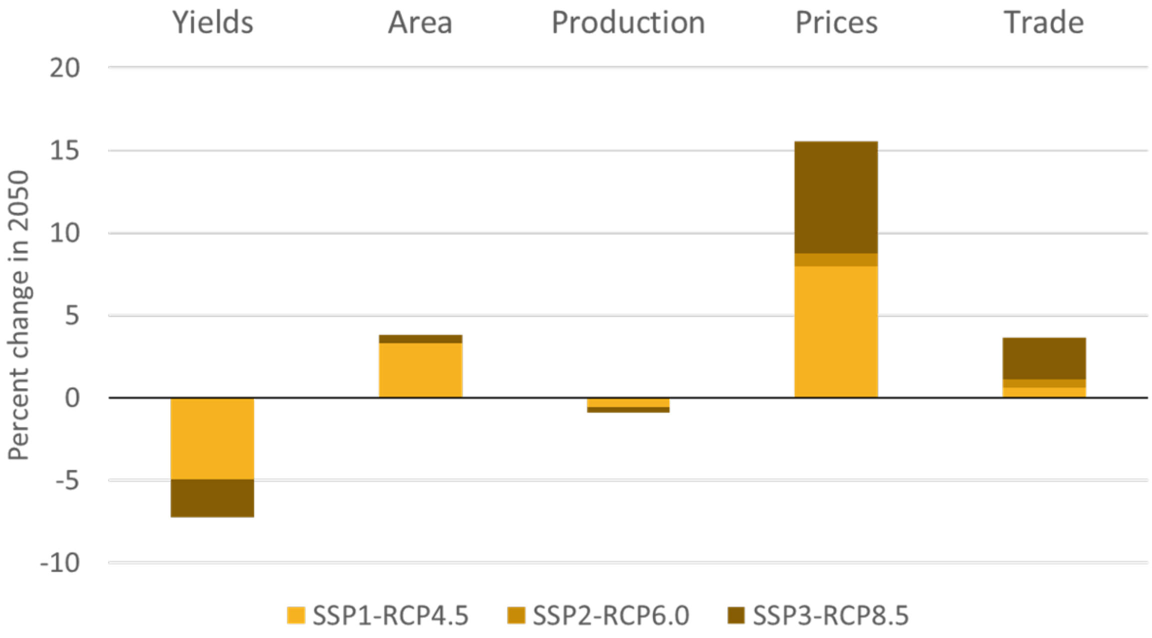
FIGURE 3.2 Net trade of all crops by region



Source: Reproduced from Rosegrant et al. (2017).

Note: The blue bars show the net trade in the year 2010. Black lines show the estimated net trade in 2050 under assumptions of no climate change. Colored dots show the estimated net trade in 2050 under RCP8.5 and two different GCMs (HGEM and IPSL). EAP: East Asia and Pacific; EUR: Europe; FSU: Former Soviet Union; LAC: Latin American Countries; MEN: Middle East and North Africa; NAM: North America; SAS: Southeast Asia; SSA: Sub Saharan Africa.

FIGURE 3.3 Impacts of socioeconomic drivers on agricultural variables



Source: Summarized from Wiebe et al. (2015).

Note: Impacts of socioeconomic drivers on coarse grains, rice, wheat, oilseeds, and sugar in 2050 at the global level.

Climate change and the ensuing higher incidence of extreme events also will affect food supply chains, the essential infrastructure for delivering food to consumers. Infrastructure and water supply networks are vulnerable to extreme weather (e.g., high winds, intense precipitation, extreme temperatures, storm surges, flooding) and to changing operation conditions (e.g., temperatures, precipitation, sea level and salt-water intrusion[264] that jeopardize the proper functioning of a supply chain, which could break down during shipping, manufacturing, wholesaling, or retailing. A climate-related disaster at one point in a food supply chain and at one particular location may have cascading impacts for actors and processes all along the chain.[265,266]

Urban areas are expected to see an increased risk of heat stress, storms, flooding, landslides, air pollution, droughts, water scarcity, sea level rise (as a large share of the world's largest and growing cities are in coastal areas), and storm surges.[267,268] Rural-urban migration and urban-rural migration are expected to increase as a result of extreme weather events, increasing the risk of violent conflicts as a result of poverty and associated economic shocks.

Therefore, supply chains must adapt to function effectively amid changing conditions. Roads, ports, buildings, and infrastructure will have to be retrofitted or overhauled to remain resilient in the face of climate-related impacts.[269] Disruptions to electrical systems in particular pose significant risks to the food supply chain, especially in the case of perishables; refrigerated food spoils within several hours and frozen food in a matter of days. Electric power also is required to run communication systems vital to food chain logistics and computer equipment needed to process economic transactions. Backup generators may not be sufficient, given that refrigeration is an energy-intensive process and that the delivery of liquid fuels may itself be impeded during a significant adverse event. Climate change is expected to affect many other supply chain activities, such as processing, packaging, and storage. Temperature increases are expected to lead to higher energy costs for the refrigeration of fruits and vegetables following harvest and to extend storage life.[270]

Globally, the energy embedded in annual food losses is believed to be around 38% of the total energy consumed by the entire food chain, although the data on these percentages are not definitive. As much as an estimated one-third of all food produced globally is not consumed,[271] but high-quality data remain sparse. In high-income countries, food waste occurs mainly at the retail, preparation, cooking, and consumption stages of the food value chain (i.e., largely in urban areas); in low-income countries, by contrast, food losses occur primarily at the production, storage, and distribution stages. In Europe and North America, food waste is between 95 and 115 kilograms per capita per year, mostly a result of the deterioration of fresh produce, a mismatch of supply and demand, poor purchase planning, careless preparation, and not consuming already prepared food. Rejection of foods that do not meet specific quality standards or are past the expiration date on the package label is another waste factor that is especially problematic in high-income countries. In the United States, food losses account for about 2% of total annual energy consumption. In low-income countries, food waste is lower. In sub-Saharan Africa and South Asia, food waste is estimated at 6 to 11 kilograms per capita per year.[272] Although these losses are much lower than in high-income countries, they still contribute to energy use and GHG emissions and, even more important, decrease farmer incomes, decrease food availability, and increase food prices for the rural and urban poor.

The potential effect on the food cold-chain are of particular concern because increases in temperatures will increase the risk of food poisoning and food spoilage.[273,274] Food utilization will be more difficult because of increasing food safety risks, such as diarrheal diseases and bacterial foodborne diseases, which grow and reproduce faster at elevated temperatures.[275,276]

A particular concern for food safety are aflatoxins, which are fungal metabolites that are mainly produced by Aspergillus flavus and Aspergillus parasiticus and that occur naturally in agricultural fields, generally at low concentration levels. Their concentration can increase under certain weather conditions that cause plant stress, such as drought; but also in response to insect damage or when crops are stored, processed, and transported postharvest. Aflatoxins have serious health implications for humans when consumed directly as food or indirectly through products like milk from animals exposed to contaminated feed. At very high levels of contamination, aflatoxin exposure can cause death shortly after consumption. At lower levels, aflatoxin can cause liver cancer, and it is also associated with childhood stunting. Crops like maize and groundnuts are particularly prone to aspergillus infection. Water stress is strongly correlated with increased concentration of aflatoxins for peanut and maize and the correlation is further influenced by temperature levels, particularly in maize while for peanut water stress during the last three to six weeks are particularly associated with contamination.[277,278] Medina et al.[279,280] have found evidence that increased CO_2 concentration leads to higher aflatoxin concentration levels. Key measures to address aflatoxin contamination include changes in diets (away from the crops mostly affected), changes in crop management pre-and post-harvest with a focus on reducing water and other crop stress pre-harvest and humidity, temperature levels and length of storage post-harvest.[281]

However, the precise impacts of climate change on poverty and food insecurity are difficult to project because climate change is only one of many determinants that drive future trends. For example, Nelson et al.[282] suggest that the positive effects of widely shared economic growth are much greater than the negative effects of climate change on productivity and prices. The authors find that climate change alters availability of certain nutrients for some groups of countries more than others. For example, climate change reduces the adequacy ratios of calcium, riboflavin, niacin, folate, vitamin A, and vitamin E for the poorest group of countries in 2050 by roughly twice as much as for the richest. However, particularly for low-income regions, per capita income growth in 2050 is a powerful driver of increased food affordability. As per capita income increases, low-income countries experience relatively large increases in meat availability, which roughly doubles for the poorest countries—although the increase is small relative to the richest group of countries. Similarly, vegetable availability roughly doubles for the poorest countries.

3.2 Adaptive Responses

3.2.1 TRADE POLICIES

The general consensus is that increased trade will play an important role in adjusting to the shifts in agricultural and food production patterns resulting from climate change.[283,284,285] Trade openness is thought to reduce both individual and institutional vulnerabilities by enhancing future food security and by reducing the cost of response to climate change–induced food availability shocks.[286] However, the positive role of international trade is a function of its flexibility, and public policies may impede these adjustments or even lead to maladaptative adjustments. Limiting trade through policies like export bans is likely to inhibit or prevent the benefits of trade from reaching the food and agricultural sectors, thereby reducing the resilience of smallholders and consumers to climatic shocks. Thus, trade must be managed in ways that maximize the benefits of increased market access while simultaneously minimizing the varied risks of increased exposure to international competition and market volatility.

Furthermore, even though it is true that international trade helps countries to access food, trade alone does not necessarily increase food access for geographically isolated people, the poor, or the socially marginalized.[287] Ultimately, global markets will be accessible only to those countries and segments of the population that have sufficient purchasing power. Low-income countries in particular may have difficulty accessing international markets to cover their increasing food import needs resulting from negative climate change impacts. For countries with a significant, sustained negative trade balance, dependence on imports to meet food needs may also increase the risk of exposure to higher market and price volatility, which in certain cases can be expected under climate change. This makes inclusive economic growth a paramount objective and an essential precondition for stable food security. This can be accomplished by expanding market infrastructure and increasing access to market information, developing contract farming arrangements to support small farmers, and expanding social safety nets to protect poor consumers.[288]

Open trading policies may provide overall welfare benefits to society, but there are always winners and losers. In particular, poor producers in developing countries and poor consumers in countries that are net food importers may be vulnerable to more competition on the open market and fluctuations in global food prices. Providing services (such as insurance) and social protection programs aimed at small producers and the urban poor can alleviate the negative impacts of open trading policies on the most vulnerable groups. Moreover, the current global food system does not adequately distribute food and nutrients across countries and populations, resulting in hunger and undernutrition in low-income countries and overnutrition in high-income countries. In addition, the environmental costs of trade can be substantial given significant energy use and associated GHG emissions from transporting traded goods.[289] Rapid land expansion in Latin America to meet food and feed demands in Asia[290] and the use of palm oil plantations in Indonesia and Malaysia to support European Union biodiesel needs[291] have been shown to adversely impact biodiversity in producer countries. Such adverse impacts need to be addressed with adequate environmental policies (including environmental protection regulations and incentive schemes) in producer countries, along with measures to protect vulnerable populations.

3.2.2 CLIMATE-PROOFING INFRASTRUCTURE

Infrastructure has long been recognized as an important element to develop and strengthen local markets to provide affordable food.[292] For new trading patterns, like those projected in Figure 3.1, to emerge or be viable, investments in maintaining, expanding, and climate-proofing existing infrastructure are necessary. Therefore, infrastructure investments should be a priority to reduce the financial and transaction costs of the movement of goods and services within and between countries. The lack of infrastructure in many food-insecure nations in Africa means that there is virtually no formal trade between landlocked countries in north-central Africa and those in the more-developed eastern and southern Africa. Given projected changes in precipitation patterns and observed inverse relationships to El Niño and La Niña in parts of eastern and southern Africa, increased trade would help mitigate the impacts of increases in climate variability.[293] High transport costs sustain elevated local producer prices by restricting imports and reducing competition from less-expensive alternatives, but this also reduces access to food for the poorest households.[294] Adaptation options may include rethinking the location and expansion of infrastructure, according to the opportunities and threats from features of the natural landscape. For instance, in the absence of properly designed drainage, a river may represent a threat; by contrast, a properly managed forested catchment may buffer the effects of extreme rainfall events. Safety-net programs, such as food-for-work programs, are used in parts of the world to both expand and climate-proof rural infrastructure. Other programs, such as Payment for Ecosystem Service programs, are being used to improve or restore important watershed functions that increase in value under climate extremes and climate change.

Investments in climate-resilient infrastructure are likely to improve economic outcomes by increasing market access for producers and reducing food price shocks for consumers. The environmental and social implications of infrastructure developments depend on how carefully these investments are planned. Improperly planned irrigation infrastructure may deplete water resources or increase health threats such as malaria incidence. Access to infrastructure, such as roads or electricity, may not be evenly distributed throughout a population, raising issues related to social equity, particularly in places where these investments do not reach the most vulnerable social groups.

3.2.3 SUPPORT FOR SMALL PRODUCERS IN LOW-INCOME COUNTRIES

Increased trade is more likely to reduce vulnerability when the benefits help resource-dependent populations diversify livelihoods and economies, by adding value and developing secondary- and tertiary-sector activities.[295] However, for some producers and consumers the exposure to the vagaries of a free-trade environment can result in increased local prices and the transmission of price shocks that generate from distant crises, such as those recorded during the food-price crises of 2008 and 2011.[296,297] As a result, programs and policies are needed to increase the competitiveness of local producers, provide a social safety net, and increase the resilience of trading systems. For this to occur, especially in low-income countries, proper infrastructure and effective policies need to be developed to support all actors along the food chain. The development of insurance products also can be critical for climate-resilient trade to spread the risk of loss of production, to overcome risk-related barriers to investment, and to minimize damage to infrastructure.[298]

3.2.4 INVESTMENTS IN IMPROVING THE SAFETY AND EFFICIENCY OF VALUE CHAINS

The increased probabilities of extreme climatic events, such as typhoons and droughts, will require, even in the short run, innovations in supply chains for most agrifood companies as a matter of immediate business survival. In the longer term, climate change will affect the very configuration of agricultural supply chains through shifts in supply zones, structural innovation with new supply configurations, changes in land use and trade patterns, increased reliance on insurance, and increased investment to enhance not only the resilience of farming operations but also farm produce distribution and processing.[299] Long-term adaptation will require public-sector support since the provisioning of resources needed for such large investments will be politically challenging. Several of the adaptation measures will have to be developed across national borders; therefore, there is a growing role for multilateral organizations and international agreements. Investments in water projects will provide an opportunity for agents in the private sector that have resources and contingency plans. To facilitate these changes, public research will be needed to support development and dissemination of technologies to adapt to the new weather patterns.[300]

More research and development work is needed to identify vulnerabilities in food supply chains and strategies to mitigate new risks.[301] In addition, innovations in packaging, processing, and storage practices are needed to extend and improve the efficiency of supply chains, reduce waste, and increase availability of nutritious but perishable foods.[302] Investments are not limited to physical infrastructure. For this purpose, rural electrification can help increase availability and reduce the cost of nutrient-rich, highly perishable foods, such as vegetables and fruits, by facilitating irrigated production of such foods and providing more cold-storage options.[303] Investments in processing and cold-storage facilities, feeder roads, and cooled transportation have the added benefit of smoothing income shocks that small producers face from seasonality, market volatility, and weather shocks.[304] Investment in small cities can support efforts to climate-proof value chains (Box 3.1).

BOX 3.1 Investments in Small Cities to Support Climate-Adapted Value Chain Development

Investments along the continuum between rural and urban areas—that is, in small towns and medium-sized cities that constitute the hidden (and sometimes nonexistent) geographic middle—can play an important role in agricultural adaptation to climate change. Rural townships and medium-sized cities can be important intermediary points that connect hinterlands to urban centers while providing social and economic benefits. They can act as service delivery nodes for rural areas and link the rural economy to markets, thereby reducing transaction and transportation costs. Towns and intermediate cities also foster nonfarm rural growth, affording smallholders access to employment in agroprocessing or other commercial or industrial activities. The development of small and medium-sized cities is encouraged by some countries, while others prefer to focus investments and services on the largest city or a few large cities.[305]

Risks of food poisoning and food spoilage will have to be abated by developing additional quality assurance and control tools and methods to prevent or control microbiological risks.[306,307] Methods to minimize the risk of aflatoxin contamination rely mostly on improved agronomic practices (to enhance soil moisture retention and reduce water stress), as well as shifting planting dates (to avoid high temperature and water stress conditions during the end of growing season). Modifying irrigation patterns or the use of drought-resistant crop varieties are also possible solutions.[308] Income growth in economically depressed populations remains a key strategy to ensure nutrition security.

Processing foods can increase stability and even improve nutrition.[309] For example, drying and salting meat and fish makes them last longer and preserves essential nutrients. This type of preservation can be done on a large scale or even by consumers at home. Berlin, Sonesson, and Tillman[310] found that processing milk into yogurt and cheese decreased waste by creating longer shelf lives and increasing incomes through higher prices. Dairy can be cultured into other products such as kefir or yogurt. Cultured dairy is more stable and provides additional probiotic nutritional benefits. Although drying fruits and vegetables removes some water-soluble nutrients, such as vitamin C and B vitamins, it increases the food's stability and preserves other nutrients. All of these methods decrease the need for cold storage and make nutritious foods more stable and thus available to consumers. Smallholder farmers, fishers, and pastoralists can use these methods to increase the marketable amount of their output and thus their incomes, and consumers can use them at home to improve their own nutrition.

New technologies can help to better connect small farmers to value chains. Sensors linked to digital information systems can improve links between farmers and processors, reduce postharvest losses, and reduce the amount of water used in producing food. Digital technology can connect farmers directly to buyers, inform buyers about the type of agriculture practiced in the field, generate better price opportunities for farmers, and enable harvest-specific loans. Digital sensors can monitor storage conditions along the value chain, track provenance for environmental purposes, and optimize supply chain connections and functioning, including reducing the costs of transportation.[311,312]

Efforts to improve value chains need to focus on combined off-grid and on-grid energy solutions that support both climate change adaptation and mitigation. Such energy solutions need to be codeveloped along with rural markets and agricultural intensification practices. As with other infrastructure investments, the expansion of energy infrastructure supporting value chain development may miss certain communities, increasing social inequality. Value chain improvements also require investments in quality assurance and control measures to prevent or minimize food safety risks while preserving the nutritional value of foods for poor urban consumers, who are most vulnerable to food safety risks. Such measures could include regulation, monitoring, and training in proper production, processing, and packaging procedures.

4. Food Security, Nutrition, and Health

4.1 Climate Change Risks to Food Security, Nutrition, and Health

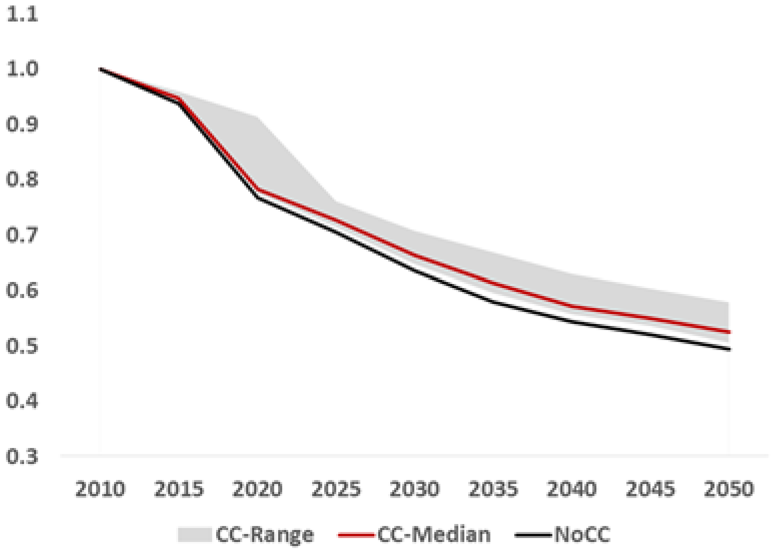
A more volatile climate is likely to increase the intensity and frequency of climate-related extreme events, some of which can have immediate, direct effects on human health. Heat stress experienced by agricultural laborers can result in premature births or low birth weight, and an increase in the number of hot days (37.8°C or warmer) at any point during pregnancy has been linked to an increase in the risk of low birth weight.[313]

In general, extreme events and related natural disasters disproportionally affect poor people, including many smallholder farmers. Severe droughts or floods, for instance, can sharply reduce incomes and cause asset losses that erode future income-earning capacity. In addition, to the extent that climate change affects food supply, food prices are expected to increase, making food less affordable. Both the urban and rural poor would be most affected, as they spend much higher shares of their incomes on food. Also affected would be poor smallholder family farmers, most of whom are net consumers of food.[314,315]

Simulations using IFPRI's IMPACT model suggest that climate change could put about 50 million more people at risk of undernourishment.[316,317] Figure 4.1 shows how climate change is projected to affect the global risk of hunger over time for a range of climate change impacts, assuming a "middle-of-the-road" socioeconomic scenario. The declining trend in the number of undernourished in both scenarios—with and without climate change—indicates that the overall impact of climate change, at least until 2050, is smaller than that of the other drivers embedded in the socioeconomic scenario, particularly income growth, but also technological change.

In the absence of climate change, most regions are projected to see declining numbers of people at risk of hunger, but these improvements are partially offset by the impacts of climate change.[318] In sub-Saharan Africa in particular (Figure 4.2), around half of the projected reduction in the number of people at risk of hunger by 2050 is lost as a result of climate change. The roughly 50 million additional people at risk of hunger are consistent with earlier estimates.[319] This may be a conservative estimate: it is based on the "middle-of-the-road" assump-

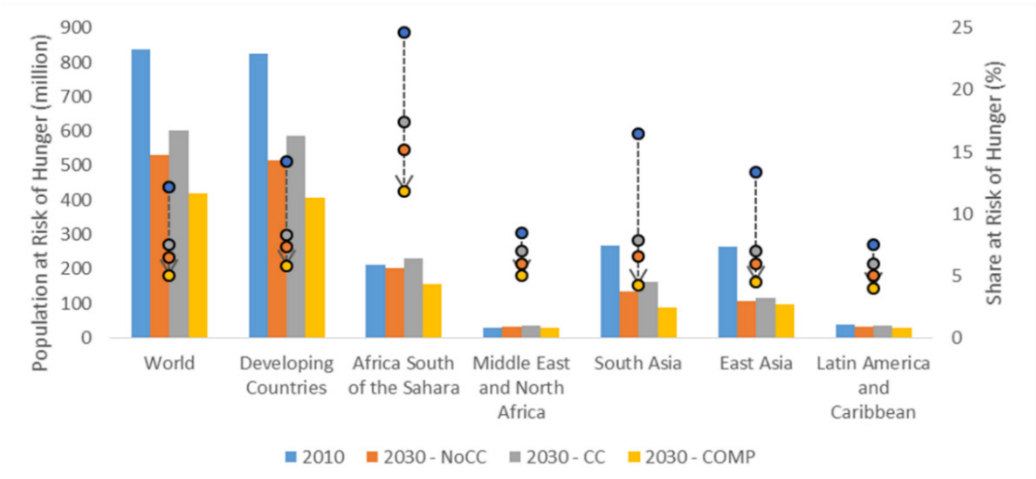
FIGURE 4.1 Population at risk of undernourishment (index, 2010 = 1)



Source: Data from Rosegrant et al. (2017, IMPACT simulations)

Note: Data with and without climate change. Range of climate change (CC) scenarios is represented by RCPs 2.6, 4.5, 6.0, and 8.5. Simulation results assume a middle-of-the road socioeconomic pathway (SSP2).

FIGURE 4.2 Population at risk of hunger by 2030



Source: Data from Rosegrant et al. (2017, IMPACT model version 3.3)

Note: 2030-NoCC assumes a constant 2005 climate. 2030-CC reflects climate change using RCP8.5 and the Hadley Climate Model, and 2030-COMP assumes climate change plus increased investment in developing countries' agriculture.

tion of economic growth as characterized by SSP2, and it does not account for the impacts of extreme events and other conditions noted above that we expect to change along with climate (and that we expect to change even more rapidly after 2050).

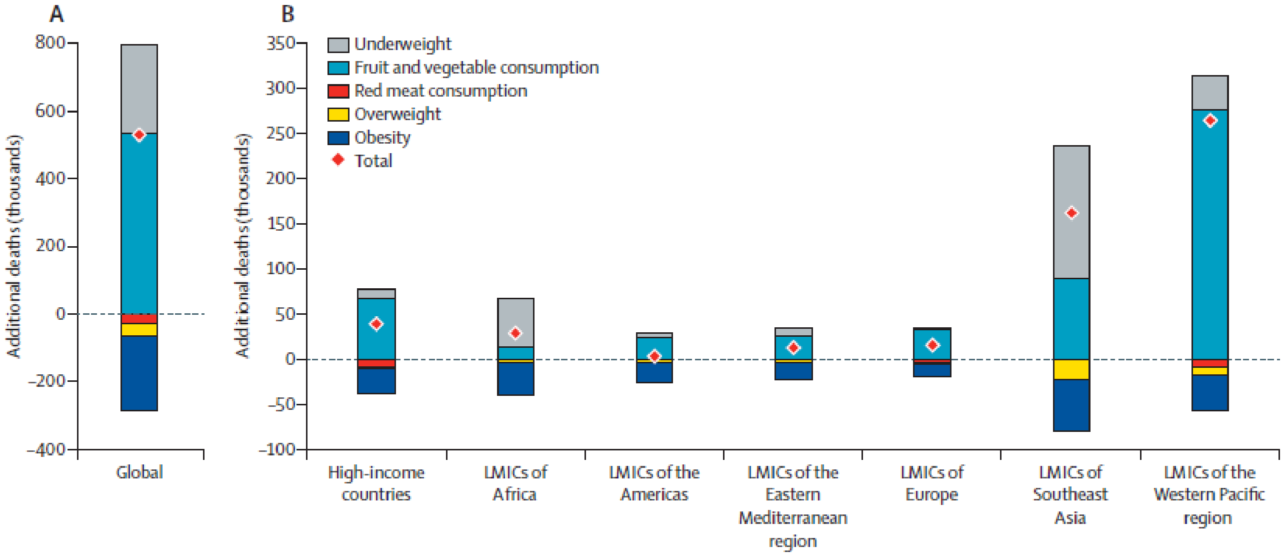
That said, the risks that climate change presents for food security extend beyond the field and agricultural production to other elements of food systems.[320]

Temperature, carbon dioxide, and ozone directly and indirectly affect the production and quality of fruit and vegetable crops. Increases in temperatures can be expected to have a significant impact on postharvest quality by altering important quality parameters, such as synthesis of sugars, organic acids, antioxidant compounds, and firmness. Prolonged exposure to high levels of CO_2 concentrations could induce higher incidences of tuber malformation, increased levels of sugars in potatoes, and diminished protein and mineral contents, leading to the loss of nutritional and sensory quality.[321,322,323,324] Increased levels of ozone in the atmosphere can induce visual injury and physiological disorders in different species,[325] as well as significant changes in dry matter, sugar content, and citric and malic acid, among other important quality parameters.[326] Other studies indicate that the nutritional quality of key food crops could suffer from climate change. A study by Myers et al.[327] found that when grown under the high levels of CO_2 expected by 2050, wheat grain had 9% less zinc, 5% less iron, and 6% less protein, with comparative losses in rice of 3%, 5%, and 8% respectively. Maize suffered similar losses of nutrients. Soybeans also lost zinc and iron, but because they are a legume and not a grass, they did not produce less protein. The most severely affected people would be the poor, especially poor children.[328]

Climate change will also affect the utilization of food. Studies indicate that increased contamination of drinking water supplies and increases in the prevalence of respiratory diseases and diarrhea are possible, both of which affect people's health and food absorption capacity. This is particularly true in semiarid lands.[329] Temperature shocks and droughts appear to be the most detrimental factors for undernutrition and child stunting.

Springmann et al.[330] explored the implications of climate change on diet and health, estimating excess mortality attributable to agriculturally mediated changes in dietary and weight-related risk factors by cause of death. The authors calculated the change in the number of deaths from climate-related changes in weight and diets for combinations of four emissions and three socioeconomic pathways; each included six scenarios with variable climatic inputs. As illustrated in Figure 4.3, according to this analysis, underweight is the primary cause of diet-related death associated with climate change (additional to those expected in the no-cli-

FIGURE 4.3 Impacts of climate change on diet-related deaths



Source: Reproduced from Springmann et al. (2016).

Note: Data are for 2050 (results for SSP2 and RCP8.5, by region).

mate-change baseline in 2050) in Africa and Southeast Asia (which in this case includes South Asia). Most diet-related deaths associated with climate change in other regions were linked to reductions in the consumption of fruit and vegetables. Reductions in red meat consumption, overweight, and obesity associated with climate change led to a reduction in diet-related deaths in all regions.

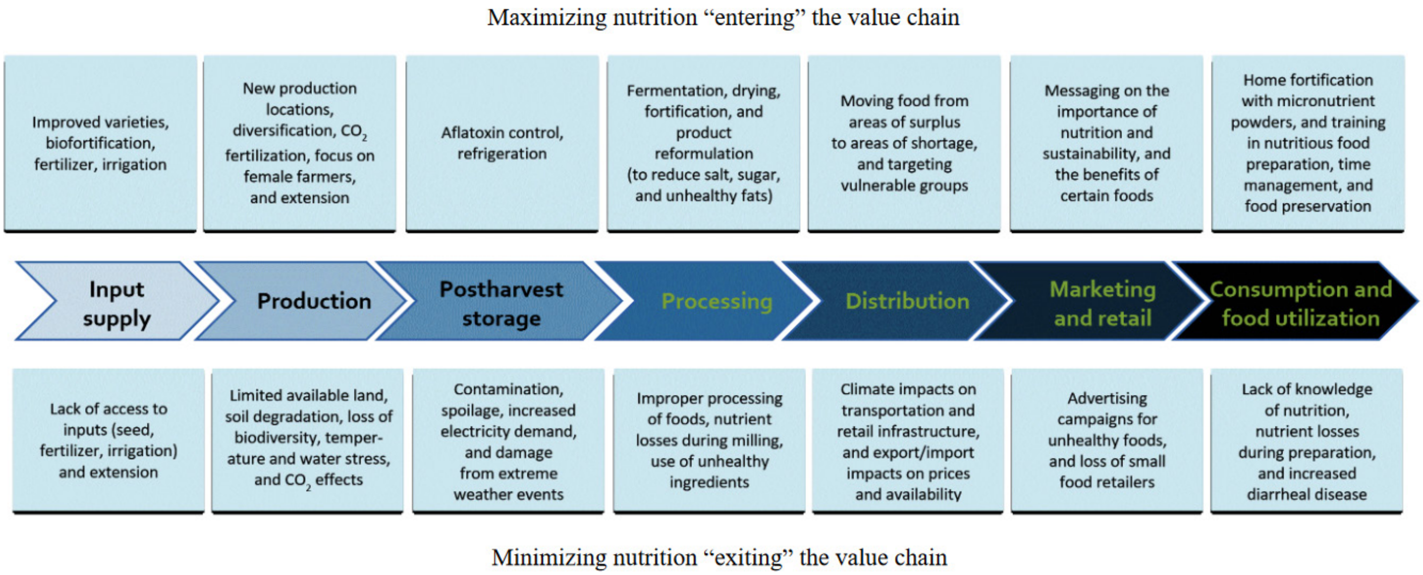
Complicating the linkage between climate change and nutrition outcomes is the shift in the burden of malnutrition from rural to urban areas.[331] The urban poor in particular face a combination of persistent child undernutrition, micronutrient deficiencies, and a dramatic rise in overweight and obesity caused by a challenging food environment. This food environment is characterized by limited economic access to healthy diets; vulnerability to food price shocks; food safety challenges; and limited access to healthcare, sanitation services, and safe water.[332] This challenge will only grow, as two-thirds of the world's population will be concentrated in cities by 2050. Options for adapting to climate change must address the unique food security and nutrition challenges of the urban poor.

Climate variability also affects food security outcomes indirectly through impacts on human health. We may, for example, consider heat waves not just as extreme events but as part of variability at large. Heat waves are known to reduce the life expectancy of both elders and children. Some regularly occurring events such as El Niño and La Niña have been associated with increased incidence of diseases such as malaria and dengue, which affect nutrition by impacting overall human health. Although we have little information and little modeling on how variability may affect food availability at national and regional scales, evidence suggests that variability may increase child malnutrition rates.[333]

4.2 Adaptive Responses

Many steps need to be taken to truly improve the diets, nutrition, and health of poor rural and urban consumers in developing countries. This need dramatically increases under climate extremes and climate change as a result of higher food prices and concomitant lower food affordability; the increased cost to store perishable, nutrient-dense foods; the increased risks to market access for both producers and consumers; and additional stresses on agricultural laborers, such as heat stress. Fanzo et al.[334] recommend a series of responses that "maximize" nutrition entering the value chain under climate change as well as those that "minimize" important nutrients from being eliminated in the value chain (Figure 4.4). A subset of these are described in the following figure.

FIGURE 4.4 Climate change impacts along the food value chain



Source: Reproduced from Fanzo et al. (2018).

For example, processing practices can improve or cause a loss in the nutritional content of foods. Given that climate change is expected to reduce the nutritional content of key crops,[335] this would be one way of restoring lost nutrients. Another example relates to increasing aflatoxin exposure with climate change.[336,337] Addressing this challenge will require improvements in farm practices as well as better storage options.

4.2.1 IMPROVING AVAILABILITY OF AND ACCESS TO HEALTHY DIETS FOR BETTER NUTRITION IN LOW-INCOME COUNTRIES

Despite strong economic growth in recent years, including in many emerging economies, global hunger increased in 2017, and increasing economic inequality remains a challenge for further reducing poverty and hunger.[338] In low-income countries, the prevalence of undernutrition and micronutrient deficiencies remains a persistent challenge. Addressing this challenge requires increasing the availability and affordability of micronutrient-rich foods such as vegetables, fruits, nuts, seeds, and pulses.[339] Efforts to increase the availability and affordability of micronutrient-rich foods should be tailored to location-specific challenges, such as resource conditions, income levels, and dietary preferences.

Increasingly, small rural markets are recognized for their role in supplying animal-source foods and other nutrient-dense foods to rural consumers. Ensuring that such markets are resilient in the face of climate extremes and climate change (i.e., that roads leading to these markets remain open during floods and that energy sources supporting such markets remain functioning during floods and droughts) will be of particular importance for the food and nutrition security of the rural poor.

Poverty, low human capital, and lack of access to both social services and adequate infrastructure all limit access to adequate diets, resulting in poor nutritional status. Thus, improving nutrition and diets also requires rural development strategies that increase incomes and extend basic services to remote communities.[340] In urban areas, the poor often lack access to healthy and safe foods, and face other health risks from poor sanitation services, lack of safe drinking water, and limited access to healthcare. Increasing access to healthy and safe foods, improving water and sanitation service provision, and establishing regulations (particularly for unsafe street foods on which many of the urban poor depend both as producers and consumers) would improve the food environment for the urban poor.[341]

4.2.2 INCENTIVIZING HEALTHY DIET CHOICES

Measures are also needed to encourage a dietary shift from carbohydrate-rich staples to a more diverse diet in rural areas.[342] Rural areas of many developing countries also need to increase consumption of animal-source foods in order to improve nutrition outcomes.[343,344] At the same time, nutrition and diet-related efforts should focus on more sustainable diets, especially in urban areas where demand for resource-intensive foods, such as animal-source foods, fats and oils, and sugar, are increasing. Such a shift is equally vital for health-related reasons. Although more than 2 billion people worldwide still suffer from micronutrient deficiencies, the number of people overweight or obese now exceeds the number of those with insufficient caloric intake.[345] Common features of a sustainable, healthy diet include a diversity of foods eaten, a balance between energy intake and expenditure, and minimally processed tubers and grains, along with unsalted seeds and nuts, legumes, fruits, vegetables, and meat and dairy (in moderate quantities). Small quantities of fish and aquatic products are included, and processed foods high in sugar, fat, or salt and low in micronutrients are heavily restricted.[346,347] The implementation of healthy diets requires careful attention to regional and cultural preferences as well as crop suitability.

That said, greater availability of healthy food alone is not likely to precipitate dietary changes. Behavior-change communication is also essential to promote a dietary shift from carbohydrate-rich staples to a more diverse diet that addresses micronutrient deficiencies and to encourage healthy diet choices in urban settings.[348,349,350] Other incentives to change behavior include nutrition labeling, advertising restrictions, taxes on unhealthy foods such as sodas, and nutrition education in schools and health centers.[351]

While incentives for behavior change are needed to encourage health food choices in both rural and urban settings, food labeling and taxes on unhealthy foods can increase food costs, particularly for the urban poor, and labeling requirements may place small producers at a disadvantage. Therefore, such measures should be accompanied by efforts that ensure that vulnerable populations have available and affordable healthy food alternatives, and that support small producers' efforts to improve processing and packaging procedures.

4.2.3 BIOFORTIFIED FOODS AND CROP VARIETIES

Efforts to develop fortified food, biofortified crop varieties, and the supplementation of targeted micronutrients must be strengthened to address potentially reduced nutrient quality in crops as a result of climate change. Breeding programs can select for cultivars based on reduced CO_2 sensitivity together with other desirable traits, such as heat and drought stress and high yields. Many international organizations, in particular the CGIAR, are actively working to create crop breeds with higher overall micronutrient contents, which would also help offset declines in nutrient density if adopted in the regions that need them. Biofortified crops, such as those developed by Harvest Plus, directly breed selected micronutrients in selected crops, such as vitamin A in orange-flesh sweet potatoes. Some advances also have been made in improving soil health for human health and nutrition, particularly under climate change; however, it is early to give clear guidelines on adaptation investments in this area. Other ways to address nutritional deficiencies in people and crops include expanded fortification programs, such as those for flour, salt, or other basic staples or ingredients.[352,353]

Investments in the development of biofortified crop varieties that supply macro and micronutrients that might be leached under climate change would ameliorate the persistence of micronutrient deficiencies in both rural and urban areas. Varieties that include traits that become more valuable under climate change, such as improved drought, heat stress, and submergence tolerance, need to be increased.

5. Environmental Sustainability of Agriculture Under Climate Change

5.1 Impacts of Agricultural Production on the Environment and the Linkages with Climate Change

Climate change is only one of many risks to global food production. Ensuring the sustainability of food supply requires addressing other environmental challenges, such as the degradation of the natural resource base, and ensuring ecosystem health and resilience to support agricultural production over the long term. Agricultural production depends on the global stock of natural resources as well as support and regulation of ecosystem services, such as nutrient cycling, water purification, pollination, and biological pest control.[354, 355] Although land, soils, water, biodiversity, and ecosystem services are essential inputs to agricultural production, unsustainable practices and trends threaten the sector's long-term sustainability and productivity.[356,357,358,359,360]

Investments that target production, incomes, food security, and water usage can have important repercussions on forests, ecosystems, GHG emissions, and environmental functionality and well-being. Rosegrant et al.,[361] for example, show that direct productivity-enhancing investments, such as in seed technologies, generally have little initial impact on environmental qualities but will foster significant improvements by 2050 at relatively low cost. Other investment scenarios, such as irrigation expansion and increased water use efficiency, have minimal negative effects on forests and GHG emissions. Improved market access through reduced marketing costs, along with improved food security, increases the conversion of forestland to other uses and increases GHG emissions. These results highlight the importance of developing an investment portfolio that combines productivity enhancement with improved water-resource management and market access while remaining mindful of their direct and indirect effects on the environment. They also underscore the need to monitor and regulate land conversions and GHG gasses as these investments take place. Roy et al.[362] suggest that those development pathways that achieve the UN SDGs and stay within the global 1.5°C warming target by the end of the 21st century are best positioned to be climate resilient. Adaptation is essential, but achieving adaptation while striving toward zero emissions will have a greater impact and be easier to achieve in the longer term.

5.1.1 CLIMATE CHANGE EXACERBATES AGRICULTURAL IMPACTS ON LAND AND SOILS, WATER, ECOSYSTEMS, AND BIODIVERSITY

Increased agricultural production to meet growing food demand has resulted in the expansion of agricultural lands, largely through the conversion of forest and pasture land to agricultural use. Globally, there has been an increase in the amount of land cleared of natural vegetation;[363] in the intensification of management activities;[364] and in the simplification of landscape structure, such as through an increase in broad-scale agricultural practices.[365,366,367] These land-use changes and management practices have contributed to increased food production, but such unsustainable crop and grazing land management is the largest global driver of land degradation.[368] The majority of the world's soil resources are in fair, poor, or very poor condition, particularly in developing countries, owing to increasing soil erosion, loss of soil organic carbon, and nutrient imbalance.[369] Climate change exacerbates land-use change and land degradation in ways that further threaten the long-term viability of agricultural production.[370] In particular, climate change accelerates soil erosion on degraded lands due to more frequent extreme weather events; increases the risk of forest fires; and changes the distribution of invasive species, pests and pathogens.[371]

Biodiversity in crops, genetic diversity within crop species, microorganisms in agricultural soils, and insect populations (through pest control and pollination) all provide essential inputs and ecosystem services for sustainable agricultural production.[372] However, unsustainable agricultural practices such as land expansion, the conversion of natural habitats to agricultural uses, and the trend toward monocultures have contributed to the loss of biodiversity.[373,374,375,376] Today, the world market relies on a small number of crop varieties, and even among some of the most significant crops, such as sugar cane, soybean, and groundnut, there are large gaps in the conservation of genetic resources.[377] Modern agriculture's dependence on a few major crops with limited genetic diversity exposes the agricultural system to major risks caused by climate change.[378] Climate change further contributes to losses in biodiversity in ways that are detrimental to agricultural production, such as the decline in global pollinators.[379,380] Historically, the world's animal, plant life, and ecosystem services have proved to be extremely sensitive to global climate changes. The dramatic climate changes projected to take place for the 21st century will result in large-scale biome shifts and significant species extinctions.[381] These trends intensify the risks to production due to pest outbreaks and increased reliance on chemical pesticides, which further diminishes natural pest regulation while causing risks to human health and the environment.[382]

Access to water for agricultural production influences everything from crop choices to yields to the stability of food supply and resilience to climate change and shocks. In rainfed systems, water scarcity often is considered to be the most limiting factor to crop productivity.[383,384] Currently, agriculture is the largest user of freshwater resources—irrigation accounts for around 70% of all freshwater withdrawals globally and an even higher share (85%) of global water consumption. However, irrigated crop areas generate 40% of global food production on less than one-third of the world's harvested land and are thus essential for current and future food production.[385] Climate change largely affects agricultural producers through changes in water availability that result from changing rainfall patterns, more frequent and extreme droughts, floods and storms, and higher rates of evapotranspiration, which will increase the water demand of crops and the need for irrigation in many parts of the world.[386] Crops grown in areas already equipped with irrigation are not as likely to be affected,[387] although some irrigated areas will see significant declines in water available for irrigation.[388] As a result of these increasing threats to planetary health and the long-term viability of agricultural systems, climate change adaptation efforts should emphasize approaches that not only ensure adequate food production but also help protect the world's natural resources, biodiversity, and ecosystems services.

5.1.2 LAND-USE CHANGES UNDER CLIMATE CHANGE

Climate change and land-use change are inextricably linked. People use land to ensure and improve their livelihoods, and climate change shapes the way land resources are used. Furthermore, land use contributes to climate change by releasing or sequestering GHG emissions through biogeochemical and biophysical processes. Since 2000, land-use change alone contributed about 10% of total anthropogenic CO_2 emissions.[389,390] Combined with forestry and other land uses, the Agriculture Forest and Other Land Uses sector contributes about one-quarter of annual GHG emissions, the equivalent of 10 to 12 Gt CO_2 e per year.[391] Deforestation and forest degradation are thought to have two opposite effects depending on the latitude at which they take place. The first is a radiative cooling due to the increase in surface albedo, and the second is a nonradiative warming effect due the decrease in evapotranspiration and in surface roughness. A reduction of forests in the boreal zones is expected to induce a net cooling because the increase in albedo is the dominating effect.[392,393,394,395,396,397] In tropical regions, the net impact is typically a warming due to the dominant influence of evapotranspiration and surface roughness.[398,399,400,401] Although these effects are important, they do not consider the importance of forests for biodiversity and ecosystem services.

Of note, IPCC (2018) mitigation pathways incorporate the use of negative emission technology to offset emissions and achieve the 1.5°C goal; AR4 also has included such options. These include Carbon Dioxide Removal (CDR) and Solar Radiation Management. A CDR tool, in turn, is Bioenergy with Carbon Capture and Storage (BECCS). BECCS assumes the conversion of large areas to the generation of energy technologies with a substantial bioenergy component. For example, Koornneef et al. (2011)[402] find a technical potential of BECCS of 10 Gt of CO_2 e and an economic potential of 3.5 Gt of CO_2 e of negative emissions per year using technologies such as biomass-integrated gasification combined cycle and advanced production of bioethanol through hydrolysis plus fermentation. These assessments generally have not fully considered national government strategies, food security goals, water and other ecosystem and ecosystem service limitations—see, for example, the work of Turner et al. (2018)[403] and Yamagata et al. (2018).[404] Stronger collaboration among agricultural research committees; climate scientists; and national ministries of agriculture, water, and the environment will be needed to identify feasible mitigation pathways that enable countries to meet both food security and adaptation goals.

5.2 Adaptive Actions

Climate change places additional pressure on a natural-resource base and on ecosystems that are already strained by human activity, in particular by unsustainable agricultural practices. Adaptation options therefore must not only sustain food security and human well-being but also consider the environmental implications of agricultural production and include actions to address the declining availability and quality of natural resources, ecosystem services, and biodiversity.[405] Key adaptation options that are essential for the agricultural sector's long-term environmental sustainability and for agricultural livelihoods fall into broad categories of practices that increase resource-use efficiency; direct actions to preserve, protect, and enhance natural resources and ecosystem services; focus on sustainable intensification in order to reduce pressure to expand agricultural lands; and promote more sustainable and healthy diets. Many of these adaptive actions have been shown to be more sustainable when they involve local communities (i.e., through community-based adaptation, see Forsyth 2013),[406] and if they link traditional hardware (such as gray infrastructure) solutions with green infrastructure solutions, such as joint dam- and wetland management to adapt to increased water variability and floods.[407]

5.2.1 RESOURCE-USE EFFICIENCY

Agricultural practices that intensify agricultural production while maximizing resource-use efficiency (of water, land, and energy) also preserve the quantity and quality of natural resources needed to sustain agricultural production and agricultural livelihoods over the long term. As climate change affects the global distribution of temperatures and precipitations, crop-growing conditions will become more uncertain and variable. The best strategies to conserve agricultural resources seek to use more coordinated planning processes to maximize synergies and minimize trade-offs across land, water, and energy resources.[408]

Precision agriculture involves the application of methods to ensure that the appropriate amounts of agricultural inputs, like fertilizer and water for irrigation, are targeted when and where they are needed for maximum efficiency. The types of precision technologies used depend on the farming system. For example, in developed and middle-income countries with high productivity, modern technologies such as monitoring and GPS guidance systems and target inputs like fertilizer micro doses can improve existing efficiency. In developing countries characterized by many small producers, limited input use, and low yields, there is considerable potential to increase agricultural productivity and contribute to the food supply through suitable increases in input intensity. However, there are still opportunities to conserve resources using practices such as the system of rice intensification. Therefore, opportunities to increase resource-use efficiency in agriculture should be appropriate for the local context. Appropriately selected practices to increase resource-use efficiency would ensure greater environmental flows of water, relieve pressure on land and soils, and protect ecosystems and forest resources.[409]

Considerable gains in water productivity and yields are possible in both rainfed and irrigated systems through the expansion of soil- and water-management practices such as mulching, water harvesting, and crop rotation. These practices increase water uptake by crops and increase water available for crops in rainfed systems[410] and, through the introduction of water-saving irrigation technologies, in irrigated systems.[411] Several practices can minimize water loss in agricultural production while providing more crop per unit of water, including the restoration of irrigation infrastructure, like canal lining; the adoption of small-scale water-conserving irrigation technologies, like sprinkler or drip systems; and the use of tools for monitoring soil moisture and groundwater levels.

The more judicious use of pesticides and herbicides as part of a precision agriculture approach, along with environmentally sound agriculture approaches (e.g., on-field crop diversification, use of wild plants) would increase production efficiency and protect the ecosystems and ecosystem services (e.g., pollinators) on which agriculture depends. Integrated pest management is a practice generally proposed to meet these goals.[412]

Increasing agricultural productivity to meet the growing demand for food, reduce yield gaps in developing countries, and improve agricultural livelihoods will require rural energy development in low-income countries, including greater energy inputs into agricultural production and value chains.[413] Given limited options to expand traditional fossil fuel systems in low-income countries, renewable energy systems and technologies have greater potential to meet growing energy demand.[414] Other practices can increase the energy efficiency of agriculture in places where energy inputs are already high, such as switching from fossil fuels to solar-powered technologies (e.g., for solar pumps or cold-storage facilities). Transitioning toward more renewable energy sources would offer the further benefits of reducing GHG emissions and reducing pressure to expand agricultural land.[415]

Investments in resource-use efficiency can also coaddress multiple climate change adaptation and mitigation goals. Importantly, advancements in resource-use efficiency need to go beyond emissions reductions to include improvements in water-use efficiency and efforts toward land restoration, biodiversity conservation, and improvements in water quality.

5.2.2 DIRECT ACTION TO PRESERVE, PROTECT, AND ENHANCE NATURAL RESOURCES, ECOSYSTEMS, AND BIODIVERSITY

5.2.2.1 Land and Soils

Land and soils are essential inputs to agricultural production. The ability of agriculture to produce crops efficiently with high yields and high nutritional value depends in large part on the quality of land and soils available for agricultural production, especially in low-input production systems. Use of land and soils for agriculture unavoidably leads to land degradation and declining soil health over time.[416] However, many of the same agricultural practices and management strategies discussed in Section 1 above slow the decline in land and soil quality so that agricultural production can be sustained and productivity increased over time. These practices include locally appropriate sustainable land management practices (e.g., integrated soil fertility management, conservation agriculture, terracing and bunds, no-till or minimum-till agriculture) that prevent land degradation, control soil erosion, improve soil-water holding capacity, improve soil organic matter, and enhance soil fertility.[417] Moreover, many of these practices have direct benefits for the environment and other ecosystem services. The selection of options should be appropriate for the local agroecological and farming context to ensure that benefits are maximized.

5.2.2.2 Water

Water is an essential resource for agricultural production. Approximately 70% of all freshwater withdrawals are used in agriculture, and a larger share is consumed in the sector. However, unsustainable use leads to declining water availability as well as water quality problems that pose challenges for human and planetary health and well-being. Unsustainable groundwater use for irrigation has been well documented for parts of South Asia[418,419] and agricultural pollutants levels in water bodies are growing.[420] These problems must be considered and addressed to ensure the sustainability of irrigated production. Therefore, efforts to protect and restore water resources are required as part of a sustainable agriculture approach. Examples include water harvesting, strengthening institutions for integrated water-resources management across scales, better monitoring systems to track water availability and quantity (including loadings of pollutants from crop and livestock production in water bodies), and reducing both energy subsidies for water extraction and input subsidies on pesticides and fertilizers.[421]

5.2.2.3 Diversification of Agroecosystems

Continuing to mismanage ecosystems and ignore the complex interactions, trade-offs, and interdependencies across the provisioning services of agriculture and other ecosystem services increases risks to food security and human well-being.[422] Diversification of agroecosystems—through greater genetic varieties of important crops and greater heterogeneity of crop varieties planted in-field as well as across agricultural landscapes—allows agricultural systems to function in ways that improve ecosystem services within agriculture, such as maintenance of soil fertility, crop production, and pest regulation.[423] Agroforestry systems provide an example of a highly complex agricultural system that have been shown to protect crops from extreme weather events and reduced soil-water availability[424] and to increase the resilience of agricultural livelihoods.[425] Care needs to be taken with the introduction of exotic species into seemingly degraded systems that might, in fact, have high levels of biodiversity.[426]

Adaptation to climate change and other related threats also relies on the availability of diverse genetic material: genes that are unique, combined in unique ways, or carried by multiple crop varieties as well as the wild relatives of these genes.[427] Genetic diversity is not only important to avoid catastrophic losses but also to consistently improve or maintain agricultural productivity. It can also enhance biomass output per unit of land through better utilization of nutrients and reduced losses to pests and diseases.[428] Many important crops could not maintain commercial status without the regular genetic support of their wild relatives.[429] There is evidence, however, of the erosion of some of the genetic diversity in plant material. This is caused by several factors, including "replacement of farmers' varieties/landraces, land clearing, overexploitation, reduced water availability, population pressures, changing dietary habits, and environmental degradation," among others.[430] This has been especially true in

East and Southeast Asia and in sub-Saharan Africa, and the overall trend is continuing.[431]

Several pathways are available to maintain plant genetic resources for food and agriculture. In situ and ex situ conservation, as well as farmer collections of crop genetic diversity and wild relatives, are important sources of genetic traits for breeding programs that provide climate-resilient cultivars. In situ conservation—the conservation of crops in their natural or farm ecosystem—by famers and indigenous communities is critical to the development of genetic material. Proper in situ management, however, depends on knowledge of the existing crop diversity, including wild relatives. Surveys, inventories, and support to farmers to maintain a diverse genetic pool are key instruments and will have to rely on better linkages and collaboration between ministries of agriculture and environment, within and across countries.[432]

National and international gene banks are the main tools of ex situ conservation. Gene banks have captured the genetic diversity of many major food crops, such as wheat and rice, other major crops are not as protected, and little attention is still paid to the wild relatives of major crops or to minor but regionally important crops. Therefore, more capacity is needed to collect and preserve both seed and vegetatively propagated species in their country of origin, with duplicates stored elsewhere in facilities that meet international standards and coordination. Additionally, the exchange of information should be promoted to avoid unnecessary redundancy.[433]

Protecting natural resources, ecosystems, and biodiversity is essential for the environmental sustainability of agricultural production and food systems under global environmental change (including climate change).[434] Some measures aimed at protecting the environment, such as protections on forested areas or the adoption of on-farm conservation practices such as conservation agriculture may have trade-offs with short-term economic benefits, particularly for small producers that lack viable alternatives. Other practices, such as integrated pest management, offer both economic and environmental benefits. Valuing the environmental externalities (costs) of agricultural production may increase incentives to engage in sustainable practices. Small producers may need additional incentives, such as payment for environmental services, to adopt and continue sustainable agricultural practices.

5.2.3 GOVERNANCE OF NATURAL RESOURCES

Improved governance and more effective institutional arrangements also are needed to identify locally appropriate practices and measures to sustainably manage natural resources for agriculture.[435] Each nation should identify and implement locally appropriate measures to manage and stabilize soil organic matter; ensure that adequate water quantity and quality are available for productive and domestic purposes; and protect the stock of natural capital (e.g., forests), ecosystems, and biodiversity.[436] Other important avenues include (1) a better understanding of the current state and trends in the condition of soils, water, biodiversity, and ecosystems through the development of improved observation and monitoring systems; (2) efforts to better mainstream agroecology and approaches to extension services grounded in ecosystem services; (3) and increased investments into integrated landscape development.[437] Institutional strengthening will be required at multiple scales—from the community to national and regional levels—to monitor environmental indicators such as the water tables and to encourage adoption of sustainable agricultural practices such as appropriate crop selection across a landscape. Policy measures can include a mix of regulation, incentives, and services to effectively manage natural resources and promote sustainable agriculture practices.[438]

Stronger governance of natural resources would improve outcomes across economic, social, and environmental dimensions. Strengthening the capacity of institutions to design effective policies, programs, and interventions—and monitoring, assessing, and addressing the negative implications of these interventions—can only lead to greater environmental sustainability, economic benefits, and social equity.[439]

5.2.4 EFFORTS TO REDUCE AGRICULTURAL LAND EXPANSION

Efforts to reduce agricultural land expansion include direct measures to preserve other land uses, such as forestry, and measures to sustainably intensify agricultural production on existing cultivated areas. Initiatives like UNFCCC REDD+, the Bonn Challenge, the CBD Aichi Target 15, and the Rio+20 land degradation neutrality goal all aim at reducing deforestation and forest degradation with potentially significant contributions to several sustainable development goals. However, the potential for success and the viability and applicability of the proposed methods to achieve each initiative's goals continue to be debated: proposed options range from those based on market mechanisms to those recommending straightforward forest protection.

Given that deforestation is intimately connected to other land uses, increasing agricultural output from intensification, rather than extensification, has been a key strategy to preserve important forest areas and was first put forward by Borlaug (1983).[440] The argument is that by increasing food production from a given amount of land, the need to clear forest for this production is reduced. Whether this is what happens in reality is the subject of some controversy.[441]

Many studies that investigate sustainable intensification opportunities emphasize the role of genomics research and improved soil and management practices rather than an increased use of fertilizer, irrigation, or pesticides, mostly because of the detrimental environmental effects that high use of these techniques has had on production systems and neighboring ecosystems following the Green Revolution. However, in tropical agriculture, management practices alone are not sufficient in themselves to increase yields significantly.[442] Even breeding crops with improved nitrogen uptake ability will be limited by the amount of nitrogen available in the soil and increasing nitrogen-use efficiency implies lower protein content, adversely affecting nutritive value. Improved cropland management, such as use of cover crops, no-till farming, and intercropping, can result in higher and more-stable yields,[443] but these benefits are often at the lower end of the yield range and can also be characterized by a time lag, during which production costs and yield variability increase.[444] The best way to increase food production is likely to be through an "integrated nutrient management" approach to intensification that combines organic and inorganic nutrient sources.[445] A potential problem is that intensification itself increases GHG emission, particularly N_2O (nitrous oxide) if nitrogenous fertilizers are used, or CH_4 if livestock numbers or rice production are increased.[446] Studies that have investigated the effect of intensification or the use of agronomic practices that increase productivity compared to those currently in use indicate that, in the long run, the land-sparing effect prevails with a consequent reduction in deforestation, forest degradation, and GHG emissions.[447,448,449,450,451,452,453]

A forthcoming study supports the finding of previous studies.[454] The authors show that the adoption of CSA practices can lead to significant land-sparing, reducing pressure for the expansion of harvested areas. They find that the combination of higher yields and the lowering of commodity prices caused by widespread adoption of CSA practices for the production of maize, rice, and wheat reduces producers' incentives to expand production into new areas. Even though harvested area for maize would still expand by 0.4 to 1.8 million hectares over a 2010–50 timeframe, the overall impact across all three crops would be a decrease in harvested area of between 4 and 26 million hectares. This result is suggestive of reduced pressure on forests and other natural areas that might be environmentally significant and rich in carbon. Furthermore, the adoption of CSA practices leads to an increase in the concentration of soil organic carbon, which is beneficial for sustainable production and production resilience because higher soil organic carbon concentrations increase soil fertility and water retention.

However, the long-run perspective of most of these studies must be noted. In reality, agricultural intensification can increase deforestation if the processes of innovation, adoption, and market adjustment are not instantaneous or uniform across farmers and regions. During the transition, early adopters of innovative technologies will gain a competitive advantage, and thus an incentive to expand their cultivation area, potentially at the expense of environmentally sensitive land. Yield-increasing innovations should therefore be accompanied by careful monitoring and regulation of land conversion.

Many practices to sustainably intensify agricultural production can be considered climate smart, but the selection of appropriate practices should consider other potential environmental externalities, such as loadings of pollutants in water bodies from an increase in fertilizer use or harm to pollinators from overuse of pesticides. Furthermore, the economic benefits of such practices depend on many other factors, such as labor requirements. Small producers may have financial, information, or (for women) social constraints that make them less able to adopt practices to sustainably intensify production.

BOX 5.1 Dietary Guidelines with Sustainability in Mind

Brazil is a trailblazer in establishing dietary guidelines that take into account core sustainability concerns. Its 2014 guidelines include as a core principle that healthy diets derive from socially and environmentally sustainable food systems. They recognize the importance of using natural resources sustainably and protecting the environment. The dietary guidelines include environmental considerations, such as soil conservation, control of pests and diseases, use of antibiotics, conservation of forests and biodiversity, and the amount of water and energy consumed.

Another example is Sweden. The Swedish Dietary Guidelines produced by the National Food Agency provides detailed suggestions not only on an environmental footprint linked set of guidelines, such as suggesting reduced consumption of meat, but it is also notable in providing more detailed advice on the selection of plant-based foods, recommending for example, root vegetables over salad greens, due to their robustness and lower environmental impact.[455]

5.2.5 ENVIRONMENTALLY SUSTAINABLE DIETS

Promoting sustainable and appropriate diets provides another opportunity for reducing the environmental footprint of agricultural production, leading to more sustainable and healthier food systems (Box 5.1). Increasing resource-use efficiency has only limited impacts on reducing the environmental burden of agricultural production, while a transition to less-impactful diets would have a greater effect and at the same time keep pace with future human food demands.[456,457] The global food system is currently characterized by an unbalanced distribution of foods and nutrients and unsustainable trends—namely, increasing demand for meat in middle-income countries. Shifting diets in developed countries away from resource-intensive foods such as meat show great potential to reduce GHG emissions from agriculture and the resource intensity of agricultural production.[458,459] Promoting plant-based diets by introducing measures to limit demand for resource-intensive foods (especially livestock) should be limited to areas where animal-source foods are overconsumed and where reduced meat consumption would provide health benefits. In this context, greater regulation of unhealthy and unsustainable foods is another policy lever to encourage behavior change. However, such changes in behavior likely will occur only over the long term, as they may conflict with social and cultural norms.

As with limiting agricultural land expansion, incentives encouraging environmentally sustainable diets would help reduce GHG emissions significantly and improve other environmental outcomes over time. However, there may be short-term costs as producers and consumers adjust their behavior to new economic incentives. Poor consumers in urban areas may face the greatest challenge in adjusting to healthy diets, particularly if alternative healthy and affordable options are not available and accessible.

6. Guiding Principles for the Implementation of Adaptation Actions

Climate change threatens the global food system both directly and indirectly, with risks to production, trade and value chains, environmental sustainability, and food and nutrition security. Many existing adaptation efforts are occurring with little organized planning, without specific information, and by incrementally adjusting to the climate threat. This form of autonomous adaptation must be encouraged, organized, and optimized. Most of these actions are good for development and should be undertaken regardless of climate change. However, because of the impending changes, the pace of adaptation must accelerate to meet key food security, nutrition, development, and sustainability objectives. Even if warming is contained to 1.5°C, significant adaptation efforts are needed to maintain and increase food production, make food value chains more resilient, and provide adequate nutrition to vulnerable populations. Seldom discussed is the possibility that more catastrophic scenarios, generally considered outliers, will come to pass. In such case, even the more "transformative" options identified in this paper might be inadequate to protect the most vulnerable. If the number of severely affected people is large, the consequences for countries, democracies, and the global economy can be devastating. Policymakers should be aware of the possibility of such an outcome and be prepared to deal with the resulting humanitarian and environmental crises.

We propose a set of guiding principles for developing a comprehensive adaptation plan based on actions that either are immediately advantageous or will become necessary as climate change impacts evolve. The relevance and need for more drastic actions ultimately depend on the frequency and intensity of extreme weather and on the severity of climate change impacts.

1. Increased investments in publicly funded agricultural research are necessary, with a particular emphasis on addressing the growing risks faced by vulnerable people.

Research underlies the pursuit of most if not all adaptation measures. Investments in agricultural research, in particular, have led to extraordinary gains in productivity over the past century. The benefits of investing in agricultural research are clear and well documented, and knowledge arising from agricultural research has been essential for reducing rural poverty. Sustained investments in public agricultural research are vital to meet the new challenges deriving from the constraints of planetary boundaries and from climate change. Key promising investments include those in heat tolerance for maize, but other documented highly beneficial impacts include drought tolerance for rainfed maize in Africa, nutrient-use efficient rice varieties, and stacked heat- and drought-tolerant varieties of several crops. Benefits from such investments tend to be higher if the crops are irrigated and, in some cases, are linked with key adaptive management practices such as no-till, precision agriculture, integrated soil and water management, and crop protection measures. The relative adaptive effect of these technologies varies by geography and crop, but accelerated investments and dissemination of these technologies can reduce the vulnerabilities of smallholder farmers as well as the efficiency of farmers in industrialized countries who will account for a growing share of food exports into some developing countries, particularly in sub-Saharan Africa, North Africa, and the Middle East.

Research in genetic engineering can play a critical role in developing crop varieties and livestock breeds that can tolerate or even thrive in new climatic environments, the necessary regulatory frameworks and agreements for their use must be established. New crop and livestock breeds derived from novel genome editing technologies hold great transformative potential. The precise modification of useful traits can lead to greater productivity, lower risk from pests and diseases, and greater suitability to unfavorable climate and growing conditions. Genome editing in staple crops is particularly promising to address food security issues and micronutrient deficiencies in developing countries, while increasing economic returns to small producers. Genetic modifications in feedstock and cattle also can help reduce GHG emissions. Alternatives to conventional agricultural production systems need to play a role in both adaptation and mitigation.

More research is needed to identify new vulnerabilities in food supply chains and strategies to mitigate the risks that a new climate regime can create for processing, packaging, and storage practices. Importantly, changes in pest and disease environments associated with increased climate-extreme events, including long-term droughts and recurring floods, have been understudied, as have been the intersections of such events, overall climate change, globalization, and spreading of plant and animal disease. Therefore, research to strengthen local forecasting of future climate risks and to better account for the costs and benefits of alternative locally relevant adaptation options also are needed.

2. The effects of climate change are multifaceted. Similarly, adaptation options should be evaluated with multiple objectives in mind. Economic, environmental, and social implications of adaptation options should all be part of decision-making processes.

There are many different approaches and perspectives on adaptation, including CSA practices, sustainable agriculture, and ecosystem-based adaptation. These approaches differ in some ways, but all acknowledge the synergies and trade-offs among economic, social, and environmental objectives. Decisionmakers will base their choices on national and local priorities, but they should have full information about benefits and trade-offs across objectives. Ideally, decisionmaking would involve input from multiple stakeholders and perspectives. This should include efforts to integrate local needs, preferences, and knowledge, such as through community-based adaptation. Even within the broad categories described in this report, specific responses can be tailored to maximize economic, social, and environmental benefits.

For any set of adaptation options, decisionmakers should consider the following:

- How compatible is the adaptation option with economic objectives? In particular, what is the potential for the option to improve the livelihoods of vulnerable producers and consumers?
- How compatible is the option with planetary health and the long-term environmental sustainability of agricultural production?
- How equitable is the adaptation option in terms of the international distribution of food and the distribution of costs and benefits across social categories?
- What is the feasibility of implementing and scaling the option based on the current state of global affairs?

3. Challenges as pervasive as those posed by climate change require responses at different scales, and multiple actors bear the responsibility of developing and implementing adaptation actions.

The growing literature on adaptation indicates that to preserve and improve the functionality of food systems, farmers, communities, state actors, and the international community all should take concurrent measures to counteract the negative effects of climate change. Farmers play an essential role in the adoption of new and beneficial agronomic practices and technologies, but these and more radical transformations require the full support of governments, research agencies, and extension services. For some adaptation options, farmers are only the beneficiaries and end users. Climate services, risk management mechanisms, and some digital technologies require that government agencies and private industries collaborate and work at a larger scale—the state or even regional level—to provide these services. Other forms of adaptation require that the international community and governments coordinate and cooperate regionally and even globally. Trade and trade policies, forms of data collection and sharing, and the management of some public goods are examples of problems that must be addressed at a global scale.

4. The effect of risks and extreme events will determine future responses to climate change but are understudied. Risk management (of which insurance is only one instrument) and education to risk management are essential components of adaptation.

Several analyses indicate that the impacts of climate change will include more frequent floods and droughts, increased variability in growing conditions, and greater uncertainty in predicting short-term weather events such as the onset of rain and dry seasons. The main focus of discussions and of quantitative modeling has been on the effects of changes in mean temperatures and precipitations; the effects of climate change on the volatility of agricultural production, crop and livestock prices, and longer-term producer responses to the associated increased risk have received much less attention. This shortcoming must be remedied. First, downscaling climate change projections, understanding how future precipitation and temperature distributions will differ from the past, and determining how to deal with multiple

TABLE 6.1 Evaluation of adaptation options across economic, environmental, and social dimensions

Area	Example adaptation option	Economic implications	Environmental implications	Social implications
Agricultural production	Expansion of irrigated area	Irrigation increases economic returns to production in most cases	Irrigation may have negative impacts on water availability and quality (depending on how and where it is implemented) and on GHG emissions	The costs and benefits are not distributed equally across farmers (e.g., in some cases women face greater constraints to adopt and benefit from irrigation technology)
Food value chains	Climate-proofed infrastructure	Climate-proofing infrastructure has upfront costs, but may contribute to long-term economic development	The design and implementation of infrastructure projects must consider and minimize any possible negative environmental impacts	The design and implementation should also consider the social implications of infrastructure developments, including which communities are affected and which are excluded
Nutrition and health	Incentivizing healthy diet choices	Incentives to encourage heathier diet choices may have negative short-term economic implications (e.g., food companies affected by labeling requirements)	Environmental implications of healthier diets are likely to be positive, particularly if incentives lower consumption of resource-intensive foods in developed countries	There may be negative social impacts of some incentives (e.g., taxing unhealthy foods may increase food costs for the poor, labeling requirements may place small producers at a disadvantage)
Environment	Resource-use efficiency	Resource-use efficiency can lower the costs of production through more precise application of inputs	Resource-use efficiency can preserve and protect natural resources and ecosystems and lower GHG emissions	Measures for resource-use efficiency may not benefit all farmers equally; some technologies may be prohibitive for the poorest and most vulnerable farmers

Source: Authors.

risk sources simultaneously are all challenges that the research community must tackle. Second, even though some instruments already exist (e.g., insurance, alternative agronomic practices and crop systems), many other forms of risk reduction must be made available to farmers and to entrepreneurs who may face different production environments but also must be able to take advantage of upside risk without running into catastrophic consequences. Third, and equally important, a culture of risk management must be developed in countries that traditionally have not used financial instruments to deal with risk.

5. Adaptation actions need to span the entire food system.

New agricultural technologies, breeds, and varieties alone will not be sufficient to ensure adaptation in the agricultural sector. With the exception of subsistence farmers, a well-functioning storage, transportation, transformation, and marketing system are all needed to connect producers to markets and to cities where most consumers reside. Adaptation measures therefore will have to be introduced along the entire value chain. Adaptation actions will also have to be adopted by consumers and their governing bodies alike. These may include reducing food waste, changing consumption patterns, and changing core dietary guidelines.

6. Transformative change will need investments in institutional capacity to manage adaptation.

Promising adaptation options require certain enabling conditions to achieve transformative systemic change. Strong governance institutions are needed to support agricultural adaptation to climate change by providing better climate science and information services at locally applicable scales, fostering innovation, and promoting farmers' uptake of adaptation options. Because other sectors (e.g., energy) will need to implement complementary adaptations to achieve transformative change, strong governance is also required for better collaboration and coordination. Governance institutions can and should mitigate negative consequences of adaptation actions (e.g., for vulnerable social groups or the environment) by effectively monitoring outcomes across economic, environmental, and social objectives and engaging multiple stakeholders in the decisionmaking process.

7. New digital technologies accompanied by capacity building can lead to transformative outcomes.

Farmers and entrepreneurs have just started to explore the power of new digital technologies. Technologies that connect buyers and sellers, enhance product traceability, improve organoleptic characteristics and product safety, and efficiently and proportionally deploy inputs not only offer opportunities to cope with a new climatic environment but also provide the chance to take advantage of future market opportunities and reduce market failures. Some of these technologies are being tested and even used in some settings, but in truth, we are only at the infancy of technological innovation, and there is significant scope for expansion. It is difficult to overestimate the potential for radical change that these technologies can bring to food systems. In general, the use of these technologies should increase the efficiency of the food production and distribution systems and therefore help in reducing GHG emissions, or at least reduce emission intensity.

8. Temporary and seasonal migration can build up household resilience and improve food security in rural areas while exacerbating food security challenges in urban areas. Without proper planning, large-scale migration could be catastrophic.

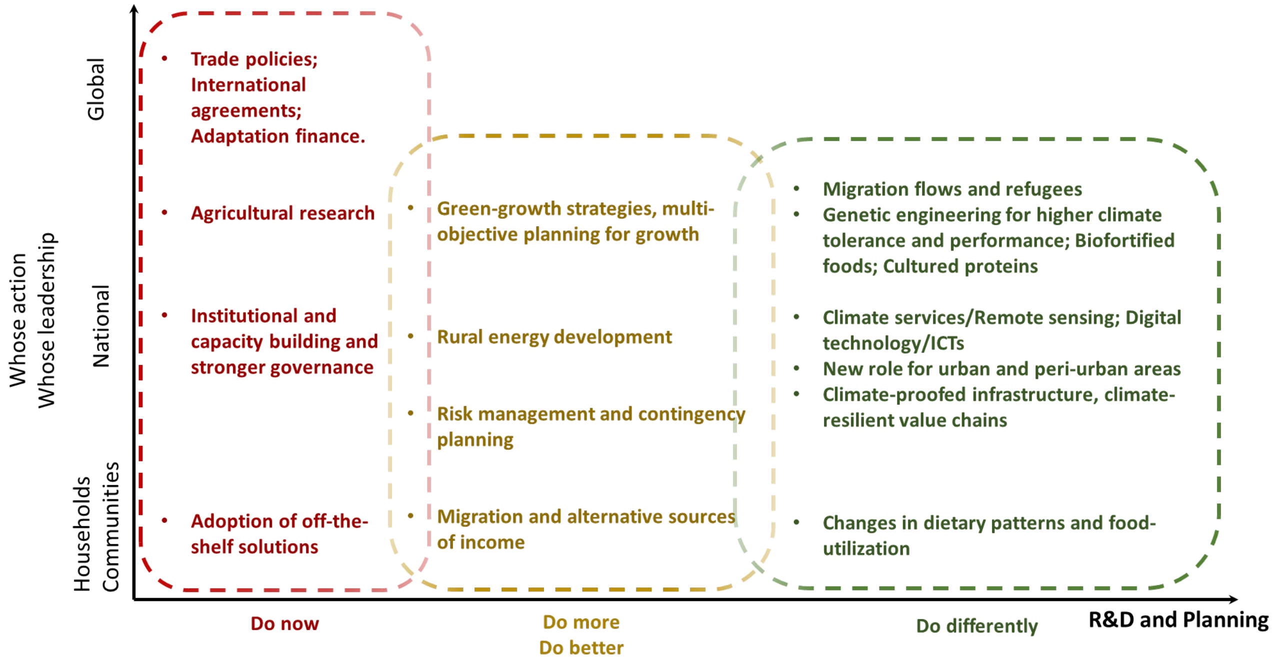
Remittances from seasonal migration can play an important role in improving rural household resilience to short- and medium-term shocks. However, rural-urban migration often contributes to a deteriorating food environment in urban areas. Moreover, long-term and large-scale migration from the Global South and out of agriculture due to increasingly unsuitable conditions for agriculture, sea-level rise and salinization, and loss of fertility and soil degradation could prove catastrophic if not accurately anticipated and planned for. In addition to all other adaptation actions, significant attention should be given to identifying where such large-scale migration flows are likely to occur and to developing policy measures and agreements to support the future livelihoods of such migrants.

9. Reducing GHG emissions can create significant constraints for some adaptation actions.

Depending on how the future unfolds, reducing GHG gases can become a major factor in deciding which adaptation measures are viable and in determining how they should be implemented. The use of adaptation measures, such as chemical fertilizers, irrigation, and cold storage, as well as trade of agricultural commodities, could be far more limited in a world that prioritizes mitigation over adaptation. In a sense, increasing the efficiency of production can be considered a win-win proposition, as it reduces emission intensity, a goal that many of the adaptation options reviewed in this paper achieve. However, depending on the level of warming that will be reached, total emissions can become a hard constraint, and the reduction of intensity might not be sufficient. Therefore, adaptation measures should be evaluated according to their potential effects on GHG emissions.

These principles and the literature reviewed here can be used to define a roadmap for adaptation actions (Figure 7.1). Adaptation actions fall into three categories: (1) actions that should be carried out immediately and require immediate support, (2) actions relying on existing knowledge and technologies that would benefit from increased investments and which should be improved and expanded, and (3) actions that are significantly different from business as usual and can transform the agricultural sector. Some of them will be needed to chart the future of adaptation (i.e., financial support, international agreements and regulatory frameworks; agricultural research). Other measures facilitate autonomous adaptation and reduce GHG emission intensity. The latter two categories need increasing investments in research and development as well as

FIGURE 6.1 Climate adaptation options, planning, and responsibilities



Source: Authors.

planning and will be responsible for combating progressively challenging climate conditions. The last category in particular offers the opportunity for large and long-lasting gains in GHG emissions abatement if mitigation is structurally embedded in them as they are developed.

These categories intersect and the boundaries among them are only indicative as there are versions of the "do now" actions that can benefit from more research and development (e.g., crop and livestock management) or that be transformational in their own right over time (e.g., rural energy). We have attempted to indicate the scale at which these activities are to be implemented or at least who should take the leadership in promoting them. Some of them fall in between scales, indicating that from the start these actions require close collaboration among actors at different scales. That said, most adaptation measures require a network of cooperating agents—farmers need significant support from government and international agencies to adopt improved farming practices, whereas trade policies and adaptation finance require the collaboration of state and international figures—and part of the adaptation process is the facilitation of this cooperation.

7. Conclusion

The world faces the unprecedented challenges of increasing food production by 60% to feed a global population that is projected to reach 9 billion people by 2050. An already difficult task is made all the more daunting by the impacts of climate change. A series of actions must be taken and the right policies and set of incentives must be in place so that the additional constraints imposed by climate change do not irreparably disrupt food systems.

Climate change will extend and exacerbate challenges to achieve global food security in 21st century. It is imperative that the world responds to these challenges swiftly and coherently in order to avoid major disruptions to the food system and irreparable damages to vulnerable communities and the environment. As demonstrated in this review, many adaptation actions are within reach, but it is essential that investments in adaptation and GHG emissions reduction be expanded significantly.

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