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# Climate Change Response Strategies for Agriculture: Challenges and Opportunities for the 21st Century



Francesco Tubiello  
Josef Schmidhuber  
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*Erick Fernandes*  
*Dipti Thapa*

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1818 H Street, NW  
Washington, DC 20433  
Telephone 202-473-1000  
Internet [www.worldbank.org/rural](http://www.worldbank.org/rural)  
E-mail [ard@worldbank.org](mailto:ard@worldbank.org)

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### **Authors**

Francesco Tubiello: GET-Carbon, New York USA, [www.get-carbon.com](http://www.get-carbon.com); Email: [franci@get-carbon.com](mailto:franci@get-carbon.com); The European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, Agriculture Unit, Via E.Fermi, 2749, I-21027 Ispra (VA) - Italy, TP 483; Josef Schmidhuber: Global Perspective Studies Unit, Food and Agriculture Organization, 00100 Rome, Italy; Email: [josef.schmidhuber@fao.org](mailto:josef.schmidhuber@fao.org); Mark Howden: Commonwealth Scientific and Industrial Research Organization, Sustainable Ecosystems GPO Box 284, Canberra ACT 2601, Australia; Email: [mark.howden@csiro.au](mailto:mark.howden@csiro.au); Peter G. Neofotis: Email: [pneofotis@gmail.com](mailto:pneofotis@gmail.com); Sarah Park: Commonwealth Scientific and Industrial Research Organization, Sustainable Ecosystems GPO Box 284, Canberra ACT 2601, Australia; Email: [sarah.park@csiro.au](mailto:sarah.park@csiro.au); Erick Fernandes: Agriculture and Rural Development Department, The World Bank, 1818 H Street, NW, Washington DC 20433; Email: [efernandes@worldbank.org](mailto:efernandes@worldbank.org); Dipti Thapa: Agriculture and Rural Development Department, The World Bank, 1818 H Street, NW, Washington DC 20433; Email: [dthapa@worldbank.org](mailto:dthapa@worldbank.org)

Cover photo: Scott Wallace, World Bank: Harvesting tomatoes. Senegal.

## Contents

Abstract.....	v
Executive Summary .....	vi
<b>1. Introduction .....</b>	<b>1</b>
<b>2. Physiological changes and agro-ecological impacts.....</b>	<b>4</b>
<b>2.1 Impacts .....</b>	<b>5</b>
Higher temperatures .....	5
Elevated atmospheric CO <sub>2</sub> levels .....	6
Interactions of elevated CO <sub>2</sub> with temperature and precipitation .....	7
Interactions of elevated CO <sub>2</sub> with soil nutrients .....	7
Increased frequency of extreme events.....	8
Impacts on weed and insect pests, diseases and animal production and health .....	8
Interactions with air pollutants .....	9
Vulnerability of carbon pools .....	10
<b>2.2 Impact assessments.....</b>	<b>10</b>
Areas of new knowledge .....	12
<b>3. Socioeconomic interactions and impacts on food security.....</b>	<b>14</b>
<b>3.1 Food security, scope, and dimensions.....</b>	<b>14</b>
<b>3.2 Climate change and food security .....</b>	<b>15</b>
The effects of climate change on food availability, agriculture production and productivity .....	18
Impacts on the stability of food supplies .....	20
Impacts of climate change on food utilization .....	22
Impacts of climate change on access to food .....	22
<b>3.3 Impacts on food prices .....</b>	<b>24</b>
<b>3.4 Quantifying the impacts on food security .....</b>	<b>24</b>
<b>3.5 Uncertainties and limitations .....</b>	<b>27</b>
<b>4. Adaptation .....</b>	<b>30</b>
<b>4.1. State-of-the-art knowledge on the strategic assessment     of adaptation capacity .....</b>	<b>31</b>
<b>4.2 Adaptation strategies for a selection of agricultural sectors .....</b>	<b>36</b>
Cropping systems .....	36
Livestock .....	37
Forestry .....	38
Fisheries.....	39
<b>4.3 Synergies of adaptation and mitigation.....</b>	<b>40</b>
<b>4.4 Financial mechanisms for mitigation and adaptation.....</b>	<b>41</b>

<b>4.5 Impact and adaptation metrics</b> .....	<b>43</b>
Tools for impact and policy assessment .....	43
Agricultural production metrics .....	43
<b>5. Conclusions and recommendations</b> .....	<b>49</b>
<b>5.1 A call for action</b> .....	<b>51</b>
<b>6. References</b> .....	<b>55</b>
<b>Endnotes</b> .....	<b>63</b>

## **Abstract**

Agriculture will face significant challenges in the 21st century, largely due to the need to increase global food supply under the declining availability of soil and water resources and increasing threats from climate change. Nonetheless, these challenges also offer opportunities to develop and promote food and livelihood systems that have greater environmental, economic and social resilience to risk. It is clear that success in meeting these challenges will require both the application of current multidisciplinary knowledge, and the development of a range of technical and institutional innovations. This paper identifies possible climate change responses that address agricultural production at the plant, farm, regional and global scales. Critical components required for the strategic assessment of adaptation capacity and anticipatory adaptive planning are identified and examples of adaptive strategies for a number of key agricultural sectors are provided. Adaptation must be fully consistent with agricultural rural development activities that safeguard food security and increase the provision of sustainable ecosystem services, particularly where opportunities for additional financial flows may exist, such as payments for carbon sequestration and ecosystem conservation. We conclude by making interim recommendations on the practical strategies necessary to develop a more resilient and dynamic world agriculture in the 21st century.

## **Executive Summary**

Agriculture, or the set of activities providing food, fiber, and forestry products, is expected to face significant challenges in the 21st century. These are largely in connection with the need to increase global food, timber, and bioenergy supplies to a world of 10 billion people, given limited soil and water resources and increasing threats from climate change. Already today, increased land competition between bioenergy and food crops, climate extremes in key food exporting regions, rapidly shifting diets in large emerging economies, and a degree of financial speculation has resulted in instability in the world's food production systems beyond that previously thought. Given further increases in these pressures in coming decades, the world's poor are particularly vulnerable, especially those located in low-income, food importing countries, where a large share of income is already devoted to purchasing basic food staples. Even if the current food security crisis has to some extent receded and prices have come down from recent peaks, this experience has demonstrated that the world food supply is highly unstable in the face of such pressures.

Nonetheless, these challenges also offer the potential to develop and promote food and livelihood systems that have greater environmental, economic and social resilience to risk. It is clear that success in meeting these challenges will require both the application of current multidisciplinary knowledge and the development of a range of technical and institutional innovations. This paper identifies possible climate change responses that address agricultural production at the crop, farm, regional, and global scales. We propose that adaptation must be fully consistent with agricultural rural development activities that safeguard food security and increase the provision of sustainable ecosystem services, particularly where opportunities for additional financial flows may exist, such payments for carbon sequestration and ecosystem conservation. Several voluntary and regulatory mechanisms currently facilitate the analytical and operational basis for payments for ecosystem services, for example, the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) and Global Environmental Facility (GEF) funding mechanisms, and a range of related carbon funds administered by the World Bank, including the most recent Climate Initiative Funds. We conclude by making interim recommendations on the practical strategies necessary to develop a more resilient and dynamic world agriculture in the face of mounting climate challenges. This paper is organized in five sections:

- Section one reviews the latest findings on impacts of key climate change variables on plant function and farm-level production systems, including changes in elevated carbon dioxide (CO<sub>2</sub>), temperature, and precipitation patterns.

- Section two presents an analysis of the repercussions of these local impacts on regional and global food productions.
- Section three presents a discussion of the adaptation strategies that are necessary to minimize the expected negative impacts on agro-ecosystems, as well as capitalize on potential new opportunities for promoting greater resilience and sustainable production.
- Section four identifies the important synergies that exist between adaptation strategies and mitigation options, such as those leading to carbon sequestration.
- Section five presents recommendations on some practical and operational steps needing to be implemented now, from the perspective of short- and long-term sustainable rural development and agricultural planning.

## **Key Findings**

*Climate change will affect agriculture and forestry systems through higher temperatures, elevated CO<sub>2</sub> concentration, precipitation changes, increased weeds, pests, and disease pressure, and increased vulnerability of organic carbon pools.*

*High temperatures* can lead to negative impacts such as added heat stress, especially in areas at low to mid-latitudes already at risk today, but they also may lead to positive impacts such as an extension of the growing season in currently cold-limited high-latitude regions. Overall, current studies project that climate change will increase the gap between developed and developing countries through more severe climate impacts in already vulnerable developing regions, exacerbated by the relatively lower technical and economic capacity to respond to new threats.

*Elevated atmospheric CO<sub>2</sub> concentrations* increase plant growth and yield and may improve plant water use efficiency. However, a number of factors such as pests, soil and water quality, adequate water supply, and crop-weed competition may severely limit the realization of any potential benefits.

*Changes in precipitation patterns*, especially in the *frequency of extreme events* such as droughts and floods, are likely to severely affect agricultural production. These impacts will tend to affect poor developing countries disproportionately, especially those currently exposed to major climate risks. However, increased frequency of extremes may also increase damage in well-established food production regions of the developed world. For instance, the European heat wave of 2003, with temperatures up to 6°C above long-term means and precipitation deficits up to 300 millimeters, resulted in crop yields falling 30 percent below long-term averages, as well as severe ecosystem, economic, and human losses.

*Weeds, pests and diseases* under climate change have the potential to severely limit crop production. Whereas quantitative knowledge is lacking compared to other controllable climate and management variables, some anecdotal data show the proliferation of weed and pest species in response to recent warming trends.



For example, the activity of mountain pine beetle and other insects in the United States and Canada is taking place notably earlier in the season and resulting in major damage to forest resources. Similarly, in 2006, Northern Europe experienced the first ever incidence of *bluetongue*, a disease generally affecting sheep, goat and deer, in the tropics. More frequent climate extremes may also promote plant and animal disease and pest outbreaks. In Africa, droughts between the years 1981–1999 have been shown to increase the mortality rates of national livestock herds by between 20 percent and 60 percent.

*Vulnerability of organic carbon pools* to climate change has important repercussions for land sustainability and climate mitigation. In addition to plant species responses to elevated CO<sub>2</sub>, future changes in carbon stocks and net fluxes will critically depend on land use actions such as afforestation/reforestation, and management practices such as Nitrogen (N) fertilization, irrigation, and tillage, in addition to plant species responses to elevated CO<sub>2</sub>.

***It is very likely that climate change will increase the number of people at risk of hunger*** compared with reference scenarios that exclude climate change; the exact impacts will however be strongly determined by future socioeconomic development. Six major points emerge from recent studies:

1. It is estimated that climate change may increase the number of undernourished people in 2080 by up to 170 million.
2. The magnitude of these climate impacts is estimated to be relatively small compared with the impact of socioeconomic development, which is expected to substantially diminish the number of malnourished and hungry people significantly by 2100. Progress in reducing the number of hungry people will be unevenly distributed over the developing world and it is likely to be slow during the first decades of this century. With or without climate change, the millennium development goal of halving the prevalence of hunger by 2015 is unlikely to be realized before 2020–30.
3. In addition to socioeconomic pressures, food production may increasingly compete with bioenergy demands in coming decades. Studies addressing the possible consequences for world food supply have only recently started to surface and provide both positive and negative views of this competition for agricultural resources.
4. Sub-Saharan Africa is likely to surpass Asia as the most food insecure region. In most climate change scenarios, sub-Saharan Africa accounts for 40 to 50 percent of undernourished people globally by 2080, compared with about 24 percent today.
5. Although there is significant uncertainty regarding the effects of elevated CO<sub>2</sub> on crop yields, this uncertainty reduces when following the supply chain through to food security issues.
6. It is important to now recognize that the recent surge in energy prices could have a more substantial and more immediate impact on economic development and food security than captured by any of the present Special Report on Emissions Scenarios (SRES).

*Benefits of adaptation vary with crop species, temperature and rainfall changes.* Modeling studies that incorporate key staple crops indicate that adaptation benefits are highly species-specific. For example, the potential benefits of adaptation for wheat are similar in temperate and tropical systems, increasing average yields by 18 percent when compared with the scenario without adaptation. The benefits for rice and maize are relatively smaller and increase yield by around 10 percent compared with the no-adaptation baseline. These improvements to yield translate to damage avoidance due to increased temperatures of 1 to 2°C in temperate regions and between 1.5 to 3°C in tropical regions, potentially delaying negative impacts by up to several decades. In terms of temperature and rainfall change, there is a general tendency for most of the benefits of adaptation to be gained under moderate warming (of less than 2°C), although these benefits level off at increasing changes in mean temperature. In addition, yield benefits from adaptation tend to be greater under scenarios of increased rather than decreased rainfall.

*Useful synergies for adaptation and mitigation in agriculture, relevant to food security exist* and should be incorporated into development, disaster relief, climate policy, as well as institutional frameworks at both the national and international level. Synergistic adaptation strategies aim to enhance agro-ecosystem and livelihood resilience, including social, economic and environmental sustainability, in the face of increased climatic pressures, while simultaneously avoiding maladaptation<sup>1</sup> actions that inadvertently increase climate change vulnerability. Such strategies include forest conservation and management practices, agroforestry production for food or energy, land restoration, recovery of biogas and waste and, soil and water conservation activities that improve the quality, availability and efficiency of resource use. Although many of these strategies are already often deeply rooted in local cultures and knowledge, this needs to be recognized, built on, and supported by key international agencies and non-governmental organizations. Clearly, potential mitigation practices such as bioenergy and extensive agriculture that result in competition for the land and water resources necessary for ecosystem and livelihood resilience need to be minimized.

*A general metrics framework is useful for planning and evaluating the relative costs and benefits of adaptation and mitigation responses in the agricultural sector.* In this framework, biophysical factors, socioeconomic data, and agricultural system characteristics are evaluated relative to vulnerability criteria of agricultural systems, and are expressed in terms of their exposure, sensitivity, adaptive capacity, and synergy with climate policy. For example,

- Metrics for biophysical factors may include indexes for soil and climate resources, crop calendars, water status, biomass, and yield dynamics.
- Metrics for socioeconomic data include indexes describing rural welfare, reflected, for instance, in regional land and production values, total agricultural value added, financial resources, education and health levels, effective research, development and extension capacity, or the agricultural share of the Gross Domestic Product (GDP). Importantly, they may include nutrition indexes comparing regional calorie needs versus food availability

through local production and trade. They could also indicate degree of protectionism and the status of crop insurance programs.

- Metrics for climate policies describe regional commitments to adaptation and mitigation policies, relevant to agriculture. For instance, such metrics measure land use and sequestration potential; number and type of CDM projects in place and committed land area; area planned for bioenergy production, and so on. These may be useful for identifying potential synergies of mitigation with adaptation strategies within regions, helping to define how vulnerability may change with time.

## **Conclusions**

This paper concludes that in the face of projected changes in climate, there can be no long-term sustainability of agro-ecosystems and associated livelihoods without the development of adaptation strategies that incorporate enhanced environmental, social, and economic resilience as an intrinsic component of sustainable rural development. In order to address the key question of what practical adaptation strategies need to be implemented, where, and by when, two important components must be considered:

1. **Assessment tools are needed to estimate climate change risks and vulnerabilities for a portfolio of development projects.** Models provide a useful tool for assessing the sources and dynamics of vulnerability, as well as scenarios of climate change and the costs and benefits of adaptation. When used in combination, models can enable a systems analysis of environmental, social and economic impacts to support all decision makers from stakeholders to policy advisors in the context of participatory and action research. For example, agro-ecological models of agriculture and forestry may be linked to economic production and trade models capable of simulating the effects of adaptation actions at both the local and regional scale. They may also enable assessment of potential synergies with mitigation actions through the simulation of energy flows and emission balances.
2. **Pathways for implementation of adaptation actions must be developed,** so that identified risks and opportunities at the macro-level can be implemented in collaboration with stakeholders to provide relevant working solutions. The development of impact and adaptation metrics can facilitate the evaluation of policy options, assess both the short- and long-term risks of climate change and identify the thresholds beyond which more fundamental transitions in land use and management are required to maintain sustainable rural livelihoods. The tradeoffs between land use for food, bio-energy and carbon sequestration, as well as the social, environmental, and economic implications of adaptation responses, increasingly need to be considered within such analyses.

The above actions need to be underpinned and supported by national and international policy and institutional structures that integrate climate change adaptation explicitly into development and disaster relief.

## **1. Introduction**

Agriculture is a fundamental human activity at risk from climate change in coming decades. At the same time it will continue to be, a major agent of environmental and climate change at local, regional and planetary scales. First, it is a major user of land resources. About 1.4 billion hectares (10 percent of total ice-free land) contribute to crop cultivation and an additional 2.5 billion hectares are used for pasture. Roughly 4 billion hectares is forested land, 5 percent of which is used for plantation forestry. On this land, 2 billion metric tons of grains are produced yearly for food and feed, providing two-thirds of the total protein intake by humans. Significant quantities of chemical inputs are applied to achieve such high levels of production; about 100 million metric tons of nitrogen are used annually, with large quantities leaching through the soil and leading to significant regional land, water and atmospheric pollution.

Second, agriculture is a major user of water. Over 200 million hectares of arable land is under irrigation, using 2,500 billion cubic meters of water annually, representing 75 percent of fresh water resources withdrawn from aquifers, lakes, and rivers by human activity. Irrigation sustains a large portion of the total food supply—about 40 percent in the case of cereals. In addition, 150 million metric tons of fish (roughly 55 percent capture fisheries and 45 percent aquaculture) are consumed annually—with 75 percent of global stocks being fully or overexploited, and estimates that an additional 40 million metric tons will be needed by 2020 to maintain current per capita consumption trends—contributing 50 percent or more of total animal protein intake in some Small Island States (SIDS) and other developing countries (mainly in Sub-Saharan Africa).

As a result of these large-scale activities, inadequate management and improper implementation, agriculture is a significant contributor to land and water degradation and, in particular, a major emitter of greenhouse gases. It emits into the atmosphere 13–15 billion metric tons carbon dioxide equivalent (CO<sub>2</sub>e) per year—about a third of the total from human activities. Overall, agriculture is responsible for 25 percent of carbon dioxide (largely from deforestation), 50 percent of methane (rice and enteric fermentation), and over 75 percent of nitrogen dioxide (N<sub>2</sub>O) (largely from fertilizer application) emitted annually by human activities [1].

If emissions of greenhouse gases are not controlled in the coming decades, including those from agriculture, continued growth of their atmospheric concentrations is projected to result in severe climate change throughout the 21st century. Stabilization of atmospheric concentrations of greenhouse gases must be achieved by implementing significant emission reductions in the

coming decades, certainly no later than 2020–30, in order to avoid serious damage to natural and managed ecosystems upon which many critical human activities depend [3].

<b>Table 1 Anthropogenic greenhouse gas emissions</b>		
<b>2005</b>		
	G t CO <sub>2</sub> e yr <sup>-1</sup>	Share %
<b>Global</b>	<b>50</b>	
<b>Agriculture</b>	<b>5–6</b>	<b>10–12%</b>
Methane	(3.3)	
N <sub>2</sub> O	(2.8)	
<b>Forestry</b>	<b>8–10</b>	<b>15–20%</b>
Deforestation	(5–6)	
Decay and Peat	(3–4)	
<b>TOTAL Ag. &amp; For.</b>	<b>13–15</b>	<b>25–32%</b>
<i>Sources: [2].</i>		

As a result of greenhouse gases already in the atmosphere from past and current emissions, our planet is already committed to at least as much warming over the 21st century as it has experienced over the 20th century (0.75°C). This implies that in addition to mitigation, adaptation to the anticipated warming is essential. Possible strategies for adapting food and forestry production to climate change have been identified [4]. Finally, the main drivers of global food security—food availability, stability, utilization, and access—have been examined in the context of climate change [5]. The joint effects of change in socioeconomic development and climate change on the numbers of people at risk of hunger over the 21st century will be examined in this paper.

Agriculture in the 21st century will therefore be undergoing significant challenges, arising largely from the need to increase the global food and timber supply for a world nearing a population of over 10 billion, while adjusting and contributing to respond to climate change. Success in meeting these challenges will require a steady stream of technical and institutional innovations, particularly so that adaptation strategies to climate change are consistent with efforts to safeguard food security and maintain ecosystem services, including mitigation strategies that provide carbon sequestration, and offsets under sustainable land management [6].

This paper reviews emerging issues in climate change, its impacts on agriculture, food production, food security, and forestry, as well as related adaptation strategies. Specifically, the study:

- Addresses the likely changes in agro-climatic conditions and their spatial and temporal impacts on agricultural productivity and production;

- Documents the complex effects on agricultural output linked to the interactions of elevated atmospheric CO<sub>2</sub> concentration, higher temperatures and changes in precipitation;
- Discusses the projected physiological and agro-ecological impacts in the context of larger-scale—that is, national and international—population and market dynamics, with a focus on rural development in developing countries, necessary to assess the impacts of projected climate change and concurrent socioeconomic pressures on world food security, including its key dimensions of production, utilization, access, and stability;
- Focuses on the adaptation strategies needed to cope with projected impacts of climate change, and reviewing their economic consequences and their synergies with climate mitigation. Examples include strategies that may contribute to sequestering carbon in land production systems and changes in management practices that might be incorporated into cropping and forestry systems.

## **2. Physiological Changes and Agro-ecological Impacts**

Climate change will affect agriculture and forestry systems through a number of critical factors:

1. Rising temperatures, can lead to negative impacts such as added heat stress, especially in areas at low-to-mid latitudes already at risk today. However, they can also lead to positive impacts, such as an extension of the growing season in high-latitude regions that are currently limited by cold temperatures.
2. Elevated atmospheric CO<sub>2</sub> concentrations, which tend to increase plant growth and yield, and may improve water use efficiency, particularly in so-called C<sub>3</sub> carbon fixation plants such as wheat, rice, soybean, and potato. The impact on so-called C<sub>4</sub> carbon fixation plants, such as maize, sugarcane, and many tropical pasture grasses, is not as pronounced due to different photosynthetic pathways [7]. How much agricultural plants in fields and trees in plantation forests benefit from elevated CO<sub>2</sub>, given a number of limiting factors such as pests, soil and water quality, crop-weed competition, remains an open question.
3. Changes in precipitation patterns, especially when considering likely changes in the frequency of extremes, with both droughts and flooding events projected to increase in coming decades, leading to possible negative consequences for land-production systems. At the same time, a critical factor affecting plant productivity will be linked to simultaneous temperature and precipitation changes that influence soil water status and the ratio of evaporative demands to precipitation.

All these factors, and their key interactions, must be considered together, across crops in different regions, in order to fully understand the impact that climate change will have on agriculture.

Importantly, the experimental measurements of crop and pasture responses to changes in climate variables are still limited to small-scale plots, so that results are difficult to extrapolate to the field and farm level. As a consequence, current computer models of plant production, although quite advanced in their handling of soil-plant-atmospheric dynamics as well as crop management, lack realistic descriptions of key limiting factors to real fields and farm operations. Therefore, the potential for negative surprises under climate change is not fully explored by current regional and global projections. Key interactions that are currently poorly described by crop and pasture models include:

- (i) nonlinearity and threshold effects in response to increases in the frequency of extreme events under climate change;
- (ii) modification of weed, pest, and disease incidence, including weed-crop competition;

- (iii) large-scale field response of crops to elevated CO<sub>2</sub> concentration; and
- (iv) interactions of climate and management variables, including effects of elevated CO<sub>2</sub> levels.

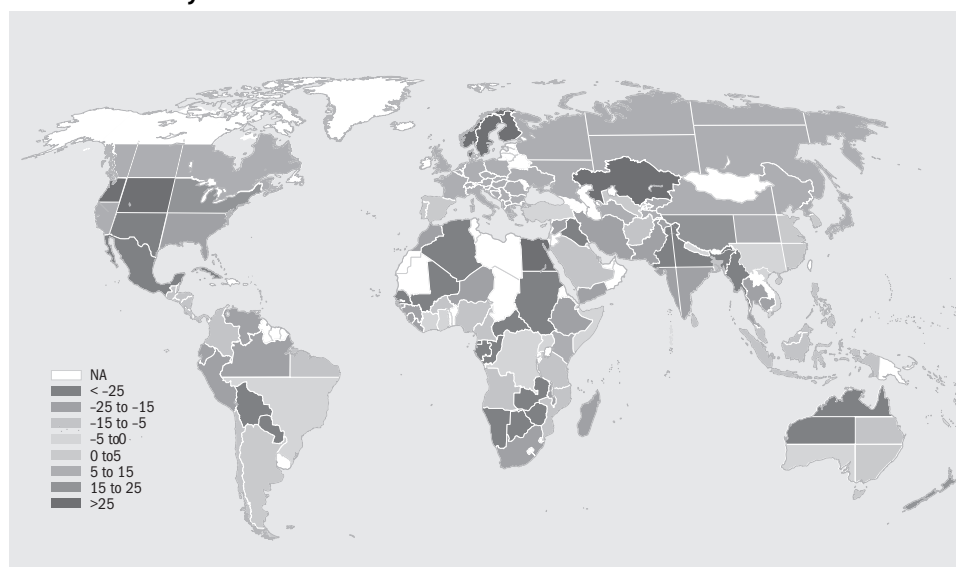
Regardless of these uncertainties, there is no doubt that plant development, growth, yield, and ultimately the production of crop and pasture species will be impacted by, and will respond to, increases in atmospheric CO<sub>2</sub> concentration, higher temperatures, altered precipitation and evapo-transpiration regimes, increased frequency of extreme temperature and precipitation events, as well as weed, pest and pathogen pressures [3,8]. Recent research has helped to better quantify the potential outcome of these key interactions.

## 2.1. Impacts

- *Higher temperatures*

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [3] provides a number of important considerations on the overall impacts of higher temperatures on crop responses. The report suggests that at the plot level, and without considering changes in the frequency of extreme events, moderate warming (i.e., what may happen in the first half of this century) may benefit crop and pasture yields in temperate regions, while it would decrease yields in semiarid and tropical regions. Modeling studies indicate small beneficial effects on crop yields in temperate regions corresponding to local mean temperature increases of 1–3°C and associated CO<sub>2</sub> increase and rainfall changes. By contrast, in tropical regions, models indicate negative yield impacts for the major crops even with moderate temperature increases (1–2°C). Further warming projected for the end of the 21st century has increasingly negative impacts in all regions. Figure 1

**Figure 1** Projected changes in crop yields in 2080; percentage changes with respect to a year 2000 baseline



Climate Change Impacts on Crop Yields, 2000–2080.

Source: Cline (2007).



illustrates the geographical distribution of climate change impacts on crop yields (average responses for wheat, maize, rice, and soybean), showing the differences between high-latitude, mostly developed countries, and low-latitude, tropical developing countries [9]. At the same time, farm-level adaptation responses may be effective at low to medium temperature increases, allowing coping with up to 1–2°C local temperature increases, an effect that may be considered as “buying time” [4].

Increased frequency of heat stress, droughts, and floods negatively affect crop yields and livestock beyond the impacts of mean climate change, creating the possibility for surprises, with impacts that are larger, and occurring earlier, than predicted using changes in mean variables alone.

- *Elevated atmospheric CO<sub>2</sub> levels*

Hundreds of studies conducted over the last 30 years have confirmed that plant biomass and yield tend to increase significantly as CO<sub>2</sub> concentrations increase above current levels. Such results are found to be robust across a variety of experimental settings—such as controlled environment closed chambers, greenhouses, open and closed field top chambers, as well as Free-Air Carbon dioxide Enrichment experiments (FACE). Elevated CO<sub>2</sub> concentrations stimulate photosynthesis, leading to increased plant productivity and modified water and nutrient cycles [10,11]. Experiments under optimal conditions show that doubling the atmospheric CO<sub>2</sub> concentration increases leaf photosynthesis by 30–50 percent in C<sub>3</sub> plant species and by 10–25 percent in C<sub>4</sub> species, despite feedbacks that reduce the response of leaf photosynthesis by elevated atmospheric CO<sub>2</sub> concentrations [12].

However, crop yield increase is lower than the photosynthetic response. On average, across several species and under unstressed conditions, compared to current atmospheric CO<sub>2</sub> concentrations of almost 380 parts per million (ppm), crop yields increase at 550 ppm CO<sub>2</sub> is in the range of 10–20 percent for C<sub>3</sub> crops and 0–10 percent for C<sub>4</sub> crops [12–14]. Increases in above-ground biomass at 550 ppm CO<sub>2</sub> for trees are up to 30 percent, with the higher values observed in young trees and a minimal response observed in the few experiments conducted to date in mature natural forests [11,12]. Observed increases of above-ground production in C<sub>3</sub> pasture grasses and legumes are about +10 and +20 percent, respectively [11,12].

Some authors have recently argued that crop response to elevated CO<sub>2</sub> may be lower than previously thought, with consequences for crop modeling and projections of food supply [15,16]. Results of these new analyses, however, have been disputed, showing consistency between previous findings from a variety of experimental settings and new FACE results [17]. In addition, simulations of plant growth and yield response to elevated CO<sub>2</sub> within the main crop simulation models, have been shown to be in line with experimental data, for example, projecting crop yield increases of about 5–20 percent at 550 ppm CO<sub>2</sub> [17,18]. Claims that current impact assessment simulation results are too optimistic because they assume too high a CO<sub>2</sub> response with respect to experimental data are, therefore, in general, incorrect [17].

Plant physiologists and modelers recognize, however, that the effects of elevated CO<sub>2</sub>, as measured in experimental settings and subsequently implemented in models, may overestimate actual field and farm-level responses, due to limiting factors such as pests, weeds, nutrients, competition for resources, and soil, water and air quality [12,13,17,19–21]. These potential limiting factors are neither well understood at large scales, nor well implemented in leading models. Future crop model development should therefore strive to include these additional factors in order to allow for more realistic climate change simulations. In the meantime, studies projecting future yield and production under climate change should do so by incorporating sensitivity ranges for crop response to elevated CO<sub>2</sub> in order to better convey the associated uncertainty range [3].

- *Interactions of elevated CO<sub>2</sub> with temperature and precipitation*

Climate changes projected for future decades will modify—and may often limit—the direct CO<sub>2</sub> effects on crop and pasture plant species that were discussed above. For instance, high temperature during the critical flowering period of a crop may lower otherwise positive CO<sub>2</sub> effects on yield by reducing grain number, size, and quality [22–24]. Increased temperatures during the growing period may also reduce CO<sub>2</sub> effects indirectly, by increasing water demand. For example, yield of rain fed wheat grown at 450 ppm CO<sub>2</sub> was found to increase up to 0.8°C warming, then declined beyond 1.5°C warming; additional irrigation was needed to counterbalance these negative effects [32]. In pastures, elevated CO<sub>2</sub> together with increases in temperature, precipitation, and N deposition resulted in increased primary production, with changes in species distribution and litter composition [25–28]. Future CO<sub>2</sub> levels may favour C<sub>3</sub> plants over C<sub>4</sub>; yet the opposite is expected under associated temperature increases. The net effects remain uncertain.

Because of the key role of water in plant growth, climate impacts on crops significantly depend on the precipitation scenario considered. Because more than 80 percent of total agricultural land—and close to 100 percent pastureland—is rain fed, Global Climate Model (GCM)-projected changes in precipitation will often shape both the direction and magnitude of the overall impacts [27–29]. In general, changes in precipitation, and more specifically in evapo-transpiration to precipitation ratios, modify ecosystem productivity and function, particularly in marginal areas; higher water-use efficiency as a result of stomatal closure and greater root densities under elevated CO<sub>2</sub> may in some cases alleviate or even counterbalance drought pressures [30,31]. Although the latter dynamics are fairly well understood at the single plant level, large-scale implications for whole ecosystems are not well understood [32,33].

- *Interactions of elevated CO<sub>2</sub> with soil nutrients*

Various FACE experiments confirm that high nitrogen content in the soil increases the relative response of crops to elevated atmospheric CO<sub>2</sub> concentrations [11]. They demonstrate that the yield response of C<sub>3</sub> plant

species to elevated atmospheric CO<sub>2</sub> concentrations is not significant under low nitrogen levels, but increases over 10 years with high levels of nitrogen-rich fertilizer application [34]. In fertile grasslands, legumes benefit more from elevated atmospheric CO<sub>2</sub> concentrations when compared to species that do not fix nitrogen [35,36]. Therefore, to capitalize on the benefits of elevated CO<sub>2</sub> levels, declines in the availability of nitrogen may be prevented by biological N<sub>2</sub>-fixation. However, other nutrients, such as phosphorus, an important nutrient for biological N-fixation, may act as a limiting factor and restrict legume growth response to higher atmospheric CO<sub>2</sub> concentrations [37].

- ***Increased frequency of extreme events***

The impacts of increased climate variability on plant production are likely to increase production losses beyond those estimated from changes in mean variables alone [38]. Yield damaging climate thresholds spanning just a few days in the case of certain cereals and fruit trees include absolute temperature levels linked to particular developmental stages that condition the formation of reproductive organs, such as seeds and fruits [39]. This means that models of yield damage need to include detailed phenology as well as above-optimal temperature effects on crops [38]. Short-term natural extremes such as storms and floods, interannual and decadal climate variations, as well as large-scale circulation changes such as the El Niño Southern Oscillation (ENSO) all have important effects on crop, pasture, and forest production. For example, El Niño-like conditions can increase the probability of farm incomes falling below their long-term median by 75 percent across most of Australia's cropping regions, with estimated impacts on GDP ranging from 0.75 to 1.6 percent [40]. Europe experienced a particularly extreme climate event during the summer of 2003, with temperatures up to 6°C above long-term means, and precipitation deficits of up to 300 millimeters. During this period, a record crop yield reduction of 36 percent occurred in Italy, in the case of corn crops in the Po valley, where extremely high temperatures prevailed [41]. The uninsured economic losses for the agriculture sector in the European Union were estimated at 13 billion Euros [42]. Likewise, in dry regions, severe soil and vegetation degradation may lead to significant reductions in the productivity of pastoral areas and farmlands.

Understanding links between increased frequency of extreme climate events and ecosystem disturbances—fires, pest outbreaks, and so on—is particularly important to better quantify impacts [43,44]. Only a few analyses have started to incorporate effects of increased climate variability on plant production.

- ***Impacts on weed and insect pests, diseases and animal production and health***

The impacts of climate change and increases in CO<sub>2</sub> concentrations on weeds, insects and diseases is understood qualitatively, but quantitative knowledge is lacking, despite data from experiments that can be relatively easily manipulated and controllable climate and management variables. However, recent research has attempted to highlight the competition between C<sub>3</sub> crop and C<sub>4</sub> weed species under different climate and CO<sub>2</sub> concentrations.

CO<sub>2</sub> and temperature interactions are recognized as a key factor determining plant damage from pests in future decades; CO<sub>2</sub> and precipitation interactions will be likewise important [45,46]. But most studies continue to investigate pest damage as a separate function of either CO<sub>2</sub> [47–49] or of higher temperatures [50,51]. For instance, some have discovered that the recent warming trends in the United States and Canada have led to earlier insect activity in spring and proliferation of some species, such as the mountain pine beetle, with major damages to forest resources.

Importantly, increased climate extremes may promote plant disease and pest outbreaks [52,53]. Studies focusing on the spread of animal diseases and pests from low to mid-latitudes as a result of warming have shown that significant changes are already under way. For instance, models have projected that bluetongue, a disease affecting mostly sheep, and occasionally goat and deer, will spread from the tropics to mid-latitudes [3]. This may already be happening, with the first ever incidence of bluetongue detected in Northern Europe in 2006, followed by major outbreaks in the subsequent years and a sustained presence in the region. Likewise, simulated climate change has increased the vulnerability of the Australian beef industry to the cattle tick (*Boophilus microplus*). Most assessment studies do not explicitly consider either pest-plant dynamics or impacts on livestock health as a function of CO<sub>2</sub> and climate combined.

The lack of prior conditioning to extreme weather events can result in catastrophic losses in confined cattle feedlots [54]. For example, in Africa, droughts (1981–1999) have been shown to induce mortality rates of 20 to 60 percent in national herds [3]. Moreover, new models of animal nutrition [55] have shown that high temperatures can put a ceiling to dairy milk yield from feed intake. In the tropics, this ceiling occurs at one third to one half of the potential of the modern Friesians cow breeds. The energy deficit of this genotype will exceed that normally associated with the start of lactation, and decrease cow fertility, fitness, and longevity [56]. Likewise, increases in air temperature and/or humidity have the potential to affect conception rates of domestic animals not adapted to those conditions. This is particularly the case for cattle, in which the primary breeding season occurs in the spring and summer months [3].

- *Interactions with air pollutants*

Tropospheric ozone has significant adverse effects on crop yields, pasture and forest growth, and species composition [3]. Although emissions of ozone precursors, chiefly mono-nitrogen oxides (NO<sub>x</sub>) compounds, may be decreasing in North America and Europe due to pollution control measures, they are increasing in other regions of the world—especially Asia. Additionally, as global ozone exposures increase over this century, direct and indirect interactions with climate change and elevated CO<sub>2</sub> levels will further modify plant dynamics [57,58]. Although several studies confirm previous findings that elevated CO<sub>2</sub> concentrations may ameliorate otherwise negative impacts from ozone, it is important to note that increasing ozone concentrations in the future, with or without climate change, will negatively

impact plant production and possibly increase exposure to pest damage [21]. Current risk assessment tools do not sufficiently consider these key interactions. Improved modeling approaches linking the effects of ozone, climate change, nutrient and water availability on individual plants, species interactions, and ecosystem functions are needed, and some efforts are under way [59,60]. Although Ultra Violet (UV)-B exposure is in general harmful to plant growth, knowledge on the interactions between UV-B exposure and elevated CO<sub>2</sub> is still incomplete, with some experimental findings suggesting that elevated CO<sub>2</sub> levels ameliorate the negative effects of UV-B on plant growth, while others show no effect [61].

- ***Vulnerability of carbon pools***

Impacts of climate change on the land that is under human management for food and livestock, have the potential to significantly affect the global terrestrial carbon sink and to further perturb atmospheric CO<sub>2</sub> concentrations [41]. Furthermore, the vulnerability of organic carbon pools to climate change has important repercussions for land sustainability and climate mitigation actions. Future changes in carbon stocks and net fluxes would critically depend on land use planning—policies, afforestation/reforestation, and so on—and management practices such as nitrogen fertilization, irrigation, and tillage, in addition to plant response to elevated CO<sub>2</sub> [8]. Recent experimental research confirms that carbon storage in soil organic matter pools is often increased under elevated CO<sub>2</sub>, at least in the short term [62]; yet the total soil carbon sink may become saturated at elevated CO<sub>2</sub> concentrations, especially when nutrient inputs are low [63].

Uncertainty remains with respect to several key issues, such as the impacts of increased frequency of extremes on the stability of carbon and soil organic matter pools; for instance, the recent European heat wave of 2003 led to significant ecosystem carbon losses [41]. In addition, the effects of air pollution on plant function may indirectly affect carbon storage; recent research showed that tropospheric ozone resulted in significantly less carbon sequestration rates under elevated CO<sub>2</sub> [64], as a result of the negative effects of ozone on biomass productivity and changes to litter chemistry [58]. Although increases were projected in carbon storage on croplands globally under climate change up to 2100, ozone damage to crops could significantly offset these gains [59].

Finally, recent studies show the importance of identifying potential synergies between land-based adaptation and mitigation strategies, linking issues of carbon sequestration, emissions of greenhouse gases, land use change, and long-term sustainability of production systems within coherent climate policy frameworks [65].

## **2.2. Impact Assessments**

The simulation results of crop models and integrated assessments performed over the last 15–20 years indicate rather consistently that the impacts of climate change on food systems at the global scale may overall be small in the first half of the 21st century, but turn progressively more negative after that, as mean temperatures increase regionally and globally above 2.5–3°C.

**Table 2** The projected impacts of climate change on crop yields in 2080 in select countries. Crop yield changes are expressed as percentages of 2000 baseline values, and are computed from aggregated crop model results for what, maize, rice, and soybean

Country	% Yield Change
Argentina	2
Brazil	-4
USA	8
Southwest	-25
India	-29
China	7
South Central	-2
Mexico	-26
Nigeria	-6
South Africa	-23
Ethiopia	-21
Canada	12
Spain	5
Germany	12
Russia	6
<i>Source:</i> [9].	

In addition, the predicted small global effects mask the fact that climate change is expected to disproportionately impact agricultural production in low-latitude, tropical developing countries, while some high-latitude, developed countries may benefit (Table 2). Such asymmetry is expected to be even larger if the differences in adaptation capacity between developed and developing nations are considered [3].

Uncertainties capable of significantly altering the above crop yield impacts were identified in several areas, and included:

- detection of the strength and saturation point of elevated CO<sub>2</sub> response of crops;
- water quality, availability, and irrigation;
- crop interactions with air pollutants, weeds, pathogens and disease;
- changes in the frequency of climate extremes versus changes in mean climate;
- implementation of the CO<sub>2</sub> effects in models and the related scale/validation issues;
- interactions of socioeconomic and climate scenarios within integrated assessments, and their validation; and
- timing and implementation of adaptation strategies.

In addition, new studies are starting to consider impacts of climate change under various mitigation scenarios, as well as to analyze the interactions between adaptation and mitigation strategies.

### *Areas of new knowledge*

Although globally aggregated climate change impacts on world food production are projected to be small by current models, especially in developed regions, large negative impacts are expected in developing regions [66–68], and there is a significant possibility of a number of unexpected negative implications, as discussed below:

1. *Increases in the frequency of climate extremes may lower crop yields beyond the impacts of mean climate change.* More frequent extreme events may lower long-term yields by directly damaging crops at specific developmental stages, such as by surpassing temperature thresholds during flowering, or by making the timing of field applications more difficult, thereby reducing the efficiency of farm inputs [38,65]. A number of simulation studies have investigated specific aspects of increased climate variability within climate change scenarios. For example, it has been assessed that, under scenarios of increased heavy precipitation, production losses as a result of excessive soil moisture—already significant today—would double in the United States to \$3 billion per year in 2030 (84). Other scenarios have focused on the consequences of higher temperatures on the frequency of heat stress during growing seasons, as well on the frequency of frost occurrence during critical growth stages [3].
2. *The impacts of climate change on irrigation water requirement may be large.* A few new studies have further quantified the impacts of climate change on regional and global irrigation requirements, irrespective of the positive effects of elevated CO<sub>2</sub> on crop water use efficiency. Considering the direct impacts of climate change on crop evaporative demand, in the absence of any CO<sub>2</sub> effects, an increase of *net* crop irrigation requirements is estimated, that is, net of transpiration losses, of 5 to 8 percent globally by 2070, and larger regional signals, for example, 15 percent in southeast Asia [69]. In another study, that included the positive CO<sub>2</sub> effects on crop water use efficiency, increases in global net irrigation requirements of 20 percent by 2080 were projected, with larger impacts in developed regions, due to increased evaporative demands and longer growing seasons under climate change [70]. New studies [70,71] have also projected increases in water stress—the ratio of irrigation withdrawals to renewable water resources—in the Middle East and southeast Asia. Furthermore, recent regional studies [3] have likewise underlined critical climate change and water dynamics in key irrigated areas, such as increased irrigation requirements in North Africa and decreased requirements in China.
3. *The stabilization of CO<sub>2</sub> concentrations reduces damage to crop production in the long term.* Recent work has further investigated the effects of mitigation on regional and global crop production, specifically, in the case of stabilized atmospheric CO<sub>2</sub>. Compared to business as usual scenarios—under which

the overall impacts were already small—by 2100, the impacts of climate change on global crop production are predicted to be only slightly under 750 ppm CO<sub>2</sub> stabilization. This is significantly reduced (–70 to –100 percent), if lower risks of hunger are considered (–60 to –85 percent), under 550 ppm CO<sub>2</sub> stabilization [71,72]. These same studies suggest that climate mitigation might alter the regional and temporal mix of winners and losers with respect to business as usual scenarios, but that specific projections are highly uncertain. In particular, in the first decades of this century and possibly up to 2050, some regions may be worse off with mitigation efforts than without, as a result of lower CO<sub>2</sub> levels—and therefore reduced stimulation of crop yields—but the same magnitude of climate change, compared to unmitigated scenarios [72]. Finally, a growing body of work has started to analyze the potential synergies as well as the incompatibilities between mitigation and adaptation strategies [3].



### 3. Socioeconomic Interactions and Impacts on Food Security

The Food and Agriculture Organization (FAO) [73] defines food security as a “situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life” [74].

#### 3.1. Food Security, Scope, and Dimensions

This definition comprises the four key dimensions of food supplies: availability, stability, access, and utilization. The first dimension relates to the *availability* of sufficient food, that is, to the overall ability of the agricultural system to meet food demands. Its sub-dimensions include the agro-climatic fundamentals of crop and pasture production [75] and the entire range of socioeconomic and cultural factors that determine where and how farmers act in response to markets.

The second dimension, *stability*, relates to individuals who are at high risk of temporarily or permanently losing their access to the resources needed to consume adequate food, either because these individuals cannot ensure *ex ante* against income shocks or they lack enough “reserves” to smooth consumption *ex post* or both. An important cause of unstable access is climate variability, for example, landless agricultural laborers, who almost wholly depend on agricultural wages in a region of erratic rainfall and have few savings, would be at high risk of losing their access to food.

The third dimension, *access*, covers access by individuals to adequate resources (entitlements) to acquire appropriate foods for a nutritious diet. Entitlements are defined as the set of all those commodity bundles over which a person can establish command given the legal, political, economic, and social arrangements of his or her community. A key element in this regard is the purchasing power of consumers and the evolution of real incomes and food prices. However, these resources need not be exclusively monetary but may also include traditional rights, for example, to a share of common resources.

Finally, *utilization* encompasses all the safety and quality aspects of nutrition; its sub-dimensions are therefore related to health, including the sanitary conditions across the entire food chain. Access to or availability of an adequate quantity of food is insignificant if an individual is unable to make use of the nutrients due to illnesses.

Agriculture is not only a source of food but, also a source of income. In a world where trade is possible at reasonably low costs, the crucial issue for food security is not whether food is available, but whether the monetary and

nonmonetary resources at the disposal of the population are sufficient to allow everyone access to adequate quantities of food. An important corollary to this is that national self-sufficiency is neither necessary nor sufficient to guarantee food security at the individual level. Note that Hong Kong and Singapore are not self-sufficient because agriculture in these countries is virtually nonexistent but that their populations are food-secure. By contrast, India is self-sufficient but a large part of its population is not food-secure.

A focus on trade implicitly argues, in the context of this paper, that these countries can limit their losses from global warming by shifting to agricultural imports rather than producing those products at home. However, it is also important to note that several limitations may exist, in particular when analyzing the food security prospects of low-income, food importing countries, the majority of which, at present have high undernourishment rates. These countries may face foreign exchange as well as supply-side constraints to increasing their imports needs. In the broader development context, it must also be noted that local agricultural development is an effective tool for poverty reduction and food security. In many African countries, food is not perfectly tradable due to high transaction costs and the prevalence of staple foods that are not available on the world market, such as roots and tubers and local cereals. Increased productivity of food staples, together with improved access to world markets, remains a key factor for regional food security and improved rural livelihoods.

Numerous measures have been used to quantify the overall status and the regional distribution of global hunger. However, none of these measures cover all the dimensions and facets of food insecurity described above. This also holds true for the FAO indicator of undernourishment [74], the measure that was used in essentially all studies reviewed in this study. The FAO measure, however, has a number of advantages. First, it covers two dimensions of food security, availability and access; second, the underlying methodology is straightforward and transparent; and, third, the parameters and data needed for the FAO indicator are readily available for past estimates and can be derived without major difficulties for the future.

### **3.2. Climate Change and Food Security**

Climate change affects food security in complex ways. It has an effect on food production directly through changes in agro-ecological conditions and indirectly by affecting growth and distribution of incomes, and thus demand for agricultural produce. More important from a long-term perspective, climate change also affects food security by altering the overall economic conditions that determine the purchasing power of consumers and consequently their access to food. How these economic conditions are likely to evolve over time is highly uncertain and subject to factors such as population growth trajectories, development, and availability of new technologies as well as policy measures adopted to adapt to or mitigate climate change.

In general, the key issues with regards to climate change and food security are:

- Climate change affects all four dimensions of food security; availability and production of, access to, stability of, and the utilization of food.
- The global food production potential is likely to increase up to a rise of 2°C; it will decline beyond a 2°C rise.
- The increase in the food production potential reflects the average of very uneven regional developments. In general, the net effect is a result of an increase in the production potential in high latitude areas that exceeds the drop in low latitude regions, that is, the generally less food secure regions.
- Increases in temperatures and precipitation will also change pest and disease pressures, overall increasing both. The exact impacts vary by region and by type of pest and disease but regardless of the magnitude, they will be felt more severely in low-latitude, poorer countries.
- Essentially all GCMs predict more pronounced climate variability and thus lower food production stability.
- Access to food will remain the most important determinant of food security; the impact of socioeconomic developments is expected to be large compared to the magnitude of climate impacts.
- Sub-Saharan Africa will surpass Asia as the most food-insecure region, with or without the impacts of climate change.

Combinations of different trajectories have been organized by the IPCC to form the Special Report on Emissions Scenarios (SRES). As they essentially capture all aspects of various economic growth and equity trajectories and therefore the main variables that determine access to food, a quick rehearsal of their main assumptions is in order before delving deeper into the production, utilization, and stability of food security.

The IPCC considers four families of socioeconomic development and associated emission scenarios, known as SRES A2, B2, A1, and B1, summarized below in Table 3 and Table 4.

The assumptions and outcomes of the various SRES scenarios directly affect future agriculture and food security predictions. Changes in agro-ecological growing conditions affect production and productivity in agriculture and thus the availability of food, while changes in the overall socioeconomic conditions and the contribution of agriculture to income generation affect access to food. As outlined in the previous section, the three factors affecting agriculture are (i) changes in temperatures, (ii) changes in atmospheric CO<sub>2</sub> concentrations, and (iii) changes in the level and distribution of precipitation. Food security will be mainly affected by changes in the levels and distribution of incomes (access) and indirectly through food production (availability) and the levels and efficiency of agriculture production (income effects through agriculture).

Table 3 Overview of the main SRES families		
Scenario	Underlying scenario themes	Scenario trajectory
SRES A1	<p>SRES A1 represents a future world of:</p> <ul style="list-style-type: none"> <li>• rapid economic growth</li> <li>• low population growth</li> <li>• rapid introduction of new and more efficient technology.</li> </ul> <p>The <b>underlying themes</b> are economic and cultural convergence and capacity building in a world in which societies value growth over environmental concerns.</p>	<p>SRES A1 scenarios describe alternative energy directions:</p> <ul style="list-style-type: none"> <li>• A1T is non-fossil fuel intensive</li> <li>• A1B is a balanced energy source scenario</li> <li>• A1FI is fossil fuel-intensive and represents the most carbon-intensive development trajectory with the highest CO<sub>2</sub> emissions and atmospheric concentrations of GHG (over 900 ppm by 2100) [76].</li> </ul>
SRES B1	<p>SRES B1 describes a world of:</p> <ul style="list-style-type: none"> <li>• global population that peaks in mid-century and declines thereafter</li> <li>• rapid changes in economic structures toward a service and information economy</li> <li>• reductions in material intensity</li> <li>• introduction of clean and resource-efficient technologies</li> </ul> <p>The <b>underlying themes</b> are global solutions to economic, social, and environmental sustainability, including improved equity, without additional climate initiatives.</p>	<p>SRES B1 is associated with the lowest emission levels and thus the lowest GHG concentration with a stabilization just over 500 ppm toward the end of the 21st century.</p>
SRES A2	<p>SRES A2 scenario describes a heterogeneous world of:</p> <ul style="list-style-type: none"> <li>• continuously increasing global population due to slowly converging regional fertility patterns</li> <li>• regionally oriented economic development</li> </ul>	<p>This scenario family represents intermediate outcomes between A1 and B1.</p> <p>Importantly for agriculture and world food supply, SRES A2 assumes the highest projected</p>

<b>Table 3</b> (continued)		
	<ul style="list-style-type: none"> <li>fragmented and slow per capita economic growth and technological changes</li> </ul> <p>The <b>underlying theme</b> is self-reliance and preservation of local identities.</p>	<p>population growth of the four (UN high variant with 11 billion in 2050 and 14 billion in 2080) and is thus associated with the highest food demand.</p>
SRES B2	<p>SRES B2 describes a world with:</p> <ul style="list-style-type: none"> <li>continuously increasing global population at a rate lower than A2</li> <li>intermediate levels of economic development</li> <li>less rapid and more diverse technological change than in B1 and A1</li> </ul> <p>The <b>underlying themes</b> are local solutions to economic, social, and environmental sustainability.</p>	<p>This scenario family represents intermediate outcomes between A1 and B1.</p>

<b>Table 4</b> Classification of SRES scenario families		
	<b>Global integration</b>	<b>Regionalism</b>
Economic emphasis	<p>A1B: Balanced energy</p> <p>A1FI: Fossil-fuel Intensive</p> <p>A1T: high-Tech renewables</p>	A2
Environmental emphasis	B1	B2

*The effects of climate change on food availability, agriculture production and productivity*

Depending on the SRES emission scenario and climate models considered, projected increases in global mean surface temperatures range from 1.8°C (spanning 1.1 to 2.9°C for SRES B1) to 4.0°C (spanning 2.4 to 6.4°C for A1) by 2100 [75]. These changes in temperature, atmospheric CO<sub>2</sub> concentration, as well as the levels and the distribution of precipitation will crucially affect future agro-ecological growing conditions and thus the overall level of agricultural output. They will also determine the distribution of output over geographic regions and different latitudes, and the composition and geographical allocation over crops and types of livestock.

Depending on the agricultural activity and the geographical location, the effects of increased temperatures due to climate change can be either positive or negative. In temperate latitudes, for instance, higher temperatures are expected to benefit agriculture by potentially increasing the area suitable for cropping, increasing the length of the growing period, and increasing crop yields. A moderate incremental warming in some humid and temperate grassland may increase pasture productivity and reduce the need for cattle sheds and stall feeding. By contrast, increased frequency of extreme events, such as the heat waves and droughts experienced in the Mediterranean region or increased heavy precipitation and flooding in temperate regions, including the possibility of increased coastal storms [77] could substantially lower production and productivity; likewise, semiarid and arid pastures are expected to experience a decline in productivity which would lead to reduced livestock productivity and increased livestock mortality [3]. In drier areas, climate models predict increased evapo-transpiration and lower soil moisture levels [3]. As a result, some cultivated areas may become unsuitable for cropping and some tropical grassland may become increasingly arid. A rise in temperatures will also expand the range of many agricultural pests and increase the ability of pest populations to survive the winter and attack spring crops.

The projected increase in atmospheric carbon dioxide (CO<sub>2</sub>) concentrations represents another important change for global agro-ecological growing conditions. Depending on the SRES emission scenario, the atmospheric CO<sub>2</sub> concentration is projected to increase from about 385 ppm today to over 500 ppm by 2100 in SRES B1, or to over 900 ppm in SRES A1FI [3]. Higher CO<sub>2</sub> concentrations will have a positive effect on many crops, enhancing biomass accumulation and final yield. However, the magnitude of this effect is less clear, with important differences depending on management (e.g., irrigation and fertilization regimes) and crop type [8]. Experimental yield response to elevated CO<sub>2</sub> (550 ppm) show that under optimal growing conditions, yields increase by 10–20 percent for C<sub>3</sub> crops (such as wheat, rice, and soybean), and only 0–10 percent for C<sub>4</sub> crops such as maize and sorghum [3]. More importantly, the nutritional quality of agricultural produce may not increase in line with higher yields. Some cereal and forage crops, for example, show lower protein concentrations under elevated CO<sub>2</sub> conditions [8].

Finally, a number of recent studies have estimated the likely changes in land suitability, potential yields and agricultural production on the current suite of crops and cultivars available today. These estimates implicitly include adaptation using available management techniques and crops, but exclude new cultivars from improved breeding or biotechnology. These studies are based on the FAO and International Institute for Applied Systems Analysis (IIASA) Agro Ecological Zone (AEZ) methodology [66]. They suggest that total land and total prime land would remain virtually unchanged at the current levels of 2600 and 2000 million hectares, respectively. The same study also shows pronounced regional shifts, with a considerable increase in suitable cropland at higher latitudes, i.e. over 160 million hectares in developed countries. Likewise, there is a corresponding decline of potential cropland of around 110 million hectares at lower latitudes

consisting of developing countries. The net decline of 110 million hectares is the result of a massive predicted decline in agricultural prime land of about 135 million hectares, which is offset by an increase in moderately suitable land of over 20 million hectares. This quality shift is also reflected in the shift in land suitable for multiple cropping. In sub-Saharan Africa alone, land for double cropping would decline by between 10 and 20 million hectares, while land suitable for triple cropping would decline by 5 to 10 million hectares. At a regional level, various studies (e.g., [66]) indicate that under climate change, the biggest losses in suitable cropland are likely to be in Africa, whereas the largest expansion of suitable cropland is in the Russian Federation and in Central Asia.

### *Impacts on the stability of food supplies*

Global and regional weather conditions are also expected to become more variable than at present, with increases in the frequency and severity of extreme events such as cyclones, floods, hailstorms, and droughts [3,8]. By causing greater fluctuations in crop yields and local food supplies and higher risks of landslides and erosion damage, they can adversely affect the stability of food supplies and thus food security.

Neither climate change nor short-term climate variability, and associated adaptation, are new phenomena in agriculture. For instance, some important agricultural areas of the world such as the Midwest of the United States, the northeast of Argentina, southern Africa, or southeast Australia traditionally have experienced higher climate variability than other regions such as central Africa or Europe [66]. They also show that the extent of short-term fluctuations has changed over longer periods of time. In the developed countries, for instance, short-term climate variability increased from 1931 to 1960 as compared to 1901 to 1930, but decreased strongly in the period from 1961 to 1990. What is new, however, is the fact that the areas subject to high climate variability are likely to expand, while the extent of short-term climate variability is likely to increase across all regions and may exceed in some regions, the historical experience [3].

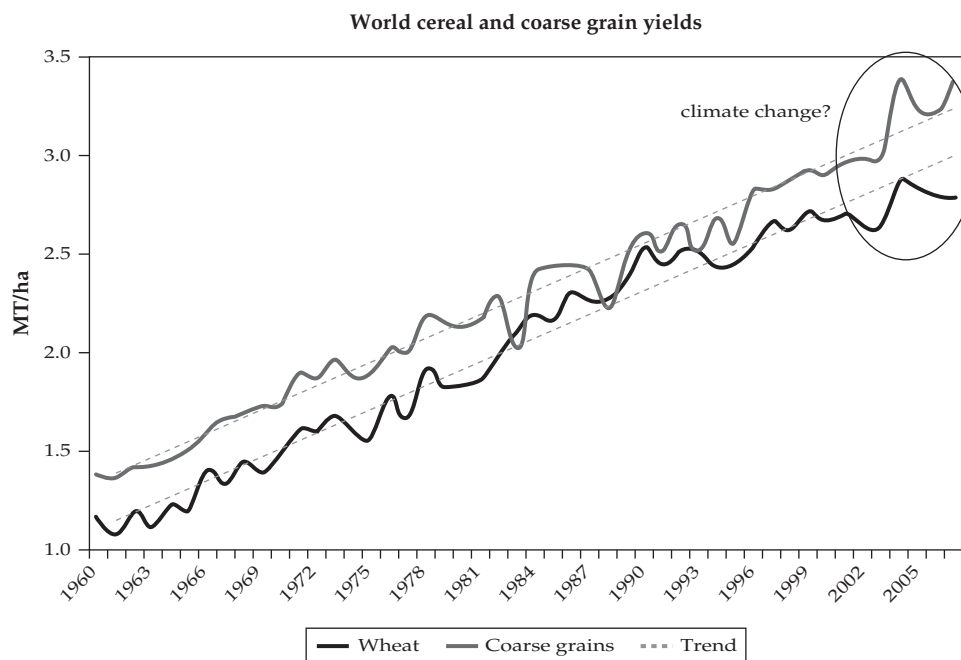
If climate fluctuations become more pronounced and more widespread, droughts and floods, the dominant causes of short-term fluctuations in food production in semiarid and sub-humid areas, will become more severe and more frequent. In semiarid areas, droughts can dramatically reduce crop yields as well as livestock numbers and productivity [8]. Again, most of this land is in sub-Saharan Africa and parts of South Asia, meaning that the poorest regions with the highest levels of chronic undernourishment will also be exposed to the highest degree of instability in food production [78].

How strongly these impacts will be felt will crucially depend on whether such fluctuations can be countered by investments in farm management, irrigation, better storage facilities, improved information provision, alternative employment options, more appropriate policy environments, or by higher food imports. In addition, a policy environment that fosters reduction in barriers to free trade and promotes investments in transportation, and communications, may help address these challenges early on by allowing countries to buffer crop and livestock losses via trade.

**Box 1 Recent changes in the global cereal production system: A harbinger of things to come? [98]**

Recent changes in cereal production could be a harbinger for future developments of yield levels and stability—both on the positive and the negative side. Contrary to common assumptions, the last four crop years have been characterized by relatively high average global yields. Particularly coarse grain yields remained above their long-term trends levels (Figure 2)

When average global cereal yields are further dissected into changes in individual countries and types of cereals, two interesting developments emerge. First, the above-trend growth for cereals as a whole is owed generally to exceptionally high yields for coarse grains and particularly rapid growth in maize yields in production systems of higher latitudes. While it is too early to ascribe these changes to climate change, the observed effect is in line with the predictions under most climate change scenarios which foresee an increase in yields for temperate zone crops (higher latitudes). The expected changes in agro-ecological growing conditions (higher temperatures, increased average precipitation and CO<sub>2</sub> fertilization) would suggest that higher average yields may remain a feature for the first decades on the 21st century. Second, a further differentiation between wheat and coarse grains reveals that wheat yields have become both lower on average and more variable across countries and years. Wheat yields were particularly negatively affected in drought-prone and/or semi-arid areas. Morocco experienced a devastating harvest in 2007 and so did other countries in the drought-prone region of North Africa and the Near-East. The same holds for other semi-arid production regions. Australia was faced with two consecutive droughts and subsequent crop failures for wheat in 2006 and 2007. Australia's wheat exports fell by half to less than 7 million tons, which contributed to a massive run-up in global wheat prices. Again, higher yield variability has been predicted by most climate change impact models and it has also been predicted that greater weather variability will be one of the first signs of changing overall climatic conditions.





### *Impacts of climate change on food utilization*

Climate change will also affect the ability of individuals to utilize food effectively by altering the conditions for food safety and by increasing the disease pressure from vector, water and food-borne diseases. The IPCC Working Group II provides a detailed account of the health impacts of climate change in Chapter 8 of its Fourth Assessment Report [3]. It examines how the various forms of diseases, including vector-borne diseases such as malaria are likely to spread or recede with climate change. This paper focuses on a narrow selection of food- and water-borne diseases that affect food safety directly.

The main concern about climate change and food utilization is that changing climatic conditions can initiate a vicious circle where infectious diseases cause or compound hunger, which in turn makes the affected populations more susceptible to infectious disease. The result can be a substantial decline in labor productivity and increases in poverty and mortality rates. Essentially all manifestations of climate change, be it droughts, higher temperatures, or heavy rainfalls, have an impact on disease pressure and there is growing evidence that these changes affect food safety and food security [3].

The recent IPCC report also emphasizes that increases in daily temperatures will raise the frequency of food poisoning, particularly in temperate regions. Warmer seas may contribute to increased cases of human shellfish and reef-fish poisoning (ciguatera) in tropical regions and a pole-ward expansion of the disease [79,80]. Although there is little evidence that climate change significantly alters the prevalence of these diseases, several studies have confirmed and quantified the effects of temperature on common forms of food poisoning, such as salmonellosis [81–83]. These studies show an approximately linear increase in reported cases for each degree increase in weekly temperatures. Moreover, there is evidence that rising temperatures are strongly associated with the increased episodes of diarrheal disease in adults and children [84–86]. These findings have been corroborated by analyses based on monthly temperature observations and diarrheal episodes on the Pacific Islands, Australia, and Israel [87,88].

Extreme rainfall events can increase the risk of outbreaks of water-borne diseases particularly where traditional water management systems are insufficient to handle the new extremes [3]. Likewise, the impacts of flooding will be felt most strongly in environmentally degraded areas, and where basic public infrastructure, including sanitation and hygiene, is lacking. This will raise the number of people exposed to water-borne diseases (e.g., cholera) and thus lower their capacity to effectively utilize food.

### *Impacts of climate change on access to food*

Over the last 30 years, falling real prices for food and rising real incomes have led to substantial improvements in access to food in many developing countries. Increases in purchasing power has allowed a growing number of people access to not only more food but also more nutritious food, rich in protein, micro-nutrients, and vitamins [89]. East Asia, and to a lesser extent the

Near-East/North African Region, have particularly benefited from a combination of lower real food prices and robust income growth. From 1970 to 2001, the prevalence of hunger in these regions, as measured by FAO indicators of undernourishment, declined from 24 to 10.1 percent and from 44 to 10.2 percent respectively [78]. In East Asia, it was endogenous income growth that provided the basis for the boost in demand for food which was largely produced in the region; in the Near-East/North African region, demand was spurred by exogenous revenues from oil and gas exports, while additional food supplies came largely from imports. Regardless of the cause of increased demand for food, improvements in the access to food have been crucial in reducing hunger and malnutrition in both regions.

The FAO longer-term outlook to 2050 [90] suggests that the importance of improved demand-side conditions will even become more important over the next 50 years. Understandably, the regions that are predicted to experience the strongest reductions in the prevalence of undernourishment are those that are expected to see the highest rates of income growth. South Asia in particular, stands to benefit the most. Spurred by high income growth, the region is expected to reduce the prevalence of undernourishment from more than 22 percent to 12 percent by 2015 and just 4 percent by 2050 [90]. Progress is also expected for sub-Saharan Africa, but improvements will be less pronounced and are expected to set in later in time. For instance, over the next 15 years, the prevalence of undernourishment will decline less than in other regions, from about 33 percent to a still worrisome 21 percent, as significant constraints (such as soil nutrients, water, infrastructure, etc.) limit the ability to further increase food production locally, and continuing low levels of income rule out the option of importing food. In the long run, however, sub-Saharan Africa is expected to see a more substantial decline in hunger; by 2050, less than 6 percent of its total population is expected to suffer from chronic hunger [90]. However, it is important to note that these FAO projections do not take into account the effects of climate change.

However, by coupling agro-ecological and economic models, other studies [66,90] have gauged the impact of climate change on agricultural GDP and prices. At the global level, the impacts of climate change are likely to be very small; under a range of SRES and associated climate change scenarios, the estimates range from a decline of 1.5 percent to an increase of 2.6 percent by 2080. At the regional level, agriculture as a source of income can be much more important, as the economic output from agriculture, over and above subsistence food production, is an important contributor to food security. The strongest impact of climate change on the economic output of agriculture is expected in sub-Saharan Africa which means that the poorest and most food insecure region is also expected to suffer the largest contraction of agricultural incomes. For the region, the losses in agricultural GDP—compared to estimates that do not take climate change into consideration—range from 2 to 8 percent for coupled atmospheric models such as HadCM3 and CGCM2 to 7 to 9 percent for the Commonwealth Scientific and Industrial Research Organization (CSIRO) projections.

### **3.3. Impacts on Food Prices**

Although the various SRES scenarios differ with regard to population and policy assumptions, essentially all SRES development paths describe a world of robust economic growth and foresee rapidly shrinking importance of agriculture in the long run, essentially the continuation of a trend that has been underway for decades in many developing regions (Fig. 1). It is a world where income growth will allow the largest part of the world's population to address possible local food production shortfalls through imports and, at the same time, find ways to cope with the safety and stability issues of food supplies [66]. It is also a world where real incomes rise more rapidly than real food prices which suggests that the share of income spent on food should decline and that higher food prices are unlikely to create a major dent in the food expenditures of the poor. However, not all parts of the world perform equally well in the various development paths and not all development paths are equally benign for growth. Where income levels are low and shares of food expenditures are high, higher prices for food may still create or exacerbate a possible food security problem.

There are a number of studies that have measured the likely impacts of climate change on food prices [66,91]. The basic messages that emerge from these studies are:

1. On average, food prices are expected to rise moderately in line with moderate increases of temperature until 2050; some studies even foresee a mild decline in real prices until 2050. Second, after 2050 and with further increases in temperatures, prices are expected to increase more substantially.
2. In some studies (32) and for some commodities such as rice and sugar, prices are forecast to increase by as much as 80 percent above their reference levels without climate change.
3. Expected price changes from the effects of global warming are, on average, much smaller than the expected price changes from socioeconomic development paths. For instance, the SRES A2 scenario would imply a price increase in real cereal prices by about 170 percent.

The additional price increase as a result of climate change in the HadCM3 climate change case would only be 14.4 percent. Overall, this appears to be the sharpest price increase reported and it is not surprising that this scenario would imply a persistently high number of undernourished people until 2080. However, it is also needless to say that a constant absolute number of undernourished people would still imply a sharp decline in the prevalence of hunger; and, given the high population assumptions in the SRES A2 world (13.6 billion people globally and more than 11.6 billion in the developing world) this would imply a particularly sharp drop in hunger prevalence from 17 percent to about 7 percent by 2080.

### **3.4. Quantifying the Impacts on Food Security**

A number of studies have recently quantified the impacts of climate change on food security [17,66,92]. In terms of quantifying agronomic yield change projections, these studies are either based on the AEZ tools developed by the

IIASA, or the Decision Support System for Agro technology Transfer (DSSAT) suite of crop models; all use the IIASA-BLS economic model for assessing economic impacts [91]. These tools, with some modifications relating to how crop yield changes are simulated, have also been employed by others to undertake similar assessments and provide sensitivity analyses across a range of SRES and GCM projections. Many other simulations have also examined the effects of climate change with and without adaptation measures (such as induced technological progress, domestic policy change, international trade liberalization, etc.), and with and without mitigation efforts (e.g., such as those aimed to stabilize CO<sub>2</sub>, temperature, rainfall change and distribution). Many provide impact assessments for different magnitudes of climate change [93]. This section focuses on the quantitative results for food security, trying to illuminate some of the differences and to extract the main messages that emerge from the various studies. Unless indicated, all simulation results discussed below include the combined effects of climate change and elevated CO<sub>2</sub> on crops. The key messages can be summarized as follows:

1. It is very likely that climate change will increase the number of people at risk of hunger compared with reference scenarios that don't take climate change into consideration; the exact impacts, however, will strongly depend on the projected socioeconomic developments (Table 5). For instance, it is estimated [67] that climate change will increase the number of undernourished people in 2080 by 5 to 26 percent, compared with no climate change, or by between 5 and 10 million (B1 SRES) and 120–170 million people (A2 SRES), with the various SRES ranges depending on GCM climate projections. Using a particular GCM scenario, others [68,92] have projected small reductions by 2080, depending on the scenario. Expected reductions range from 5 percent or by 10 (B1) to 30 (A2) million people, while slight increases of 13 to 26 percent, or 10 (B2) to 30 (A1) million people are predicted.
2. Second, it is likely that the magnitude of these climate impacts will be small compared with the impacts of socioeconomic development [12]. As evident from Table 5, and within the limitations of socioeconomic forecasts, these studies suggest that high economic growth and declines in population growth projected for the 21st century will, in all but one scenario (SRES A2), significantly reduce the number of people at risk of hunger in 2080. At any rate, the prevalence of undernourishment is expected to decline since all scenarios make the assumption that the world population will continue to grow up to 2080, albeit at lower rates. While the FAO estimates the existence of 820 million undernourished in developing countries at present, several other studies [66,68,91,92] have estimated reductions of over 75 percent by 2080, that is, by about 560 to 700 million people, projecting 100 to 240 million undernourished by 2080 (A1, B1 and B2). As mentioned earlier, the only exception is scenario A2, where the number of the hungry is forecast to decrease only slightly to 2080; but the higher population growth rates in A2 compared to other scenarios mean that also here the *prevalence* of undernourishment will decline drastically. Regardless of the rate of reduction in food insecurity, essentially all quantitative analyses confirm that

Scenario	Year 2020		Year 2050		Year 2080	
	AEZ- BLS	DSSAT- BLS	AEZ- BLS	DSSAT- BLS	AEZ- BLS	DSSAT- BLS
Reference						
A1	663	663	208	208	108	108
A2	782	782	721	721	768	769
B1	749	749	239	240	91	90
B2	630	630	348	348	233	233
CC						
A1	666	687	219	210	136	136
A2	777	805	730	722	885	742
B1	739	771	242	242	99	102
B2	640	660	336	358	244	221
CC, no CO <sub>2</sub>						
A1	NA	726	NA	308	NA	370
A2	794	845	788	933	950	1,320
B1	NA	792	NA	275	NA	125
B2	652	685	356	415	257	384

*Source:* [4].

The first set of rows in the table depicts reference projections, under SRES scenario and no climate change. The second set (CC) includes climate change impacts, based on Hadley HadM3 model output, including positive effect of elevated CO<sub>2</sub> on crops. The third (CC, no CO<sub>2</sub>) includes climate change, but assumes no effects of elevated CO<sub>2</sub>. Projections from 2020 to 2080 are given for two crop modeling systems: on the left, AEZ; on the right, DSSAT, each coupled to the same economic and food trade model, BLS (3). The models are calibrated to give 824 million undernourished in 2000, according to FAO data.

progress in reducing the number of hungry will be unevenly distributed over the developing world and that progress will be slow during the first decades of the outlook. Inevitably, with or without climate change, the Millennium Development Goal (MDG) of halving the prevalence of hunger by 2015 is unlikely to be realized before 2020–2030 [67].

- In addition to the socioeconomic pressures considered by the IPCC SRES scenarios, food production may increasingly compete with bioenergy in coming decades. Studies addressing possible consequences for world food supply have only started to surface, providing both positive [94] and negative views [95]. Importantly, none of the major world food models discussed herein have yet considered such competition.
- Fourth, sub-Saharan Africa is likely to surpass Asia as the most food insecure region. However, this is largely independent of climate change and is mostly the result of the socioeconomic development paths assumed for the different developing regions in the SRES scenarios. Throughout

most SRES and climate change scenarios, sub-Saharan Africa accounts for 40 to 50 percent of the global undernourished by 2080, compared with about 24 percent today [67]; in some simulations sub-Saharan Africa accounts for 70 to 75 percent of the global undernourishment by 2080. Such high estimates have emerged from the slower growth variants of the A2 and B2 scenarios [92]; Another A2 variant with slower population growth yields a sharper concentration of hunger in sub-Saharan Africa [91]. For regions other than sub-Saharan Africa, results are largely dependent on GCM scenarios and consequently are highly uncertain.

5. Fifth, although a significant amount of uncertainty is expected regarding the effects of elevated CO<sub>2</sub> on crop yields, this uncertainty is much less when it concerns the expected effects on food security. This is evident from a comparison of climate change simulations with and without CO<sub>2</sub> fertilization effects on crop yields. As can be seen from Table 2, higher CO<sub>2</sub> fertilization does not greatly affect global projections of hunger. In view of the fact that essentially all scenarios are characterized by much higher real incomes, improved transportation and communication options as well as sufficient global food production, the somewhat smaller estimates will not be able to make a dent in global food security outcomes [91]. Many studies [67,68,92] find that climate change without CO<sub>2</sub> fertilization would reduce the number of undernourished by 2080 only by some 20 to 140 million (i.e., by 120 to 380 million for SRES A1, B1 and B2 scenarios without the CO<sub>2</sub> fertilization effect and by 100 to 240 million with the effect). The exception in these studies is SRES A2, which estimates 950 to 1300 million undernourished people in 2080 under the assumption of no CO<sub>2</sub> fertilization, compared with 740 to 850 million projected with CO<sub>2</sub> effects on crops.
6. Finally, recent research suggests large positive effects of climate stabilization for the agricultural sector. However, as the stabilizing effects of mitigation measures can take several decades to be realized from the moment of implementation, the benefits for crop production may be realized only in the second half of this century [91,97]. Importantly, even in the presence of robust global long-term benefits, the regional and temporal patterns of winners and losers that can be projected with current tools are highly uncertain and they depend critically on the underlying GCM projections [91].

### **3.5. Uncertainties and Limitations**

The fact that socioeconomic development paths have an important bearing on future food security and that they are likely to dominate the effects of climate change should not be interpreted as a probability-based forecast. This is because SRES scenarios are not able to accurately project future changes in economic activity, emissions, and climate. They merely offer a range of possible outcomes without projecting “any sense of likelihood” [99].

Second, the existing global assessments of climate change and food security have only been able to focus on the impacts on food availability and access to

**Box 2 The Impacts of climate change on smallholder and subsistence agriculture [96]**

Although there has been much recent public discussion of the effects of climate change on rural areas of developing countries, there has been little discussion that both engages with the science of climate change impact on agriculture, and with the specificities of smallholder and subsistence systems.

Impacts on these systems should be considered in terms of hard to predict compound impacts highly specific to location and livelihood systems in different ecosystems and regions of the world. These livelihood systems are typically complex; they involve a number of crop and livestock species, between which there are interactions—for example, intercropping practices or the use of draught animal power for cultivation, and potential substitutions such as alternative crops. Many smallholder livelihoods will also include use of wild resources, and nonagricultural strategies, such as use of remittances. Coping strategies for extreme climatic events such as drought typically involve changes in the relative importance of crops, livestock species and nonagricultural activities, and in interactions between them. Positive and negative impacts on different crops may occur in the same farming system. Impacts on maize, the main food crop, will be strongly negative for the Tanzanian smallholder, whereas impacts on coffee and cotton, significant cash crops, may be positive.

There is evidence of increased risk of crop pests and diseases of crops under climate change, although knowledge of likely impacts in the tropics and on smallholder systems is much less developed. Modeling responses of both pathogens and (where relevant) insect vectors to rising temperatures and changing precipitation is complex, but there is cause for concern over possible spread of major diseases that attack smallholder crops in Africa: for example, Maize Streak Virus and Cassava Mosaic Virus in areas where rainfall increases, and sorghum head smut (a fungal disease) in areas where rainfall decreases (which would be compounded by farmers switching adaptively to sorghum in areas where maize becomes marginal). For diseases of livestock, modeling studies suggest overall slight declines in habitat suitable for tsetse-transmitted trypanosomiasis and East Coast Fever, although effects will be localized. Increased frequency of floods may increase outbreaks of epizootic diseases such as Rift Valley Fever and African Horse Sickness.

Another class of impacts is felt at the level of communities, landscapes, and watersheds, and has been less considered in literature on climate change and agriculture, although there is some overlap with consideration given to extreme events. One such impact is the effects of decreasing snowcap on major irrigation systems involving hundreds of millions of smallholders, particularly in the Indo-Gangetic plain. As a result of warming, less precipitation falling as snow, and earlier spring melting, there will be a shift in peak water supply to winter and early spring and away from the summer months when irrigation is most needed, with likely severe effects in areas where storage capacity cannot be expanded. Combined with increased water demand, and preexisting vulnerability of many poorer irrigated farmers, such an impact could be catastrophic.

Climate change effects on soil fertility and water-holding properties will also be important. Global warming and accompanying hydrological changes are likely to affect all soil processes in complex ways, including accelerated decomposition of organic matter and depression of nitrogen-fixing activity, resulting in increased soil erosion worldwide.

food, without quantifying the likely climate change effects on food safety and vulnerability (stability). This means that such assessments neither account for the potential problems arising from the additional impacts of extreme events such as drought and floods [90] nor do they quantify the potential impacts of changes in the prevalence of food-borne diseases or the interaction of nutrition and health effects due to changes in the proliferation of vector-borne diseases such as malaria. With respect to food availability, they exclude the impacts of a possible rise in sea levels for agricultural production or those that are associated with possible reductions of marine or fresh water fish production.

Third, it is important to note that in terms of food availability, the current assessments of world food supply have only focused on the impacts of mean climate change, that is, they have not considered the possibility of significant shifts in the frequency of extreme events on regional production potential, nor have they considered scenarios of abrupt climate or socioeconomic change; such scenario variants are likely to significantly increase the already negative projected impacts of climate change on world food supplies. Models that take into account the specific biophysical, technological, and market responses necessary to simulate realistic adaptation measures in the face of such events are not yet available.

Fourth, we stress that recent global assessments of climate change and food security rely on a single modeling framework, the IIASA system, which combines the FAO/IIASA AEZ model with various GCM models and the IIASA BLS system, or on close variants of the IIASA system [100]. This has important implications for uncertainty, given that the robustness of all these assessments strongly depends on the performance of the underlying models. There is therefore a need for continued and enhanced validation efforts of both the agro-climatology and food trade tools developed at IIASA and widely employed in the literature.

Fifth, the recent surge in energy prices could have a more substantial and more immediate impact on economic development and food security than captured by any of the SRES scenarios.

Finally, we note that the assessments that not only provide scenarios but also attach probabilities for particular outcomes could provide an important element for better-informed policy decisions. A number of possibilities to address the related modeling challenges have been suggested [101]. One option would be to produce probability-based estimates of the key model parameters. Alternatively, the various scenarios could be constructed so that they reflect expert judgment on a particular issue. It would be desirable to attach probabilities to existing scenarios because such information on the likelihood of the suggested outcomes would contribute greatly to their usefulness for policy makers and help justify policy measures to adapt to or mitigate the impacts of climate change on food security.



## **4. Adaptation**

Agriculture is practiced across a broad range of climates, environmental conditions, and within countless cultural, institutional, and economic structures that, define the management practices used. A correspondingly large array of adaptation options is therefore available to improve the resilience of the agricultural system to the uncertain future impacts of climate change. The argument for an increased focus on adaptation of agriculture to climate change is based on several considerations:

- Past emissions of greenhouse gases have already committed the globe to further warming of around 0.1°C per decade for several decades [76], making a certain level of impacts and the necessary adaptation or coping responses, unavoidable;
- Emissions of major greenhouse gases are continuing to increase rapidly [102]. The current lack of progress in developing global emission-reduction agreements beyond the Kyoto Protocol [103] is leading to concerns about the future level of emissions;
- The high end of the IPCC scenario range for climate change has increased over time and potentially higher global temperatures implies the increased likelihood of non-linear and increasingly negative impacts on existing agricultural activities [1];
- Observed changes in atmospheric CO<sub>2</sub> concentrations, global temperatures and sea levels that are already at the high end of those implied by IPCC scenarios [104] and certain other climate change impacts are happening faster than previously considered likely (such as the breakdown of the Greenland Ice Sheet [105]);
- Potential impacts of climate change on agriculture, especially in tropical regions, are proving to be more substantial than previously assessed [1];
- Climate changes may provide opportunities for agricultural investment that reward early action-takers [103].

Importantly, the collective set of adaptation responses that will be needed to limit risks and maximize opportunities from climate change in coming decades, will entail an additional cost to society over and above the investments planned for ongoing development in the relevant agricultural sectors. Much of this additional investment will need to be in developing countries. Recent estimates by UNFCCC put those extra costs conservatively at about US \$100 billion per year globally in 2030, expressed as the additional investment and financial flows needed to minimize damage risks in the sectors relevant to rural development in developing countries. Although these projected adaptation costs are small compared to current and projected world agricultural GDP, it must be noted that they represent sizeable increases (of 10 to 20 percent) over projected domestic investments in these sectors.

Furthermore, they are much larger (as much as 5 to 10 times depending on the region) than the combined volume of projected foreign direct investments, development assistant funds, and debt financing for agriculture and rural development in developing countries [118].

## **Options for implementation**

It must also be recognized that several barriers exist to the implementation of successful response options by farmers, especially in developing countries, where the existing human, technical, and economic capacity is low even when assessed against current production needs. Such barriers include lack of access to credit for investment; lack of access to knowledge, advice and inputs; existing social and cultural institutions; land tenure insecurity; inherent climate variability; limiting natural resources, including the quality of available land and water resources, especially in arid and semiarid tropical regions. In the next sections, we indicate in broad terms, the supportive actions and complementary investments that are necessary to overcome these barriers and to increase the adaptive capacity of farmers, focusing in particular on research and advisory services.

To this end, anticipatory and planned adaptation measures that incorporate a comprehensive and strategic assessment of adaptive capacity is required in order to inform an evidence-based decision-making process. To support this, future efforts should be focused on analyzing in more regional detail, the basic design features of various research and advisory services, including national agricultural research systems and existing regional programs, such as the Consultative Group on International Agricultural Research (CGIAR) system. The following analysis provides (a) state-of-the-art knowledge on the critical components to be included in a strategic assessment of adaptation capacity and anticipatory adaptive planning, and (b) examples of key adaptation strategies for a selection of agricultural sectors: cropping, livestock, forestry, as well as fisheries and aquaculture.

### **4.1. State-of-the-art Knowledge on the Strategic Assessment of Adaptation Capacity**

Adaptation research aimed at moving from the technical assessment of climate change impacts to practical adaptation actions can be enhanced through a strategic assessment approach that adopts a systems perspective to defining the specific research needs. The necessary components of such an assessment include:

- Recognition of the scale and nature of decision-making;
- Mainstreaming of adaptation into broader policies to promote resilience and sustainable development;
- Developing a mix of complementary mitigation and adaptation actions;
- Informing investment and disinvestment decision-making at all levels;

- Enhancing adaptation capacity through collaboration with decision makers; and
- Integration of climate change risk with other key sources of risk within a comprehensive risk management framework.

### *Recognition of the scale and nature of decision-making*

The aim of adaptation research is to help inform decision makers at the farm, business investment and policy level, of the implications of actions taken across a range of spatial scales, timeframes and at various institutional and administrative levels. These actions range from short-term tactical decisions taken at the management unit level to longer-term strategic planning and policy making undertaken at local, regional, national, and international scales. It is, therefore, important to align adaptation assessments and strategies to the scale and nature of the decisions being taken, bearing in mind the reliability of the information and knowledge being used. This should facilitate the development of products, technologies, and policies that are closely aligned to the specific needs of agricultural decision makers at various levels of engagement.

### *Mainstreaming of adaptation into broader policies to promote resilience and sustainable development*

With a few notable exceptions [5], adaptation to climate change is presently dealt with largely in isolation from other issues, focusing on the quantitative impacts of a single harvestable component. This is so despite the fact that agricultural systems provide an array of the essential commodity and non-commodity outputs and functions required for a sustainable livelihood, such as environmental services, landscape amenities, and cultural heritages. Therefore, progress is required to integrate climate change impacts and the required adaptation capacity into a much broader set of policies that recognize the multi-functionality of agriculture and the complex socioeconomic environment in which it operates. Ensuring that policies and programs are integrated across the value chain will help avoid poorly targeted and maladaptive strategies and foster support for effective adaptation. To ensure global food security, it is important that such policies do not increase competition for resources, for example, agriculture for food versus bioenergy and forestry for emission reduction. By mainstreaming climate change adaptation into broader policies on sustainable development and natural resource management, it is anticipated that enhanced environmental, economic, and social resilience to uncertain future impacts will contribute to improvements in sustainable development [106].

As policies can modify the decision-making environment within which management-level adaptation activities typically occur, they are an important tool in adaptive planning. Importantly, policy must be dynamic, enabling iterative management to cope with the high level of uncertainty in the timing and magnitude of potential changes as well as a rapidly evolving knowledge base. However, there are often environmental, economic, informational, social, attitudinal, and behavioral barriers to the implementation of adaptation

measures (4). Identifying where these barriers occur may be facilitated by an adaptation metrics framework, for example, a livelihoods analysis can be applied to the assessment of resource availability and interpreted in terms of adaptive capacity. Table 6 suggests a range of policy approaches aimed at dealing with barriers, building adaptive capacity and changing the decision-making environment to promote appropriate adaptation actions [107].

<b>Table 6 Barriers to adoption and remedial policy approaches</b>	
<b>Barrier</b>	<b>Policy focus</b>
Enterprise managers need to be convinced that projected climate changes are real in order to effect a change in management. Enterprise managers need to be confident that projected changes will significantly impact their enterprise.	Maintenance of climate monitoring and effective communication of information.  Support for research, systems analysis, extension capacity, industry and the regional networks that provide this information.
Technical and other resource options necessary to respond to projected changes need to be available and accessible to all stakeholders.	Promotion of an enabling environment with support for research, development and extension of appropriate technologies, such as improved germplasm.
Climate impacts may lead to the need for major land use change.	Support for transitions such as industry relocation and people migrations. This may be facilitated by direct financial and material support, creating alternative livelihood options, providing food aid and employment to the more vulnerable, and developing contingency plans.
Lack of knowledge regarding new management and land use arrangements or adoption pathways.	Infrastructure, policies, and institutions developed to support new management and land use arrangements may include addressing climate change in development programs, ensuring appropriate transport and storage infrastructure, revising land tenure arrangements including attention to property rights, and occupational education and extension services.
Gender inequity and the persistent biases in the access of women and other marginalized stakeholders to production resources, occupational education and training, information, and extension services.	Targeted support for participation in activities relating to livelihood decision making processes and enterprise management, and the development of innovative institutional arrangements and support organizations and networks.

*Developing a mix of complementary mitigation and adaptation actions*

Identifying and evaluating various adaptation strategies as well as mitigation options is of fundamental value to determining a set of dynamic climate policy options aimed at the “avoidance of dangerous anthropogenic interference” as stated in Article 2 of the UNFCCC. This is because maximizing societal welfare under future climate risk will likely involve a mix of both mitigation and adaptation; the percentage contribution of each being dependent on monetary and nonmonetary cost/benefit analyses.

Adaptation and mitigation are inextricably linked; mitigation policies can affect the range of adaptation options available to practitioners, whilst adaptation has the potential to “buy time” until effective mitigation responses can be implemented. The linkages are particularly important in avoiding maladaptation and ensuring that adaptive actions do not increase the environmental footprint of agricultural production, as would be in the case of increased use of fossil fuel-powered irrigation pumps. Adaptation analyses may therefore be used to inform both the magnitude and timing of mitigation.

Fortunately, many of the land-based carbon sequestration strategies that are being considered today, such as reduced tillage or no-tillage in agricultural soils, enhanced agro-forestry techniques, increased rotation and mixed production systems, are considered to be “good practice” land management strategies as they were originally developed for soil conservation and ecosystem resilience, and thus have significant adaptation potential.

Effectively integrating mitigation impacts and adaptation to inform public policy development remains a significant, although not intractable, challenge for the science community. This interaction of science and policy needs to evolve as the scientific knowledge base changes and attention is focused on the importance of integrative rather than disciplinary science within the science-policy interface (e.g., [4]).

*Informing investment and disinvestment decision making at all levels*

Adaptation analyses can be used to inform decision-making regarding present and future climate sensitive investment and disinvestment options at all levels of the agricultural industry. This is particularly important for long-term investments such as plant and animal breeding programs, capacity building in science and user communities, developing quarantine systems. Climate risks are, of course, only one consideration within a complex decision-making processes, as noted above.

*Enhancing adaptation capacity through collaboration with decision-makers*

Involving stakeholders in the development of adaptation options from the inception of the project is critical if the science of climate change impact is to be reflected in altered strategies and actions. This is particularly important for women practitioners where their labor contribution to agricultural production is significant, but their decision-making ability is not.

Participatory research confers many benefits; not only in helping agricultural decision makers evaluate the benefits of acting promptly to existing climate trends, but also in enabling the integration of stakeholders' knowledge, skills, and experience into the assessment. Adopting a participatory approach that cycles systematically between the biophysical and the socioeconomic aspects of a system enables scientific knowledge regarding agricultural systems to be integrated within stakeholder values and decisions. Such an approach can promote the relevance, credibility and legitimacy of the assessment process, which is critical to the development of flexible, dynamic policy and management frameworks that can accommodate for changes in climate conditions and in the underlying knowledge base [4].

Measuring increases in adaptive capacity requires an objective assessment technique. The difficulty arises when trying to capture the multitude of facets underpinning an individual, family, or community livelihood strategies, and, hence, their adaptive capacity, within a common metric. In the development arena, assessment of livelihood strategies has been undertaken using a framework that simultaneously considers assets, activities undertaken and access to resources. More recently, such an approach has been applied in the assessment of the vulnerability of Australian land owners to climate risk, and in the identification of focus areas for future research and policy support [116,117].

Although the livelihoods framework offers a useful tool for assessing adaptive capacity, the value of adaptation will only be realized if the strategies developed are both appropriate to the needs of the stakeholder and effectively implemented in a timely manner. Development of adaptation strategies in participation with decision makers is critical to ensuring appropriate actions are identified and in particular, the potential barriers to adoption are addressed. Such barriers may include natural, physical, human, social, and financial constraints, and therefore should be addressed within a broader livelihood strategy framework.

#### *The integration of climate change risk within a comprehensive risk management framework*

Managing risk under climate change is similar to the task of managing the risk associated with other aspects of the agricultural system, such as climate variability, changes in market forces or institutional factors. As such, the assessment of the likely impacts on the system is made under alternative management scenarios. Several innovations for managing climate risk in agricultural systems under current conditions may therefore be useful for helping adaptation planning under climate change. First, new and effective rural climate information services, developed by better integrating knowledge at relevant scales, from local to regional to international, would enable farmers to adopt technologies and change their management practices effectively. Second, new information and decision support systems are now available to better synthesize, monitor, and forecast climate information into forms that are directly relevant for decision-makers working to improve farmer livelihoods. Finally, innovations in index-based insurance and credit may increasingly

overcome some of the limitations of traditional insurance, and allow increased risk-taking often associated with higher-yielding production decisions that lead to increased incomes and overall improved adaptation capacity.

Isolating climate change from other drivers of risk may be helpful during the initial stages of assessment when awareness of the relative importance of this risk factor is still low. Operationally, however, translating adaptation options into adaptation actions requires consideration of a more comprehensive risk management framework. This would enable the exploration of quantified scenarios integrating all of the key sources of risk, thereby providing a more effective decision-making and learning environment for farmers, policymakers, investors and researchers and lead to an increase in “climate knowledge” [108].

## **4.2. Adaptation Strategies for a Selection of Agricultural Sectors**

This section provides a range of adaptation options aimed at managing the risk of climate change within four key agricultural industries: cropping, livestock, forestry, and fisheries/aquaculture. The management options detailed below are illustrative in nature, but require further research within the strategic assessment context detailed above in order to determine their appropriateness and likely effectiveness at each scale. Adaptation strategies can be categorized as follows:

- Those broadly seeking to improve the management of a limited resource, for example, water; technological fixes based on reductionist analysis, engineering design principles, or computer-aided models;
- Altered system design and management (typically requiring changes in attitudes and/or behavior, referred to as attitudinal fixes);
- Decision-making tools (including the use of climate forecasting and information sources); and
- Institutional changes.

Adaptation assessments to date have focused largely on altering system designs and management through an extension or intensification of existing climate risk management or production enhancement activities in response to a relatively small potential change in the climate risk profile. Adapting to ongoing and larger changes in climate may require the adoption of more innovative and transformational strategies. Designing and implementing greater transformational adaptive strategies remains a major challenge to the scientific, policy, investment, and stakeholder communities.

### *Cropping systems*

Cropping systems may be altered in many ways to more effectively manage projected climatic and atmospheric changes. Options include:

- Altering inputs such as plant varieties and species to those with more appropriate thermal time and vernalization (i.e., a need for cold winter

periods) requirements and/or with increased resistance to heat shock and drought; altering fertilizer rates to maintain grain or fruit quality; altering the amounts and timing of irrigation and other water management activities;

- Improved water management through the use of technologies to “harvest” water, conserve soil moisture (for example, through crop residue retention) and use and transport water more effectively; as well as to prevent water logging, erosion, and nutrient and sediment transportation resulting from more extreme rainfall events;
- Altering the timing or location of cropping activities;
- Diversifying the livelihood strategy to include income from other farming and non-farming activities;
- Improving the effectiveness of pest, disease, and weed management practices through wider use of integrated pest and pathogen management, development, and the use of varieties and species resistant to pests and diseases; and maintaining or improving quarantine capabilities and monitoring programs; and
- Using climate forecasting tools to reduce production risk.

Eco-physiological models offer a useful tool for quantifying the impacts of climate change and the effectiveness of adaptation strategies. A synthesis of climate change impact simulations for the recent IPCC Fourth Assessment report, featuring major cereal crops such as wheat, rice, and maize grown under a range of agro-climatic zones and management options, shows that the benefits of adaptation vary with crop species, temperature and rainfall changes. For example, the potential benefits of management adaptation for wheat are similar in temperate and tropical systems (17.9 percent versus 18.6 percent), whereas the benefits for rice and maize are relatively smaller than for wheat at 10 percent. These improvements to yield translate to damage avoidance of 1 to 2°C in temperate regions and between 1.5 to 3°C in tropical regions, potentially delaying negative impacts by up to several decades. There is a general tendency for most of the benefits of adaptation to be gained under moderate warming (of less than 2°C) before leveling off at increasing changes in the mean temperature. The yield benefits from adaptation tend to be greater under scenarios of increased, rather than decreased rainfall.

Although this analysis gives a quantitative estimate of impacts and adaptations, simulation studies need to be considered in the context of a number of limitations (see Box 3). Notwithstanding these limitations, modeling offers a useful tool to integrate current knowledge of climate, animal, and agro-ecological sciences.

### *Livestock*

Adaptation responses to climate change in the case of field-based livestock include taking additional care to continuously match stocking rates with pasture production, altering the rotation of pastures, modifying the of times of grazing, altering forage and animal species/breeds, altering the integration within mixed livestock and crop systems including the use of adapted forage



**Box 3 Limitations of modeling adaptation**

Impact and adaptation simulation studies commonly contain some the following limitations:

- Potential impacts of changes in pest and disease populations or air pollution are not taken into account;
- Relationship between CO<sub>2</sub> and crop growth is not robustly represented for many crop species;
- Variability of the climate and the frequency of climate extremes are rarely represented in climate change scenarios but are critical in determining yields and farm system design and management;
- There is often the assumption of full capacity to implement the adaptations whereas this may not be the case, particularly in regions where subsistence agriculture is predominantly practiced (47);
- Studies including irrigated production rarely take into account the implications of possible reductions in water available for irrigation.

crops, reassessing fertilizer applications, ensuring adequate water supplies and the using supplementary feeds and concentrates [4]. It is important to note, however, that there are often limitations to these adaptations, for example, more heat-tolerant livestock breeds generally have lower levels of productivity. Also, livestock-intensive industries in cold climates may have a reduced need for winter housing and for feed concentrates, whereas in warmer climates there might be an increased need for management and infrastructure to ameliorate heat stress-related reductions in productivity, fertility, and increased mortality. Furthermore, the capacity to implement infrastructural adaptation measures could be low in many tropical regions, whereas in the mid-latitudes, the risk of reduction in water availability for agriculture may limit adaptation options that require water for cooling.

*Forestry*

A large number of adaptation strategies have been suggested for planted forests, including changes in management intensity, hardwood/softwood species mix, timber growth and harvesting patterns within and between regions, rotation periods, salvaging dead timber, shifting to species or areas more productive under the new climatic conditions, landscape planning to minimize fire and insect damage, adjusting to altered wood size and quality, and adjusting fire management systems [4]. Adaptation strategies to control insect damage can include prescribed burning to reduce forest vulnerability to increased insect outbreaks, the use of nonchemical insect control mechanisms (e.g., baculoviruses), and adjusting harvesting schedules, so that those most vulnerable to insect defoliation are harvested preferentially. Under moderate climate changes, these proactive measures may potentially reduce the negative economic consequences of climate change. However, as with other primary industry sectors, there is likely to be a gap between the potential adaptations and the realized actions. For example, large areas of forests, especially in developing countries, are under minimal direct human

management, limiting adaptation opportunities. Even in more intensively managed forests where adaptation activities may be feasible, the long time lags between planting and harvesting trees will complicate the decisions as adaptation may take place at multiple times during a forestry rotation.

### *Fisheries*

From local to global levels, fisheries and aquaculture are essential for food supply, food security and income generation. Well-managed fisheries have considerable potential to contribute to economic growth and poverty reduction. Some 42 million people work directly in the sector, with the great majority in developing countries. If you include those who work in associated processing, marketing, distribution, and supply industries, the sector supports several hundred million livelihoods. Aquatic foods have high nutritional quality, and contribute to 20 percent or more of the average per capita animal protein intake for more than 2.8 billion people, mostly from developing countries. They are also the most widely traded foodstuffs and are essential components of the export earnings of many poorer countries. The sector has particular significance for small island states.

There are three main pathways through which climate change will affect fisheries and aquaculture, as well as the dependent communities and their economic activities:<sup>2</sup>

1. Physical and chemical changes in oceans and freshwaters, including increases in water temperature and changes in salinity, among others;
2. Change in fish production, catch composition, and species distribution resulting from a complex interplay of ecological changes; and
3. Physical changes to coasts, estuaries, wetlands, lakes, and rivers caused by changing weather patterns, weather-driven natural disasters, and sea-level rise.

Natural climate variability in the marine environment occurs on a cascade of periods and spatial scales to which marine ecosystems respond in a multitude of ways. The contribution of anthropogenic climate change is expected to dominate over natural variability throughout the 21st century, and nonlinear, abrupt changes in marine ecosystems are expected to increasingly occur as anthropogenic climate change increases.

Fishery resources are highly sensitive to environmental changes, be they fluctuations in ocean currents, river flows, and lake-levels, or related changes in ocean, coastal, and floodplain productivity. Fisheries have always had to cope with variable production and unpredictable changes in weather, but future climate change is likely to increase variability and in particular will be impacted by extreme events.

Fishing communities and fisher livelihoods, particularly in developing countries, are the most vulnerable to these potential impacts, as they face the dual challenge of changes in the distribution and abundance of fish stocks, as well as increasing threats of flooding from sea-level rise and greater intensity of extreme weather events. The fact that fishermen in many developing

countries are amongst the poorest, generally have little, if any, transferable skills, and usually do not have safety nets, means that declines in fish stocks will have a profoundly negative effect on their, and their families', livelihoods.

With such high exposure to climate-related risks, adaptation to climate change is a high priority for fishery sector policy. Improving the governance of fisheries to increase the resilience of fish populations and fishing communities to climate change, and particularly to extreme climate shocks, is a key objective of such policy.

### **4.3. Synergies of Adaptation and Mitigation**

Actions to limit the damages from climate change need to be implemented now in order for them to be effective. Mitigation actions involve the direct reduction of anthropogenic emissions or the enhancement of carbon sinks that are necessary for limiting long-term climate damage. Adaptation is necessary to limit the potential risks of residual climate change at present and in coming decades. Importantly, there are significant differences in the nature of policies underlying adaptation and mitigation actions. The benefits of adaptation measures will be realized almost immediately but will make the most difference under moderate climate change—perhaps up to about mid-century. By contrast, benefits of mitigation may only be realized decades from now, becoming relevant only toward the end of the century.

It follows that a significant challenge of climate policy is to identify and then develop instruments that allow for a portfolio of adaptation and mitigation strategies that are effective in time and space and focus on balancing actions across the most appropriate sectors, and within the chosen scope of specific climate response policies. Useful synergies exist for adaptation and mitigation in agriculture, relevant to food security. They could form the core of climate policy planning and implementation at national and international levels. These include avoided deforestation, forest conservation and management, agro-forestry for food of energy, land restoration, recovery of biogas and waste, and, in general, a wide set of strategies that promote the conservation of soil and water resources by improving their quality, availability, and efficiency of use. These strategies are often deeply rooted in local cultures and knowledge, and are the focus of much of the research, support and implementation efforts of key international agencies and nongovernmental organizations (NGOs). They tend to increase resilience of production systems in the face of increased climatic pressures, while providing carbon sequestration or reducing land-based greenhouse gas emissions. As shown in Box 4, many of these synergies are also relevant to social, economic, and environmental sustainability. It is important to recognize, however, that these synergies are often region and system specific, and need to be evaluated case by case.

Although a number of tradeoffs between mitigation practices and adaptation exist—for instance, bioenergy and certain land conservation programs may involve actions that introduce new competition for land and water resources otherwise necessary for enhancing system resilience and safeguarding food

**Box 4 Examples of synergies in adaptation and mitigation [2]**

Reducing methane emissions via integrated rice and livestock systems traditionally found in West Africa, India, Indonesia, and Vietnam, is a mitigation strategy that also results in better irrigation water efficiency—it can also provide new sources of income while improving performance of cultivated agro-ecosystems, and enhance human well-being.

Reducing N<sub>2</sub>O emissions—can lead to improved groundwater quality and reduced loss of biodiversity as well as reducing costly production inputs.

Integrating animal manure waste management systems, including biogas capture and utilization, for reductions of CH<sub>4</sub> and N<sub>2</sub>O—could result in greater demand for farmyard manure and create income for the animal husbandry sector where many poor are engaged.

Methane emitted by ruminant livestock—represents energy lost to the animal that could otherwise be used to increase animal production. Modification of the quality and quantity of feed by having feeds that are not as badly affected by inclement climate conditions can result in lower methane emissions and increased production. In addition, increased efficiency of production from more climate adapted systems results in less methane per unit product—allowing growth in livestock production without equivalent growth in methane emissions [120].

Restoring land by controlled grazing—can lead to soil carbon sequestration, have positive impacts on livestock productivity, reduce desertification, and also provide social security to the poor during extreme events such as drought (especially in sub-Saharan Africa).

Practicing agro-forestry—can promote soil carbon sequestration while also improving agro-ecosystem function and resilience to climate extremes by enriching soil fertility and soil water retention.

Producing bio-energy—can lead to reduced greenhouse gas emissions via substitution of fossil fuels and generate income and employment for rural regions, providing an indirect but powerful adaptation strategy. However, experience with such schemes needs to be built around the world and the net impacts for a region as a whole need to be assessed on a case-by-case basis.

production under climate change—many more adaptation practices exist that may positively reinforce land mitigation potentials under specific conditions. For example, the increased irrigation and fertilization necessary to maintain production in marginal semiarid regions under climate change conditions may also greatly enhance the ability of soils in those areas to sequester carbon (Box 4). This would be especially true in sub-Saharan Africa where small improvements in the efficiency of fertilization or irrigation can have very large effects on the biomass production of crops and, hence, on their soil inputs. Under scenarios with increased precipitation, especially at mid-latitudes, a shift from fallow systems to continuous cultivation would maximize production under the new precipitation conditions and, at the same time, increase the soil carbon sequestration potential.

#### **4.4. Financial Mechanisms for Mitigation and Adaptation**

The Bali Roadmap indicates that actions aimed at safeguarding food security and rural livelihoods under climate change in coming decades must necessarily focus on synergies between adaptation and mitigation strategies

for the rural poor, in order to address the climate, environmental, social, and economic concerns expressed within both the UNFCCC and MDGs. In particular, a focus on agriculture, land use, land use change, and forestry in developing countries would offer the opportunity to address these issues from within the dominant economic sectors of most developing countries, strengthening their basis for sustainable development.

Recent work by FAO and the International Fund for Agricultural Development (IFAD) [118] indicate that there is scope for enhancing the ability of carbon markets to reach rural communities by strengthening the number of these project categories as well as widening their geographic distribution. Importantly, the economic potential of additional carbon sequestration activities—largely linked to reducing emissions from deforestation and degradation (REDD) and sustainable forest management actions, but also including agro-forestry techniques, soil conservation in agriculture, and renewable energy from biomass—is substantial, corresponding to 5–10 billion tons of CO<sub>2</sub>e per year by 2030 at carbon market prices ranging from 4 to 10 USD per ton CO<sub>2</sub>e (IPCC AR4 WGIII). Annual financial flows from these additional carbon sequestration activities could help meet the projected costs of adaptation to climate change in developing countries.

Many of these activities are currently allowed under a number of voluntary schemes and pilot funds, but are excluded under the CDM, the largest of the existing carbon markets. In particular, allowing credits from REDD, as well as from a range of agricultural and forestry activities, has the potential to greatly increase carbon flows to the rural poor in developing countries. Significant efforts should therefore be directed towards implementing enhanced land-based mechanisms for use within voluntary and post-2012 Kyoto carbon markets. In particular, the FAO is proposing “premium carbon crediting” mechanisms [118], designed to pay for projects that in addition to providing carbon offsets can, at the same time, result in system adaptation. In addition, the World Bank has given formal approval to the creation of the Climate Investment Funds (CIF), designed to provide funding to help developing countries in their efforts to mitigate rises in greenhouse gas emissions and adapt to climate change as elaborated in Box 5.

**Box 5 The World Bank Climate Investment Funds (CIFs)**

The World Bank has approved two trust funds to be created under the Climate Investment Funds, with total investments targeted to reach 5 billion USD. One of the funds, the Clean Technology Fund, will provide new, large-scale financial resources to invest in projects and programs in developing countries that contribute to the demonstration, deployment, and transfer of low-carbon technologies. The second fund, the Strategic Climate Fund, will serve as an overarching fund for various programs to test innovative approaches to climate change. The first such program is aimed at increasing climate resilience in developing countries. Clearly, the land use, land use change, agriculture, and forestry sectors are important areas where a number of projects could be tested under such funds.

## 4.5. Impact and Adaptation Metrics

In support of adaptation planning at regional and international levels, recent research has started to focus on the need to develop a set of impact and adaptation metrics that can help decision makers evaluate climate response actions, their timing, and their effectiveness. These decisions need take into consideration key agricultural system characteristics. To this end, a set of operational metrics can help quantify, using both monetary and nonmonetary terms, the severity of impacts; system capacity to respond to climate change; and adaptation options that minimize risk and/or maximize benefits under given climate scenarios. A set of metrics can also help communicate in a simple and concise manner, the importance of the observed and projected impacts of climate change, including their temporal and spatial distribution; to what extent local adaptation (or global mitigation) measures can be effective; and ultimately to quantify the benefits of taking action [112]. Likewise, there is a need to review current national and international monitoring and evaluation activities, to identify where they can be drawn from to meet the needs of informed climate change adaptation—and also to identify gaps in these programs where new activities may be needed. For instance, climate stress insurance indicators—a set of metrics developed by the World Bank’s Agriculture and Rural Development Department [119]—are based on the following criteria: (1) observable and easily measured in a timely manner; (2) objective; (3) transparent; (4) independently verifiable; and (5) stable but flexible in the long term. Similarly, criteria for developing metrics can be expressed as (1) relevant for assessing impacts and responses to climate change in both nonmonetary and monetary terms; (2) appropriate for global-, regional-, and/or national-level planning, including adaptation responses; and (3) computationally easy with respect to observed and/or model-generated data. Such evaluation frameworks can utilize new approaches for mapping and assessing adaptive capacity to climate change based on rural livelihoods analyses that focus on human, social, physical, financial, and environmental capital [116,117]. As shown in Figure 3, an effective assessment framework enables the integration of a range of considerations that are important to household and regional decision-making.

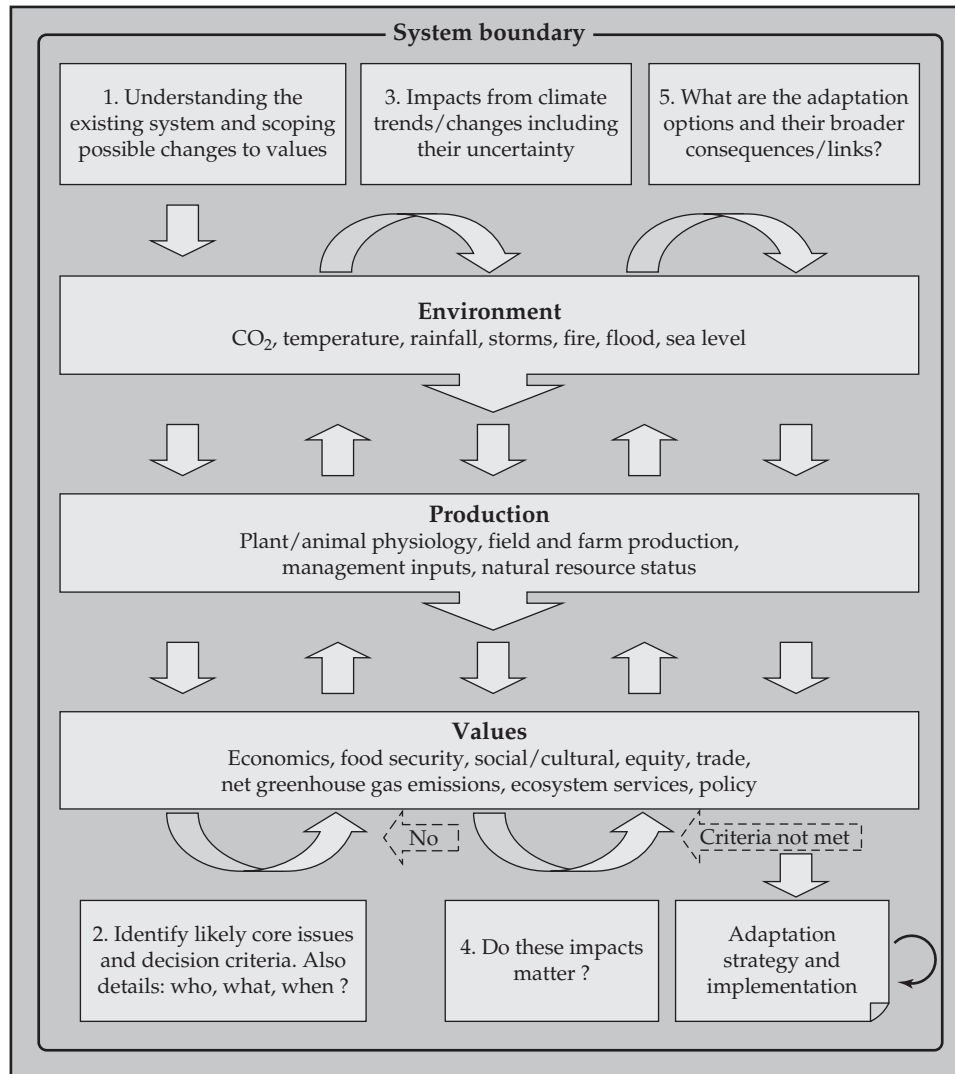
### *Tools for impact and policy assessment*

Models are necessary, in addition to observed data, to project the impacts of future climate change and socioeconomic development on agricultural systems, and to derive the associated metrics to estimate climate benefits. Two distinct model classes are useful to estimate metrics in agriculture: dynamic crop/agro-ecosystem models, with or without coupling to economic trade models, such as DSSAT, AEZ and the Erosion Productivity Impact Calculator (EPIC) and those that are based on Ricardian economic approaches [113].

### *Agricultural production metrics*

Developing a set of metrics that would apply to all scales (local, regional, national, and global) would be extremely complex in practice. The development of a more practical application than those that exist at present

**Figure 3 A general framework for operational adaptation frameworks noting that this approach will have to be reconfigured to specifically address local issues and institutions [4]**



would require the following needs to be taken into consideration. First, metrics should help characterize the status of current agricultural production systems, over short-term (20 to 30 years) and long-term (80 to 100 years) horizons. Second, they need to be assessed against the backdrop of socioeconomic development. Third, they should quantify benefits of adaptation and mitigation strategies [113].

In addition, *vulnerability thresholds* should be derived from the impact metrics beyond which the ability of a system to cope with a new climatic range is significantly diminished.

Table 7 A Comparison of models used to estimate metrics in agriculture	
Dynamic crop models	Ricardian approaches
<b>Dynamic crop models</b> are biophysical representations of crop growth and production including explicit land and crop management.	<b>Ricardian approaches</b> provide assessments of the monetary impacts on agricultural systems, such as land value at risk under climate change [114].
<i>What are their assumptions and what do they compute?</i>	
They compute seasonal dynamics of crop yield as well as its interannual variability, at local, regional, and global scales under current and future climate conditions.  They can be coupled with agricultural-economic models to better estimate regional and global food demand, production and trade as a function of agro-climatic and socioeconomic factors. Coupled with trade models, they link regional agricultural production to trade, food supply, and nutrition levels.	They calculate the overall cost of impacts, and thus overall system vulnerabilities, by implicitly including all existing adaptation options.  The statistical approaches underlying this methodology assume efficient geographic distribution of agricultural activity as a function of climate. They implicitly describe full adaptation under the climate considered based on historical statistics and based on the assumption that an equilibrium response is reached in a short time.
<i>What can the models be used to evaluate?</i>	
They can identify and explicitly evaluate the farm-level responses of key importance to regional and national adaptation and mitigation policy. They can provide quantifiable answers to how vulnerable local or regional agricultural production systems are to climate change and what the adaptation strategies and their effects are.	Within this context, they provide extremely valuable first-order, yet static, analyses of the economic vulnerability of regionally or nationally aggregated production systems.
<i>How are these models constrained?</i>	
Such models cannot cover all possible adaptation solutions, however, and thus may tend to overestimate climate change impacts and their costs.	They may provide overestimates of adaptation efficiency and underestimates of climate change impacts because they are constrained in the context of dynamic value and cannot provide insight on [113]: <ul style="list-style-type: none"> <li>• specific adaptations that would work in practice,</li> <li>• their spatial distribution &amp; cost</li> <li>• when they should be considered for implementation</li> <li>• the practical, institutional, and technical constraints to adaptation</li> </ul>



Key characteristics of agricultural systems may be described by local, regional, and global metrics based on the long-term sustainability of production, with respect to climate, land, and water resources. Long-term means (of at least 20 years) and the variability of yield and production, income, and aggregate value-added may be used for this purpose. Regional and national data on agricultural income and production, available from FAO and related studies, may be used to describe total and regional GDP, GDP per capita, share of agricultural GDP, agricultural GDP per capita, and total and regional production of cereals, and/or other crops.

Another quite useful metric is the nutrition index, that is, an indicator of the number of people at risk of hunger in a given region, computed as the sum of local production and net imports divided by total food demand [67]. Temperature and precipitation (means and variability), are key determinants affecting the variability of agricultural output, including the extent of area planted and harvested, the amount and schedule of inputs used (water, nitrogen, etc.), the length of the growing season, and plant sensitivity to extremes.

Benchmarking the state of current and future agricultural systems is useful for comparisons across different production regions and future socioeconomic scenarios. Criteria for system vulnerability can then be developed and evaluated through interactions with national and regional stakeholders and experts, as a function of their knowledge of production and societal trends of importance to agriculture in the coming decades.

A general metrics framework is useful for planning and evaluating the costs and benefits of adaptation and mitigation responses in the agricultural sector as it identifies the key categories relating to vulnerability criteria of agricultural systems, i.e., the biophysical factors, socioeconomic data, and agricultural system characteristics, as expressed in terms of their exposure, sensitivity, adaptive capacity, and synergy with climate policy (Table 8). Specifically, metrics for biophysical factors may include indexes for soil and climate resources, crop calendars, water status, biomass, and yield dynamics.

Metrics for socioeconomic data include indexes describing rural welfare, reflected, for instance, in regional land and production values, total agricultural value added, or the agricultural share of GDP. Importantly, they may include, nutrition indexes comparing regional calorie needs versus food availability through local production and trade. Additionally, they could indicate the degree of protectionism and the status of crop insurance programs.

Finally, metrics for climate policies describe regional commitments to adaptation and mitigation policies, relevant to agriculture. For instance, such metrics measure land use and sequestration potential; the number and type of CDM projects in place and the committed land area; the area allocated for bioenergy production, and so on. These may be useful for identifying potential synergies of mitigation with adaptation strategies within regions, helping to define how vulnerability may change with time.

<b>Table 8 General framework for agricultural metrics</b>		
<b>Categories</b>	<b>Vulnerability criteria</b>	<b>Measurement class</b>
Biophysical indicators	Exposure	Soil and climate Crop calendar Water availability and storage Biomass/yield
Agricultural system characteristics	Sensitivity	Land resources Inputs and technology Irrigation share Production
Socioeconomic data	Adaptive capacity	Rural welfare Poverty and nutrition Protection and trade Crop insurance R&D and extension services
Climate policy	Synergies of mitigation and adaptation	Kyoto commitment capacity Regional support policy, such as CAP Carbon sequestration potential CDM projects in place, planned Bioenergy Irrigation expansion projects Land expansion plans Change in rotations/cropping systems
<i>Source:</i> [113].		

Depending on the framework adopted, many potential metrics are available for system characterization. A specific set of operational metrics for policy applications is shown in Table 9. It includes agricultural system characteristics, such as land resources, regional cereal production, percentage of irrigated land, and a water index related to the ratio of water withdrawals to available renewable water resources; socioeconomic data, such as aggregate economic value-added of production, land value at risk and a nutrition index related to the number of people at risk of hunger; and, finally, metrics for interactions with climate policy, such as competition for land for afforestation/reforestation or bioenergy projects for mitigation.

<b>Table 9 A practical set of metrics for impact assessment</b>		
	<b>Metric</b>	<b>Description (units)</b>
Biophysical indicators	Crop suitability	Soil and climate factors (no single unit, i.e., different units for different factors)
	Crop yield	Grain production (Tonne/ha)
	Water stress index	Ratio of actual versus potential ET (no units—a ratio)
	Drought duration index	Cumulative water stress over time (no units—a ratio)
Agricultural system characteristics	Land resources	Ratio of used vs. available land (no units—a ratio)
	Regional cereal production	Major cereal crops (Tonne/yr)
	Water resources	Irrigation requirements over availability (no unit—a ratio)
Socioeconomic data	Economic value at risk	Net production value; agricultural GDP (\$)
	Land value at risk	Land value of areas most affected (\$)
	Nutrition index	Food demand over supply (no units—a ratio)
	Risk of hunger	Cumulative number of people whose calorie intake falls below a (FAO-defined) specific value (millions)
Climate policy	Mitigation potential	C-Sequestration committed (Tonne C yr <sup>-1</sup> )
<i>Source: [113].</i>		

## **5. Conclusions and Recommendations**

Understanding the processes and dynamics that characterize the interactions of key environmental and climate factors affecting plant productivity and ecosystem vulnerability, remains a priority for better quantifying future impacts of climate change on managed land systems. Examples include the effects of elevated CO<sub>2</sub> concentrations as modulated by changes in climate and extreme events, soil and water quality limitations, and reduced yields from increased incidence of pest, weed, and disease.

In terms of experimentation, there is still a lack of knowledge of CO<sub>2</sub> and climate responses for many crops other than cereals, including many of importance to the rural poor. Even after taking into consideration the numerous experiments that in the last 15 to 20 years have added so much to our knowledge of climate change impacts on plant dynamics, scaling results to farmers' fields and even further to regional scales (including predicting the CO<sub>2</sub> levels beyond which saturation may occur), remain a critical challenge.

In terms of simulation studies, there is a need to enhance the comparisons between different crop models. It is important that the uncertainties associated with crop model simulations of key processes related to climate change (for e.g., temperature and water stress), and their spatial-temporal resolution, be better evaluated and understood, otherwise findings of integrated studies are likely to remain dependent on the particular crop model used. Importantly, it is still unclear how the implementation of plot-level experimental data on CO<sub>2</sub> responses compares across models—especially when simulations of several key limiting factors such as soil and water quality, pests, weeds, disease, and the like, remain either unresolved experimentally or untested in models.

In general, greater collaboration between experimentalists and modelers, and across disciplines, is necessary to bridge some of the existing knowledge gaps and to better understand related uncertainties.

A major research challenge is to better understand how climate change impacts at the crop level, which depend on agro-climatic knowledge and local agronomic field management, may scale up and interact with key socioeconomic drivers to determine food production and supply at regional, national and international levels, including key issues of food security. What is certain is that climate change will affect all four dimensions of food security, namely food availability (i.e., production and trade), access to food, stability of food supplies, and food utilization [115]. The importance of the various dimensions and the overall impact of climate change on food security will differ across regions, over time and, most importantly, will depend on the overall socioeconomic status that a country has accomplished.

All current quantitative assessments show that climate change will adversely affect food security. Climate change will increase the dependency of developing countries on imports and accentuate the existing focus of food insecurity on sub-Saharan Africa and to a lesser extent on South Asia. Within the developing world, the adverse impacts of climate change will fall disproportionately on the poor. Many quantitative assessments also show that the socioeconomic environment in which climate change is likely to evolve is more important than the impacts that can be expected from the biophysical changes of climate change.

Less is known about the role of climate change for food stability and utilization, at least in quantitative terms. However, it is likely that differences in socioeconomic development paths will be the crucial determinant for food utilization in the long run and that they will be decisive in determining the ability of a region to cope with problems of food instability, be they climate-related or caused by other factors.

Finally, all quantitative assessments reviewed in this study show that the first decades of the 21st century are expected to see low impacts of climate change, as well as low overall incomes but still a high dependence on agriculture. During these first decades, the biophysical impacts of the changes in climate will be less pronounced than later in the century, but will nevertheless affect those in particularly vulnerable areas that are still significantly dependent on agriculture and have lower overall incomes to cope with the impacts of climate change. By contrast, the second half of the century is expected to bring not only more severe biophysical impacts but also a greater ability to cope with them. The underlying assumption is that the general transition in the income formation away from agriculture toward non-agriculture sectors will be successful.

Importantly, current projections do not include the possibility for negative surprises, especially a pronounced increase in the frequency of extreme events such as droughts, heat waves and flooding that have the potential to significantly worsen the expected impacts on agriculture, extending them to regions outside currently critical marginal areas in poor developing countries. They also have the potential to anticipate impacts to much earlier than currently projected, perhaps as early as 2020–2030. In addition, it should be noted that the socioeconomic scenarios used in all current projections use smooth growth curves until the end of the century. By contrast, additional negative surprises may stem from socioeconomic crises—given the fact that smooth socioeconomic development has not been experienced in the past—that unexpectedly reduce the projected ability of developed and developing regions alike to cope with climate change challenges, either regionally or globally.

In general, however, the degree to which the impacts of climate change will be felt over all decades will crucially depend on the future policy environment for the poor. Reducing barriers to free trade can help to improve the access to international supplies; investments in transportation and communication infrastructure will help provide secure and timely local

deliveries; improvements in irrigation; the promotion of sustainable agricultural practices; and continued technological progress can all play a crucial role in providing steady local and international food supplies under climate change.

### **5.1. A Call for Action**

With these considerations in mind, there is increasing urgency for a stronger focus on adapting agriculture to future climate change. There are many potential adaptation options available at the management level, often variations of existing climate risk management. However, as yet, there are relatively few studies that assess both the likely effectiveness, and adoption rates, of possible response strategies. A synthesis of studies for cropping systems indicates, first, that the potential benefits of adaptation in temperate and tropical wheat growing systems are similar and substantial, even though the likely adoption rates may differ. Second, most of the benefits of marginal adaptation efforts within existing systems accrue with moderate climate change and there are limits to their effectiveness under more severe climate changes. Hence, more systemic changes in resource allocation, including livelihoods diversification, need to be considered. We argue that increased adaptation action will need integration of climate change risk within more inclusive risk management frameworks, taking into account climate variability, market dynamics and specific policy domains. Many barriers to adaptation exist and overcoming them will require a comprehensive and dynamic policy approach, covering a range of scales and issues, from individual farmer awareness to establishment of more efficient markets. A crucial part of this approach is the development of an adaptation assessment framework that can equitably engage farmers, agribusiness, and policy makers, leveraging off the substantial collective knowledge of agricultural systems, yet focusing on the values of importance to stakeholders. To be effective, science has to adapt as well, by identifying research needs and by enhancing integrative science at the center of the communication and management tools developed for decision makers.

Importantly, it must increasingly be recognized that at present, there are many adaptation strategies to climate change that are not only relevant to safeguarding food security and improving livelihoods in rural communities but also lead to carbon sequestration in soils and vegetation through improved land management, additional economic uses of land, and conservation. For crop agriculture, these strategies include a wide set of so-called “good agricultural practices” that are typically aimed at conserving and improving water and land resource use, such as improved crop rotation systems, higher-efficiency water and fertilizer application techniques, agro-forestry, reduced tillage, and so on.

Importantly, a number of critical strategies to this end have been identified in forestry and natural ecosystem conservation or sustainable exploitation. These include avoided or reduced deforestation and forest degradation projects (REDD), and sustainable forestry projects that target local indigenous

populations and their welfare over large-scale industrial extraction of wood and other products. All of these, and many other practices—many of which have well-known implementation technologies due to extensive scientific research and/or traditional knowledge—lead to increased ecosystem resilience to climate variability and extremes, and tend to create additional and diversified income opportunities for local communities. Such opportunities may arise from the creation of new nonfood land-based products from low-impact collection in natural ecosystems, dedicated agro-forestry production, or bioenergy products from specifically designed local-scale systems.

Furthermore, the benefits of identifying synergies between *needed* adaptation to climate change and *desirable* mitigation actions stem from the fact that, by designing systems that provide both classes of services, project developers can access significant additional financial and investment flows linked to the international carbon markets, that is, access funds for more successful adaptation by also generating voluntary or regulatory carbon credits through a number of already available possibilities. These include several voluntary schemes such as the Chicago Climate Exchange, many newly identified carbon offsetting opportunities, as well as regulatory markets such as the UNFCCC mechanisms, including the Clean Development Mechanism, the Joint Implementation, and several existing and developing funds under both the Global Environmental Facility and the World Bank.

A number of considerations and recommendations can be drawn from:

- (1) current knowledge on land-based production systems,
- (2) dynamics of change under the socioeconomic and climate pressures expected in coming decades, and
- (3) climate policy as well as growing public awareness on the need for synergies between agricultural sustainability, climate change impacts and ecosystem services.

In particular, adaptation strategies need to become an intrinsic component of sustainable rural development projects: long-term sustainability cannot be expected without stronger resilience to expected climate change. To this end, two important steps must be implemented:

- (1) Assessment tools must be developed to estimate the risks and vulnerabilities associated with climate change and how practical adaptations may change these risks and vulnerabilities, for a portfolio of existing and future development projects at global and regional levels.
- (2) A practical system for the actual implementation of adaptation actions must be developed, so that after risks and opportunities are identified at the macro-level of economic and vulnerability analyses, practical projects with real solutions can be implemented with little delay.

With respect to the first need, the necessary tool is an agro-ecological model of agriculture and forestry linked to an economic production and trade model, capable of estimating explicitly the effects of a number of adaptation actions

both locally and regionally. This would allow vulnerability maps to be produced globally but with regional detail. Global and regional maps of adaptation costs and benefits would be necessary to identify key areas and production systems that can be effectively targeted today and in coming decades. Such an analysis, if extended to the long term, would be able to provide a window into identifying strategies likely to be unsustainable due to evolving climate change stressors—such as, for instance, irrigation projects that may safeguard production in a given region in the short term but fail in the longer term as a result of increasing aridity trends. The same model could be extended to compute carbon balances of land-based systems, either dynamically or by IPCC accounting methodology, in order to assess the potential synergies of proposed adaptation strategies with mitigation. Importantly, the agro-ecologic and economic linkages would allow an explicit assessment of climate change impacts on regional and global food security. Understandably, the development of such a model is no small task. As discussed in the IPCC AR4, only a handful of models currently exist that could be expanded to further include the suggested added features. Significant resources will be necessary to first fully evaluate and then further develop these necessary modeling tools.

With respect to the second task, it is to be noted that once the decision to respond and adapt is taken, scientific knowledge in itself is not sufficient to respond to the critical questions concerning what adaptation strategies need to be implemented, in which regions and when.

In a practical sense, the actual job of implementing adaptation actions in agriculture and forestry is largely an “engineering” or policy task, one that needs to be implemented through existing and new technology, and supported by enhanced collaboration of climate adaptation scientists with international agencies—such as the World Bank, FAO, IFAD and the World Food Programme (WFP)—that have strong, multi-decadal experience from firsthand rural development work. Such collaborations need to be extended to NGOs and especially to rural communities themselves in order to be successful, because they are the actors that intimately know their production systems and their underlying ecosystem dynamics. Recognizing that a significant amount of adaptation will be implemented by local actors as a function of their own perceptions of climate and market trends, and that certain adaptation strategies will necessarily be region specific, it is important to develop coordinating responses, regionally and internationally, in order to avoid systems “locking in” to undesirable configurations. Planned policy for adaptation is also necessary, in order to facilitate response actions and to support the development, implementation, and access to the necessary technological solutions over time.

To this end, impact and adaptation metrics can be used to facilitate the evaluation of policy options, assess both the short- and long-term risks of climate change, to evaluate adaptive capacity and how to improve it, and to identify the potential thresholds beyond which significant adaptation of management techniques may be required to maintain system productivity



and income. The necessary additional work consists of developing and evaluating metric and associated decision-supported frameworks across a range of agricultural systems, socioeconomic pathways, and climate change regimes, and including the effects of increased climate variability. In particular, incorporating the impacts of increased frequency of extreme events on agricultural production would likely have important implications for estimates of the benefits of climate change policies. Additionally, there is a need to refine and extend predictions of water resources as a function not only of climate but also of agricultural land use and sector competition. The ability of farmers to irrigate may largely shape system vulnerability and the ability to adapt to increased heat stress. Finally, the tradeoffs among land use for food, bioenergy, and carbon sequestration, as well as the implications of adaptation responses, increasingly need to be considered within such impact analyses.

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## Endnotes

<sup>1</sup> Poor or inadequate adaptation that is more harmful than helpful.

<sup>2</sup> FAO. (2007). *Building adaptive capacity to climate change. Policies to sustain livelihoods and fisheries. New directions in fisheries—A series of policy briefs on development issues*. No. 08. Rome. 16 pp. Also available from: <http://www.sflp.org/briefs/eng/policybriefs.html>



Agriculture & Rural Development Department  
World Bank  
1818 H Street, NW  
Washington, DC 20433  
<http://www.worldbank.org/rural>