CGE Training Materials for Vulnerability and Adaptation Assessment

Chapter 7

Agriculture

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7.1. Introduction

According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) Working Group II (Porter et al., 2014), climate change will have, with varying degrees, a broad range of impacts on agricultural crops and livestock. Compared to the previously published IPCC Fourth Assessment Report (AR4) by Easterling et al. (2007), there is more emphasis on food security, and the potential impact on food access, utilization and price stability. At present, approximately 40% of the Earth's land surface is managed for cropland and pasture (Foley et al., 2005). It is further estimated that the livelihoods of approximately 450 million people in developing areas are entirely dependent on managed ecosystem services (FAO, 2004), reflecting the significant scale of the issue for human wellbeing. The basic question now is how to feed the world in 2050 (FAO, 2009).

Many studies document the implications of climate change for agriculture and pose a concern that climate change is a significant threat to sustainable development, especially to Parties not included in Annex I to the Convention (non-Annex I Parties). Identifying which regions, populations and food production systems are at greatest risk from climate change can help in setting priorities for adaptation. This chapter focuses on the methods for making these assessments, and includes examples of applications in developing countries and an overview of existing knowledge on the subject. The merits of each approach vary according to the level of impact being studied, and approaches may frequently be mutually supportive. For example, simple agroclimatic indices often provide the necessary information on how crops respond to varying rainfall and temperature in wide geographical areas. Crop simulation models are used to test alternative management that can in turn be used as a component of an economic model that analyses regional vulnerability or national adaptation strategies. Therefore, a 'mix and match' of approaches, methods and tools is often the best approach.

This chapter provides an overview of the methods, tools and associated data requirements that are commonly used in the agricultural sector for vulnerability and adaptation (V&A) assessment. Background information on the vulnerability of agriculture to climate change and adaptation options is included in appendixes to this chapter:

- Appendix 7-1 discusses climate and non-climate drivers of change in agriculture;
- Appendix 7-2 summarizes literature on potential impacts of climate change on agriculture;
- Appendix 7-3 briefly presents options for adaptation in agriculture.

Other chapters in these training materials contain important information for conducting assessments of climate change V&A in agriculture. In particular:

- Chapter 2 discusses impacts and V&A frameworks;
- Chapter 3 addresses baseline socioeconomic changes. As noted in this chapter, agriculture can change substantially over the coming decades;

- Chapter 4 is on climate change scenarios;
- Chapters 5, 6 and 8 are on coastal resources, water resources, and human health, respectively. There will be important interactions between agriculture and all of these sectors;
- Chapter 9 discusses integration across sectors as well as adaptation, mainstreaming, monitoring and evaluation;
- Chapter 10 is on communication of V&A results.

7.2. Situation summary

A considerable body of literature relating to the impacts of climate change and agriculture has been published by multilateral organizations, national governments and academics. It is increasingly clear that climate change will have varied impacts both spatially and temporally on key subsectors including crop and livestock systems.

Importantly, projected changes in the frequency and severity of extreme climate events may have more serious consequences for food and forestry production, than will changes in projected annual changes of temperature and precipitation (Porter et al., 2014). Moderate warming from climate change may benefit crop and pasture yields in the mid- to high-latitude regions. However, slight warming will likely decrease yields in seasonally dry and low-latitude regions (Porter et al., 2014). These are discussed in more detail in appendixes 7-1 and 7-2. Most studies so far have concentrated on the potential impact of climate change on arable farming. However, livestock and fisheries are also extremely sensitive to weather and thus to long-term climate change. Tools to address these are far more limited compared to those available for traditional agronomic crops.

7.3. Methods, tools and data requirements

7.3.1. General considerations

The methods for assessing climate impacts in agriculture and evaluation of adaptation strategies have been refined over many years and widely used by scientists, extension services, commercial farmers and resource managers. A major challenge facing all agriculture–climate evaluations is the analysis of important biophysical and socioeconomic impacts, because these must be derived from complex interactions among biophysical and socioeconomic systems that are inherently difficult to model. Although traditionally the emphasis has been on yield impact assessment, the emphasis is now shifting towards economic returns of small-hold farmers. Ultimately, both food security as well as the economic sustainability of small-hold farmers are important for regional and national assessments.

The tools presented in this chapter are adequate to be used with changed mean climate conditions. To evaluate changes in the frequency and intensity of extreme events, such as droughts or floods, it is important to include a combination of empirical yield responses based on statistical data and modelling approaches. However, this is an area that requires further improvement with respect to tool development.

A number of approaches to the assessment of impacts of climate change on agriculture have been developed from the many studies conducted to date (see table 7-1). Approaches used to assess biophysical impacts include:

- Index-based;
- Statistical models and yield functions;
- Process-based models.

Table 7-1
Summary of the characteristics of the main agricultural models and related tools

Type of model/tool	Description and use	Strengths	Weaknesses
Agroclimatic indices	Based on combinations of climate factors important for crops. Used in many agricultural planning studies. Useful for general audiences.	Simple calculation. Effective for comparing across regions or crops.	Climate-based only, lack management responses or consideration of carbon fertilization. Cannot capture adaptation.
Statistical models	Based on the empirical relationship between observed weather and crop responses. Traditional tools used for yield prediction.	Crop yield and weather variations are well-described and can capture annual variability for long-term data.	Do not explain causal mechanisms, especially short stresses that occur during the growing season. Cannot capture future climate-crop relationships, carbon dioxide (CO_2) fertilization and adaptation. Management and other variables often incomplete or lacking.

Type of model/tool	Description and use	Strengths	Weaknesses
Process-based crop models	Based on the dynamic simulation of crop growth and development using local weather and soil information, crop management and genetics as input. Used by many agricultural scientists for research and development.	Process-based and calibrated. Can be used for testing a broad range of adaptation and mitigation strategies simultaneously. Available for most major food, feed and fibre crops.	Require detailed weather, soil and management data for best results. Some models also require some genetic information. Do not represent all types of management. Do not represent pests, diseases and weeds.
Economic models	Used to calculate economic impacts of climate change and the value of adaptation and mitigation.	Useful for representing net impacts of climate change, assuming farmers adapt efficiently to climate change.	Not all social systems, households and individuals appropriately represented. 'Reduced-form' models assume historical effects of policies, social conditions and adaptation capability are the same in the future, and assume prices are constant. 'Structural' models are more flexible but require more data. Assume profit and utility-maximizing behaviour. Models are complex and require much data.
Household and village models	Description of coping strategies for current conditions by household and village as the unit of response.	Useful to understand causal relationships in complex farming systems and related household behaviour.	Models are complex and case-specific; require large amounts of detailed data.
Geographic information system (GIS)	Tool to scale up point or grid-based simulations to a regional or national scale.	Useful for regional assessments.	Requires extensive spatial data as input, depending on the tool used. Requires some special GIS skills.

In addition, different tools can be used to examine the socioeconomic impacts of climate change. A relatively simple economic forecasting tool, such as that developed by the United States Country Studies Program (Benioff and Warren, 1996), is often useful. More complex approaches, such as economic regression models, microeconomic and macroeconomic models, farm models and household and village models, can also be used.

Each of these methods yields information on different types of impacts. For example, simple agroclimatic indices can be used to analyse large-area shifts of cropping zones, whereas process-based crop growth models should be used to analyse changes in specific crop yields. Effects on income, livelihoods and employment are assessed using economic and social forms of analysis.

In addition, studies can be undertaken using a regional or a site-specific approach.

In a ***regional approach**,* several existing simple tools can be applied and tested under a range of conditions in a given region and the results visualized on maps. This simple regional approach is essential for integrating climate change, crop production, water demand indices and socioeconomic indices on a regional scale, thus providing a first-order evaluating tool to analyse possible adaptation strategies.

The United Nations Framework Convention on Climate Change (UNFCCC) *Compendium on Methods and Tools to Evaluate the Impacts of, and Vulnerability and Adaptation to Climate Change* was first published in 1999 with the most recent update published in 2009 (UNFCCC, 2009). It provides an overview of the range of tools that can be used within the agricultural sector to evaluate the impacts of, and V&A to climate change. The tools listed in the compendium range from sector-wide economic analyses to farm-level crop models. The crop-process models address the impact of various management and climate change scenarios on single crops, multiple crops, components of cropping systems such as crop rotations and entire ecosystems. Other tools may be used to analyse particular ecological factors or processes (e.g. ACRU[1]) or support bigger picture strategic adaptation decisions (e.g. MAACV, RRI, CLOUD, CRAM). The economic models also assist the user in evaluating the economic impacts of changing land values, supply and demand and commodity production resulting from climate change. The compendium includes a total of 128 entries; some have been used for limited research applications only, while others have had broader applications. Examples of models and tools that are readily available and commonly used within the agricultural sector are listed in box 7-1.

A ***site-specific approach*** involves local studies that analyse the sensitivity of crop yield, farm management and water use to climate at the local scale and the implications for policy decisions that affect water management. Crop models typically focus on optimizing timing of production and efficiency of nutrient use (primarily nitrogen) and irrigation water.

Because economic sectors vary greatly among countries and physical environments, different methods of impact assessment will be appropriate. It is likely that a *mix of approaches* will lead to the most robust set of results for a given area.

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[1] See <http://cwrr.ukzn.ac.za/acru>.

Box 7-1

Common models and tools used for climate change applications in the agricultural sector

(see table 7-1 for a detailed description of the models and tools)

Agronomic models[a]

- DSSAT (Decision Support System for Agrotechnology Transfer)
- APSIM (Agricultural Production Systems Simulator)
- WOFOST (World Food Studies)
- EPIC (Erosion Productivity Impact Calculator)
- AquaCrop
- CENTURY
- ORYZA 2000
- AgroMetShell
- Local Climate Estimator (New_LocClim)
- FAOClim 2.0
- CLIMWAT 2.0
- CROPWAT

Economic models

- TOA-MD (Tradeoff Analysis Model for Multi-Dimensional Impact Assessment)
- Microeconomic models: reduced-form econometric models
- Microeconomic models: structural-form econometric, optimization and simulation models
- Economic land-use models
- Partial and general equilibrium economic models
- Regional and global integrated assessment models

a. See Pinto et al., 2008 for more information on these models.

7.3.2. Limitations and sources of uncertainty

Climate change scenarios. Climate change scenarios are derived from global climate models (GCMs) driven by changes in the atmospheric composition of greenhouse gases (GHGs), derived from different representative concentration pathways (RCPs) depending on future gas emissions scenarios (see chapter 4). A main challenge is how to interpret the results derived from the climate scenarios and apply them to sector impact studies, such as agriculture. In all regions, uncertainties with respect to the magnitude of expected changes result in uncertainties in the potential impact on both crop and livestock production. For example, in some regions, projections of rainfall, the main input variable for rain-fed cropping systems, could either be positive or negative, depending on the climate scenario used. The uncertainty derived from the climate model is related to the limitation of current models to represent all atmospheric processes and interactions of the climate system. In addition there is the uncertainty associated with future GHG emissions.

Climate variability. Regional climates naturally fluctuate about the long-term mean, which changes over time. For example, rainfall variability occurs with regard to timing and quantity, affecting agriculture each year. Much of the historical variability that has occurred in the past will continue to occur, with climate change modifying these variability patterns (e.g. resulting in changes in the number and intensity of droughts and floods that have to be carefully assessed in any impact assessment), particularly with respect to changes in future rainfall patterns. In addition, many regions across the globe are impacted by the El Niño Southern Oscillation (ENSO) and other sea-surface temperature anomalies that causes short-term changes in seasonal weather. In general, agriculture is more susceptible to the occurrence of extremes, such as drought and floods or heat or frost events, versus a gradual change in local weather conditions.

Agricultural models. Agricultural models contain many simple, empirically derived relationships that do not completely represent actual plant processes. When models are adequately tested against observed data (calibration and validation process), the results represent agricultural output under current climate conditions. Nevertheless, the simplifications of the crop models are a source of uncertainty of the results. For example, agricultural models in general assume that weeds, diseases and insect pests are controlled; that there are no problem soil conditions, such as high salinity or acidity; and that there are no catastrophic weather events, such as heavy storms. The agricultural models simulate the current range of agricultural technologies available worldwide. They do not include potential improvements in such technology, but can be used to test the effects of some potential improvements, such as improved varieties and irrigation schedules. A range of agricultural models are used widely by scientists, technical extension services, commercial farmers and resource managers to evaluate agricultural alternatives in a given location under different conditions (e.g. drought years, changes in policy regarding application of agrochemicals, changes in water input, among other conditions).

Effects of carbon dioxide on crops. Carbon dioxide (CO_2) is a component of plant photosynthesis and therefore influences biomass production. It also regulates the opening of plant stomata and therefore affects plant transpiration. As a result, in theory, plants growing in conditions of increased CO_2 will produce more biomass and will consume less water. Experiments in greenhouses confirm this. C3 crops such as wheat, rice and soybean respond more to increased CO_2 levels compared with C4 crops such as maize.[2] Nevertheless, because of the multiple interactions of physiological processes, actual changes are smaller than the theoretical ones. In field conditions, the changes are even smaller. Most of the crop models used for climate change evaluations include an option to simulate the effects of CO_2 increase on crop yield and water use (Rosenzweig and Iglesias, 1994, 1998). However, it is difficult to evaluate the crop model results because there are only a limited number of these experiments worldwide, raising uncertainty about the simulated results.

Issues of aggregation and scale. Scaling-up the V&A results to a regional level is, as in most scaling exercises, not an easy task. Ideally, it is possible to use information from farms that are representative of agriculture in the region. However, the degree of their representativeness would need to be established. More frequently, regional assessments have relied on the input provided by regional planners and economists as to regional-scale effects, based on local data supplied to them and discussed by a full range of stakeholders.

Socioeconomic projections. The limitations of projecting socioeconomic changes affect not only the socioeconomic scenarios but also the potential adaptive capacity of the system. For example, uncertainty about population changes (density, distribution, migration), gross domestic product (GDP) and technology, determines and limits the potential adaptation strategies that can be employed (see chapter 3 for further information on the development of socioeconomic scenarios).

7.3.3. Combining climate change scenarios with agricultural tools and models

Given the uncertainties of the scenarios (magnitude of change and sometimes direction of change), a good approach is to use several possible scenarios as inputs for the agricultural models. In addition to the use of several scenarios, the use of crop model ensembles is also encouraged (Rotter et al., 2011). Other approaches include sensitivity scenarios combined with agricultural models (e.g. changes in temperature up to +3°C and changes in precipitation from –30% to +30%), which can provide an idea of the tolerable thresholds of change for a particular system.

One method shown to be effective for generating climate change scenarios is to study the changes in the last few decades and then project those changes into the near future. For example, divide the long-term climate database of one region (or site) into two periods (e.g. 1930–1970 and 1970–2010). The longer the period, the easier it will be to identify the change in long-term climate versus short-term climate variability. It is possible to study the statistical climate properties of each one of those two datasets (means, but also frequency, of dry spells, of storms, probability of subsequent days with rainfall, and so on).

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[2] Plants need CO_2 for carbon fixation or photosynthesis in order to produce carbohydrates. In general a higher concentration of CO_2 increases plant biomass growth. There are two different pathways for carbon fixation, referred to as C_3 and C_4 photosynthesis.

This can be done with ‘weather generators.’ The last step is to continue (project) the trend observed in all these statistical parameters and create a synthetic scenario for the near future (e.g. 10–20 years). However, the best approach is to partner with a climate scientist who has significant expertise in local climate variability and climate change.

In addition to performing statistical analysis of climate trends, the output of regional climate models (RCMs) such as Providing Regional Climates for Impacts Studies (PRECIS; see chapter 4) can be used as input data for the crop simulation models listed in table 7-2. Daily time series of maximum and minimum temperature, precipitation and solar radiation from RCM experiments can be used, for instance, as the Decision Support System for Agrotechnology Transfer (DSSAT) input weather file and the desired crop yield changes can be modelled to a future timeframe.

Table 7-2

Most common crop models used for simulation applications, including those related to climate change impact and adaptation assessment

Crop	Model
Generic	AquaCrop – specific parameters for many crops (<http://www.fao.org/home/en/>)
Generic	WOFOST – specific parameters for maize, wheat, sugar beet and other crops (<http:// www.wageningenur.nl>)
Generic	EPIC – specific parameters for maize, soybean, wheat and other crops (<http://epicapex.tamu.edu/>)
Generic	CropSyst – specific parameters for maize, wheat, potato and other crops (<http://modeling.bsyse.wsu.edu/CS_Suite_4/CropSyst/index.html>)
Generic	APSIM – specific parameters for maize, wheat, potato, rice and others crops (<http://www.apsim.info>)
Generic	DSSAT – specific models for different crops (see below; <http://dssat.net/>)
Barley	Cropping System Model (CSM)-CERES-Barley (DSSAT)
Cotton	CSM-CROPGRO-Cotton (DSSAT), GOSSYM
Dry beans	CSM-CROGRO-Dry Bean (DSSAT)
Maize	CSM-CERES-Maize (DSSAT), CSM-CERES-IXIM (DSSAT)
Peanuts	CSM-CERES-Peanut (DSSAT)
Pearl millet	CSM-CERES-Millet (DSSAT)
Potatoes	CSM-SUBSTOR-Potato (DSSAT)

Crop	**Model**
Rice	CSM-CERES-Rice (DSSAT), ORYZA2000
Sorghum	CSM-CERES-Sorghum (DSSAT)
Soybeans	CSM-CROPGRO-Soybean (DSSAT), GLYCIM
Sugarcane	CSM-CANGRO (DSSAT)
Wheat	CSM-CERES-Wheat (DSSAT), APSIM-Wheat, AFRC-WHEAT, NWHEAT, SIRIUS

Note: See Pinto et al., 2008 for more information on these models.

7.3.4. Agroclimatic indices and geographic information systems

Simple agroclimatic indices combined with geographic information systems (GIS) have been used to provide an initial evaluation of both global agricultural climate change impacts and shifts in agriculturally suitable areas in particular regions. Agroclimatic indices are based on simple relationships of crop suitability to climate conditions (e.g. identifying temperature thresholds of a given crop or using accumulated temperature over the growing season to predict crop yields; Holden, 2001). This type of empirically derived coefficient is especially useful for broad-scale mapping of areas of potential impact.

When combined with a spatially comprehensive database of climate, crops and GIS, simple agroclimatic indices are an inexpensive and rapid way of mapping altered crop potential for quite large areas. Applying agroclimatic indices in Africa (Badini, Stöckle and Franz, 1997) has provided an understanding of the relationships among weather, soils and agricultural production systems and the complexities associated with their variability. Carter and Saarikko (1996) describe basic methods for agroclimatic spatial analysis.

7.3.5. Statistical models and yield functions

Complex multivariate models attempt to provide a statistical explanation of observed phenomena by accounting for the most important factors (e.g. predicting crop yields on the basis of temperature, rainfall, sowing date and fertilizer application). A possible weakness in their use for examining the impacts of future climate change is their limited ability to predict effects of climatic events that lie outside the range of present-day variability. Their use has also been criticized because they are based on statistical relationships between factors rather than on an understanding of the important causal mechanisms.

Multiple regression models have been developed to represent process-based yield responses to these environmental and management variables. Yield functions have been used to evaluate the sensitivity and adaptation to climate, for example, in China (Rosenzweig et al., 1999) and globally (Parry et al., 2004).

7.3.6. Process-based crop models

The aim of process-based models is to predict the response of a given crop to specific weather, soil, management and crop factors governing agricultural production. These models normally use simplified functions to express the interactions among crop growth, development and ultimately yield, and the major environmental factors that affect crops, especially weather and soil conditions, crop management and genetic characteristics. Process-based crop models are the most commonly used tool for climate impact assessments (White et al., 2011). Most model were originally developed as tools for optimizing crop management, particularly for providing information on the optimal amounts of input, such as irrigation, fertilizer and pesticides and the optimal timing of the application. Most of the crop models are embedded in decision support systems (DSS) to evaluate alternate management practices (Tsuji, Hoogenboom and Thornton, 1998). Dynamic crop models are available for most of the major food, feed and fibre crops. However, simulation models for specialty crops (such as vegetables, tree fruit, nuts, and so on) are less common. Although these models are able to simulate the impact of abiotic stresses, especially drought stress, very well, they are weak with respect to simulating the interaction with biotic stresses, such as pests, diseases and weeds.

DSSAT originated from the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project as a systems based approach for addressing food security in developing countries. The original DSSAT software included crop models for maize, wheat, rice, peanut and soybean. The software has advanced over the years and its simple user interface has made it relatively easy to use for climate change studies by non-modellers (Jones et al., 2003; Hoogenboom et al., 2014). More information about DSSAT can be found in box 7.2. DSSAT has been one of the main crop modelling systems that has been used extensively in the Agricultural Model Intercomparison and Improvement Project (AgMIP; see box 7-3).

Box 7-2

Description of DSSAT

DSSAT is a DSS that encompasses process-based computer models that predict growth, development and yield as a function of local weather and soil conditions, crop management scenarios and genetic information.

The crops that are covered include: grain cereals such as rice, wheat, maize, barley, sorghum and millet; grain legumes such as soybean, peanut, dry bean and chickpea; tuber crops such as potato and cassava, cotton, sugarcane and vegetables; and various other species (see table 7-2). DSSAT also includes a basic set of tools for the preparation of the input data, as well as application programmes for seasonal, crop rotation and spatial analysis. The crop models not only predict crop yield, but also resource dynamics, such as for water, nitrogen and carbon, and environmental impact, such as nitrogen leaching. DSSAT includes an economic component that calculates gross margins based on harvested yield and by-products, the price of the harvested products, and input costs.

The models use daily weather data, soil profile information and basic crop management data as input. Model outputs are normally compared with local experimental data in order to evaluate model performance and determine the genetic characteristics of local varieties.

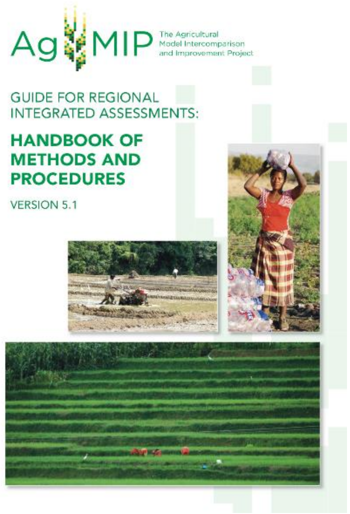
DSSAT can be used at a farm level to determine the impact of climate change on production and potential adaptation practices that should be developed for farmers. It can also be used at a regional level to determine the impact of climate change at different spatial scales, the main consideration being availability of accurate input data. DSSAT can be used for any region across the world, as long as the local input data are available.

DSSAT has been distributed to over 6,000 users in more than 120 countries and has been tested in most regions of the world. DSSAT has been used extensively for impact assessment and adaptation to climate change. The software is supported through the DSSAT Foundation and the most recent version of DSSAT is available as a free download from the DSSAT portal (see <http://dssat.net/>). Workshops are held on a regular basis to provide in-depth training on the proper use and application of DSSAT and its associated crop simulation models.

Box 7-3

AgMIP

AgMIP[a] is a new global community of scientists who are working to improve agricultural systems models and their use for climate impact assessment and analysis of agricultural system sustainability (Rosenzweig et al., 2015). Teams within AgMIP are addressing the many data, methodological and modelling issues related to the use of agricultural systems models. Of particular interest to climate impact assessment are:



AgMIP The Agricultural Model Intercomparison and Improvement Project

GUIDE FOR REGIONAL INTEGRATED ASSESSMENTS:

HANDBOOK OF METHODS AND PROCEDURES

VERSION 5.1

New regional integrated assessment methods. AgMIP's team of climate scientists, crop and livestock modellers, economic modellers and information technology (IT) experts have developed a new approach to regional integrated assessments that provides a consistent, protocol-based approach to climate impact, adaptation and vulnerability assessment (see figure 7-1). The approach utilizes documented, publicly available data tools and models, together with region-specific socioeconomic pathways and scenarios. These methods are summarized in the *Handbook of Methods and Procedures*[b] (This approach has been implemented successfully by multi-disciplinary teams in Africa, South Asia, the United States, Europe and Latin America. AgMIP and its partners can provide training in the use of the data tools and models, including the DSSAT and APSIM crop models and the TOA-MD economic impact assessment model[c]

Representative agricultural pathways (RAPs). AgMIP has developed methods that can be used by global and regional impact assessment researchers to create agriculture-specific pathways that can be linked to the global pathways and scenarios.[d]

Global integrated assessment. AgMIP's global economics team carried out the first systematic intercomparison of global agricultural economics models (see Nelson et al., 2014), and is continuing to improve those models and develop agriculture-specific pathways and scenarios that link to the new shared socioeconomic pathways (SSPs; see chapter 3).

Global gridded crop and livestock models. AgMIP's global gridded crop modelling team is working with experts around the world to improve the use of crop models with the globally gridded soil and climate data that are used in global climate impact assessments. A new set of studies was published in the *Proceedings of the National Academy of Sciences* in 2014 (Rosenzweig et al., 2014) and work by this team continues to improve the application of crop models to climate impact assessments.

[a] <http://www.agmip.org/>.

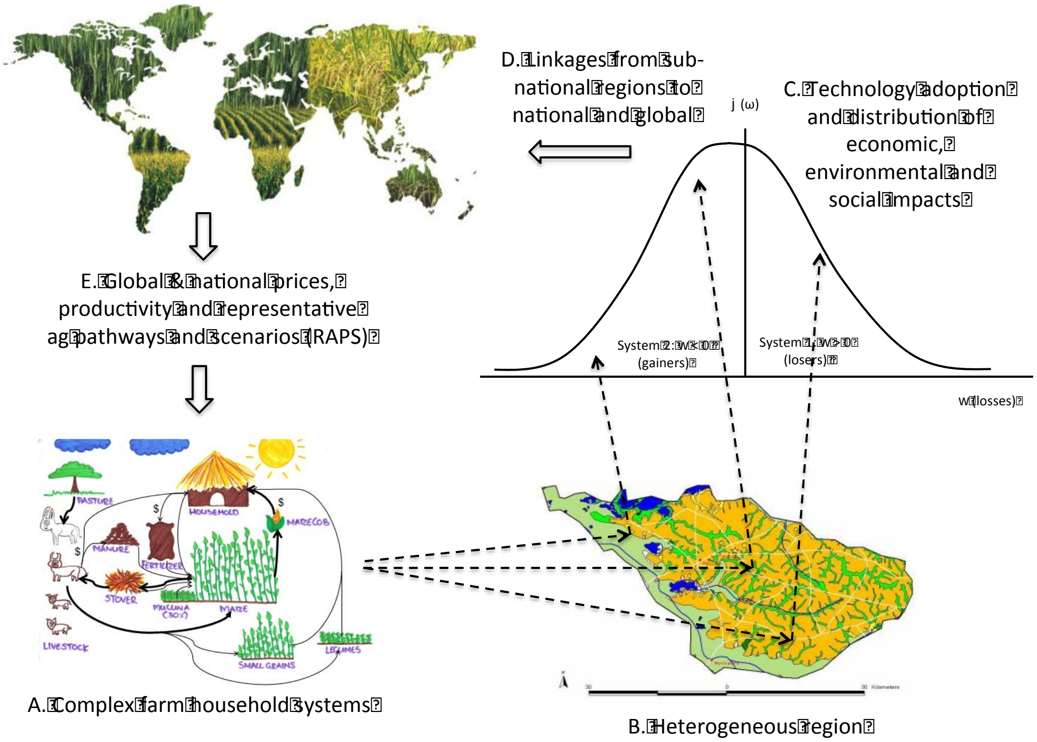
[b] available at <http://www.agmip.org/regional-integrated-assessments-handbook/#>.

[c] <http://tradeoffs.oregonstate.edu/>; also see <http://www.agmip.org/economics-team/>.

[d] The methods are described in Valdivia et al. (2015) and at <http://www.agmip.org/representative-agricultural-pathways/>.

Figure 7-1

AgMIP regional integrated assessment framework



Climate change impacts, adaptation and vulnerability assessments are linked across scales, from the field and farm scale (A) (from Masikati et al., 2015) to the landscape/sub-country scale (B), leading to analysis of technology adoption and impact assessment in heterogeneous farm household populations (C). This regional analysis may feed back to the country and global scales (D). The entire analysis uses consistent inputs and assumptions from global and national price and productivity projections and RAPs (E).

Source: Antle et al., 2015.

APSIM is another commonly used crop simulation model that is used across the globe and also has been one of the main crop modelling systems that has been used extensively in the AgMIP Project. The WOFOST model suite was also originally developed to study agricultural production across the globe. It is a very generic model and includes model parameters for a range of important agricultural crops (Supit, Hooijer and van Diepen, 1994; Boogaard et al., 1998). The EPIC model (Sharpley and Williams, 1990) incorporates simplified crop growth functions that respond to climate, environment and management. It has been used in some climate impact assessments, especially in the United States of America. AquaCrop is a crop model developed by the Food and Agriculture Organization of the United Nations (FAO) to simulate yield response to water. It has also been used extensively in developing countries, partially through training workshops supported by FAO and other organizations.

Table 7-2 summarizes the main crop models that have been used for evaluating potential impact and adaptation to climate change. Rosenzweig and Iglesias (1998) provided some initial guidelines for using crop models in climate change impact studies.

Box 7-2 provides additional information on DSSAT as an example of a crop-specific family of models, and box 7-4 provides additional information on CROPWAT as an example of a generic and simple model.

Box 7-4

Description of CROPWAT

CROPWAT is a Windows-based decision support tool developed by the Land and Water Development Division of the FAO. CROPWAT is used to perform standard calculations for evapotranspiration and crop water-use studies, particularly the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices and the planning of irrigation schedules under varying water supply conditions. CROPWAT 8.0 can also be used to estimate crop performance under both rain-fed and irrigated conditions. All calculation procedures used in CROPWAT 8.0 are based on the two FAO publications in the Irrigation and Drainage Series, namely,. Allen, Pereira, Raes, and Smith, 1998) and No. 66, *Crop yield Response to Water (*Steduto, Hsiao, Pereira. And Raes, 2012

The tool can be applied for testing the efficiency of different irrigation strategies (e.g. irrigation scheduling, improved irrigation efficiency) under climate change conditions. The simulation of the direct effects of changing atmospheric CO_2 concentrations on crop water use is beyond the scope of the tool. The tool requires climatic and crop data (available from the CLIMWAT database, included with the tool) for calculations of crop water requirements and irrigation requirements. The development of irrigation schedules and the valuation of rain-fed and irrigation practices are based on a daily soil-water balance using various options for water supply and irrigation management conditions.

CROPWAT for Windows and its manual are available from the FAO portal (<http://www.fao.org/nr/water/infores_databases_cropwat.html>).

Crop simulation models have been used extensively for climate change studies. White et al. (2011) reviewed 211 peer-reviewed papers that mainly examined the response to climate change of wheat, maize, soybean and rice (170 papers), with the United States (55 papers) and Europe (64 papers) as the dominant regions. The results of climate change studies that have been published in peer-reviewed papers to date are rare.

AgMIP has been able to provide financial support through t**he UK Department for International Development's (DFID)** to conduct scientifically sound climate change studies for various regions in West, East and South Africa, as well as in Pakistan, India, Bangladesh, Nepal and Sri Lanka (Rosenzweig et al., 2015). Although the overall approach was centred around crop simulation models, especially the DSSAT and APSIM suite of crop models, the AgMIP methodology was carefully integrated with climate change scenarios provided by local climate scientists, and socio-economists for the economic components and linkages to economic models. In order for the studies to be comparable, a handbook was developed that provided detailed procedures on data collected, modelling, and analysis. Further details can be found in box 7-3. The results of the study were published in two volumes of the series, *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments* (Rosenzweig and Hillel, 2015).

7.3.7. Calibration and evaluation of crop models

In the application of crop models as tools for assessing V&A to climate change, stakeholder participation is essential. A mandatory first step is that technical stakeholders assemble local agricultural data for the calibration and evaluation of crop models. Then regional stakeholders evaluate the representativeness of agricultural model results to facilitate spatial up scaling of the model results.

In all numerical models, including agricultural models, the procedure involves adjusting coefficients that describe crop characteristics and responses to environmental conditions. Table 7-3 summarizes the steps involved in calibrating and evaluating agricultural models with specific references relevant to the DSSAT crop simulation models, as an example. Most crop simulation models include a set of parameters and coefficients that are normally not adjusted by the model user, unless they are very experienced. However, one of the main unknowns for many crop models is the characteristics of the local variety, cultivar or hybrid. For most crops, new varieties and hybrids are released annually, and for model developers it is a challenge to provide these with the crop models. Therefore, it is highly recommend that users adjust these cultivar coefficients, sometime referred to as ‘genetic’ coefficients, to ensure that the crop simulation model accurately simulates a locally representative cultivar.

Table 7-3
Summary of steps for calibration and evaluation of crop models

Step	Concept/procedure	Example
1. Calibrate crop phenology	The crop developmental stage determines how the biomass is accumulated and to which organ of the plant growth is directed. First adjust the reproductive development coefficients so that the simulated flowering date matches the observed flowering date; then adjust the next set of coefficients so that simulated physiological maturity date matches the observed maturity date from the field data.	In the CSM-CERES-Maize model, this is described by the coefficients P1 (thermal time from seedling emergence to the end of the juvenile phase), P2 (extent to which development is delayed for each hour increase in photoperiod) and P5 (thermal time from silking to physiological maturity). By adjusting these coefficients, simulated crop development should match observed crop development.

Step	Concept/procedure	Example
2. Calibrate vegetative growth and biomass	The leaf area index (LAI) and above-ground biomass determine light capture and potential photosynthetic rates. Adjust the vegetative growth and development coefficients so that the simulated maximum LAI and total biomass match the observed data.	In the CSM-CERES-Maize model, the PHINT (phyllochron interval) is the only cultivar coefficient that handles vegetative growth.
3. Calibrate grain production	The adequate rate and quantity of reproductive accumulation determines final crop productivity. Adjust the reproductive growth coefficients so that the simulated grain yield and yield components match the observed data.	In the CSM-CERES-Maize model, this is described by the coefficients G2 (maximum possible number of kernels per plant) and G3 (kernel-filling rate during the linear grain-filling stage and under optimum conditions).
4. Evaluate the calibrated model	Ensure that the crop model can predict the yield accurately for similar conditions based on the calibrated cultivar coefficients. Determine if the simulated flowering and maturity dates and grain yield represent data collected from farmers' fields or similar experiments.	Well-calibrated models should always simulate correctly the dates of crop maturity. Simulated yields may be higher than the ones observed on farms, but they should represent the geographic variation of farm yields arising from different soils or management conditions.

In the DSSAT models, the coefficients that need to be adjusted are included in a file of 'genetic coefficients' that conceptually represent each crop variety. A file with cultivar coefficients for each crop based on a limited set of field experiments is included with the software. These coefficients are only a starting point; they should be further adjusted during the calibration process to represent crop growth and development of the selected variety under the climate and management conditions of the particular area. The cultivar coefficients that describe each variety represent the phenology or time of developmental phases, such as juvenile stage, flowering or anthesis, beginning grain or seed fill, and physiological maturity, and the accumulation of dry matter for the different organs (e.g. roots, leaves, stems, reproductive structures such as grain and seed). These coefficients only represent a limited number of characteristics of each crop variety with the ultimate goal being able to simulate growth and development and, ultimately, yield and yield components fairly accurately.

7.3.8. Coupling crop models and statistical models for yield response

Process-based models provide the means to derive information of crop response to climate and management when experimental data are not available (Hansen and Jones, 2000; Iglesias, Rosenzweig and Pereira, 2000; Porter and Semenov, 2005; Steduto et al., 2009; Lobell and Burke, 2010). However, crop simulation models are data intensive, including daily weather data, local soil characteristics and the definition of crop management. In many cases data constraints can limit the use of models to those sites where the information necessary for calibration is available.

An alternative methodology is to simulate crop responses to climate and management using dynamic crop simulation models such as DSSAT for a selected set of representative sites. The resulting output can then be used to define statistical models of yield response for each site. This approach has proven useful for analysis in China (Rosenzweig et al., 1999), Spain (Iglesias, Rosenzweig and Pereira, 2000; Iglesias and Quiroga, 2007; Quiroga and Iglesias, 2009), and globally (Parry et al. 2004; Rosenzweig et al., 2004; Lobell and Burke, 2010). Variables that explain a significant proportion of simulated yield variance are crop water (sum of precipitation and irrigation) and temperature over the growing season. The functional forms for each region represent the realistic water limited and potential conditions for the mix of crops, management alternatives and potential endogenous adaptation to climate assumed in each area. This methodology: expands process-based crop model results over large areas and therefore overcomes the limitation of data requirements for process-based crop models; includes conditions that are outside the range of historical observations of crop yield data; and includes simulations of optimal management and, therefore, estimates agricultural responses to changes in regional climate.

7.3.9. Gridded modelling

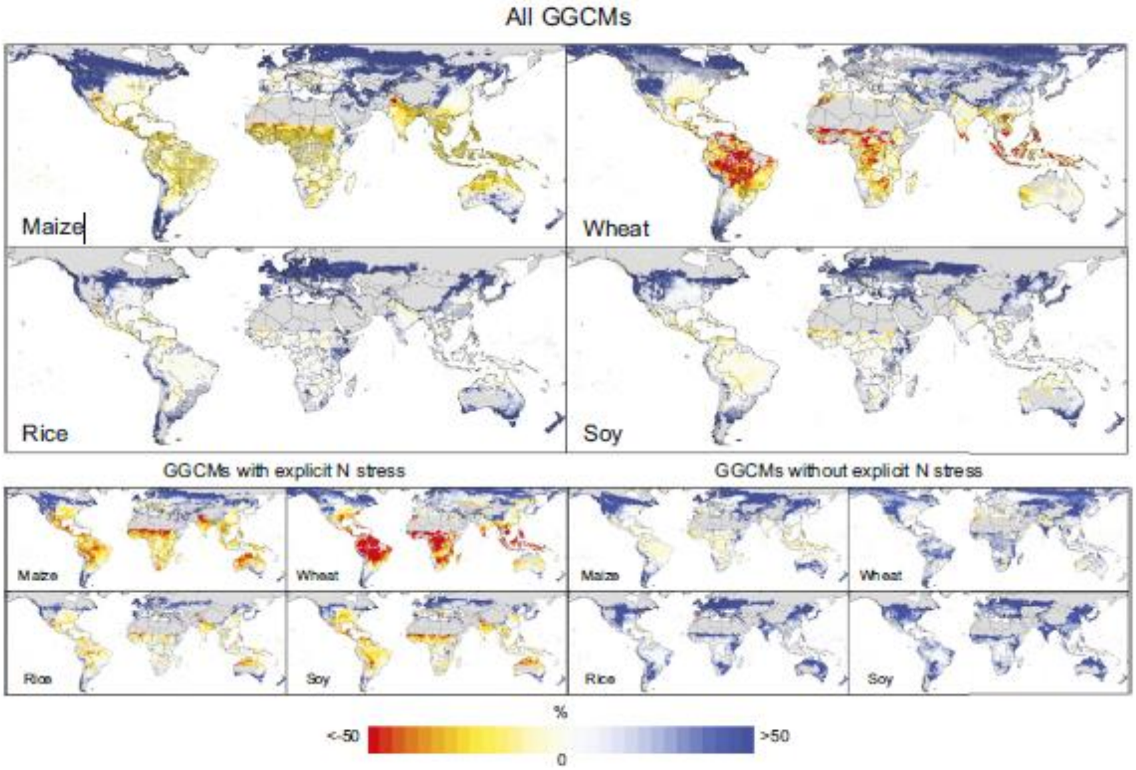
With the rapid increase in computer power, both for high-performance computers (HPCs) as well as for personal computers, simulations using complex dynamics simulation models can be more easily conducted. Where previously it took more than five minutes to simulate a growing season from planting to harvest now this can easily be completed in less than one second. As such, the potential for applications has expanded. One issue that has faced users of crop simulation models is that these models are point-based systems, making it rather difficult to address policy questions at a regional or national scale, such as with respect to climate change policy setting. An approach has recently been developed in which the crop models are run for a fixed spatial area, sometimes referred to as a grid. It is assumed that the conditions within the grid (including crop management, land use, weather conditions and soil surface and profile characteristics) are the same or uniform. However, the conditions for each individual grid can be unique. This then makes it possible to scale up the outputs from each individual grid to a regional scale and allow for regional assessments. The size of the grid can vary and is defined by the availability of input data for the environmental conditions, including weather and soil, crop management and land use. It is also somewhat limited with respect to the computer power that is available to the user.

The Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) was one of the first projects to assess climate change impact at a global level for different sectors using a gridded approach. AgMIP contributed to the agricultural crop modelling component to this effort (Rosenzweig et al., 2014), with a global summary (shown in figure 7-2) that includes simulations made with DSSAT, EPIC and PEGASUS. Additional efforts with the global gridded agricultural community have resulted in the AgMIP GRIDded Crop Modeling

Initiative (AgGRID) and the Global Gridded Crop Model Intercomparison (GGCMI) (Elliott and Müller, 2015).

Figure 7-2

Median yield changes (%) for RCP8.5 (2070–2099 in comparison to 1980–2010 baseline) with CO_2 effects over all five GCMs x seven GGCMs (6 GGCMs for rice) for rain-fed maize (35 ensemble members), wheat (35 ensemble members), rice (30 ensemble members), and soy (35 ensemble members)



Grey areas indicate historical areas with little to no yield capacity. The bottom eight panels show the corresponding yield change patterns over all five GCMs x four GGCMs with nitrogen stress (20 ensemble members from EPIC, GEPIC, pDSSAT and PEGASUS; except for rice which has 15) (Left); and 3 GGCMs without nitrogen stress (15 ensemble members from GAEZ-IMAGE, LPJ-GUESS and LPJmL) (Rosenzweig et al., 2014).
Abbreviation: GGCM = gridded global crop model.

7.3.10. Economic models

Various economic models have been utilized to project the potential impacts of climate change, at various spatial and temporal scales, ranging from the farm level to global, for single growing seasons and over multi-year periods. Some models are strictly empirical, while others link some type of economic model with biophysical models. Another distinction is between microeconomic models that take prices as givens, versus market models that determine prices.

Reduced-form econometric models

Reduced-form econometric models are based on the idea that adaptive responses to climate change can be represented by equations that relate climate variables directly to economic outcomes such as land values, farm revenue, crop yields or farm net returns. These models are estimated econometrically using cross-sectional or panel data (pooled cross-section and time series), and are then simulated using future projected climate variables, to project impacts of climate change on the dependent variable in the model (Mendelsohn, Nordhaus and Shaw, 1994; Schlenker, Hanemann and Fisher, 2005; Deschenes and Greenstone, 2007; Mendelsohn and Dinar, 2009). Some economists argue that these models effectively represent the various economic adjustments or adaptations that occur in response to climate change, and can be interpreted as a type of 'analog' approach to climate impact assessment. There has been extensive critical discussion in the literature over the pros and cons of this approach (e.g. Schlenker, Hanemann and Fisher, 2006; Fisher et al., 2012; Ortiz-Bobea and Just, 2013).

There are significant limitations of reduced-form models:

- They do not represent many of the outcomes of interest to policy decision makers such as price changes;
- They cannot account for unobserved changes in environmental conditions, such as CO_2 fertilization;
- They do not represent costs of adaptation and cannot be used to estimate the effects of adaptation distinct from the effects of climate change; and these models implicitly hold prices and all other non-climate factors constant, and cannot account for the effects of possible changes in socioeconomic conditions.

Various studies have shown that the impacts of climate change may be very different under changing socioeconomic conditions, and that changes in socioeconomic conditions may be at least as important, if not more important, to future outcomes as climate change (Parry, Rosenzweig and Livermore, 2005; Parry et al., 2007; Nelson et al., 2009; Claessens et al., 2012; Porter et al., 2014).

Recent reduced-form econometric studies include:

- Kelly, Kolstad and Mitchell (2005), which provides one of the first analyses of how total farm profits are affected by both climate and unexpected weather;
- Schlenker, Hanemann and Fisher (2006), which uses a 30-, 15- and 10-year moving average of weather variables to estimate impacts of climate change on farm land values; and
- Deschenes and Greenstone (2007), which uses growing-season degree days and total precipitation to examine climate effects on farm net returns. More recently, Deschenes and Kolstad (2011) propose a model to incorporate both weather and a five-year moving average of weather variables as a proxy for expected weather or climate in farmers' decisions for agricultural production.

Microeconomic structural models: econometric, optimization and simulation

There are various types of economic models that can be used for farm-level and regional impact assessment, including; structural econometric models; farm-level and regional optimization models (e.g. Mérel and Howitt, 2014); and regional simulation models for technology adoption and impact assessment (e.g. Antle, 2011; Claessens et al., 2012). Some regional models are formulated on a commodity basis, while other models represent production of crops and livestock as integrated systems. Some models incorporate a household production component and non-agricultural, income-generating activities. These models can utilize variables from global models as inputs, notably prices, productivity and land use. However, global models do not project the level of detail needed for a number of important input variables (e.g. farm size, household size, family and hired labour use, cost of production) and thus many of these inputs must be projected into the future using pathways and scenarios (e.g. RAPs). Like global models, these regional models can be linked to biophysical crop and livestock production models to incorporate the effects of climate change on productivity. van Wijk et al. (2014) recently reviewed 126 farm-level and regional models.

As the name implies, structural models represent economic decision-making more explicitly than reduced-form models and can simulate resource allocation decisions with and without economic responses to climate change. The main disadvantages of these models, compared with reduced-form models, are increased data requirements and model complexity. Some of these models relate economic decisions directly to climate variables through econometric estimation, and some link biophysical process models to economic decision models. Seo and Mendelsohn (2008), Seo et al. (2009) and Seo (2010) use household survey data from South America, Africa and Latin America to examine the ways in which farmers adapt to climate change via switching crops or livestock species. Fleischer, Mendelsohn and Dinar (2011) use a cross-section of farms in Israel and observe that farmers can respond to climate change by modifying their technologies or management practices or both. Kaminski, Kan and Fleischer (2013) develop a structural land-use model wherein farmers maximize profit by allocating their land among crop-technology bundles as adaptation to climate change.

Antle et al. (2004) and Valdivia, Stoorvogel and Antle (2012) develop a spatially explicit, econometric-process simulation model that combines econometric production models and biophysical simulations to evaluate how economic adaptations on the intensive and extensive margins offset climate impacts. An important feature of these models is that, through their linkages to process-based models, they can account for biophysical responses to effects such as increased concentrations of atmospheric CO_2 on crop growth (so-called CO_2 fertilization), and as-yet unobserved temperature thresholds. The TOA-MD model (Antle and Valdivia, 2011) is a generic, documented, publicly available economic model designed for multi-dimensional assessment that can be used with various types of data, including biophysical simulations, to assess climate impact, adaptation, mitigation and vulnerability (e.g. see Claessens et al., 2012). The TOA-MD model is being used by the AgMIP across Africa and South Asia (see Rosenzweig and Hillel, 2015).

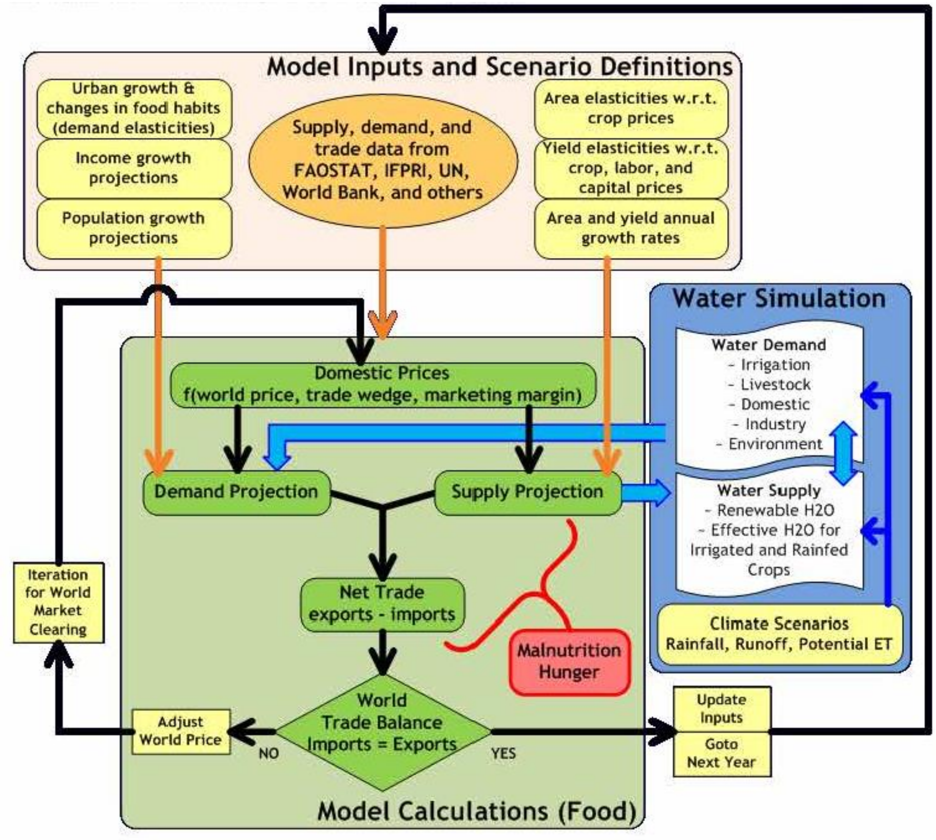
Land-use models

Many studies have investigated various drivers of land-use change using econometric models. For example, Wu et al. (2004) present an empirical modelling framework that uses spatially explicit data from the National Resources Inventory in the United States to assess the environmental and economic effects of incentive programmes on crop choices, crop rotations and the adoption of conservation tillage practices in the Midwest of the United States. Radeloff et al. (2012) use a similar model to project future land use for crop, pasture, range, forest and urban to the mid-century under alternative land-use policy scenarios. Mu, McCarl and Wein (2013) use a land-use model to assess the potential for climate change adaptation in the United States.

Market equilibrium models

Two types of economic model have been used for national and global assessments of climate impacts: partial equilibrium and computable general equilibrium models. A **partial equilibrium model** represents one or a few sectors of the economy, whereas **computable general equilibrium models** represent the entire economy, including linkages between sectors (manufacturing, agricultural, service, etc.) to produce economy-wide final outputs (e.g. van der Mensbrugghe, 2013). These models represent production according to spatial units that are typically subnational regions for large countries, or individual countries, and represent consumption and trade at national levels. They can simulate the effects of exogenous 'shocks' or changes in productivity, policy or other factors such as climate on various economic outcomes, including market equilibrium prices, production, productivity, consumption, trade and land use. For climate impact assessment, these models can be linked to biophysical simulation models and down-scaled climate data. For example, the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model, a partial equilibrium model developed by the International Food Policy Research Institute, is linked to a globally gridded version of the DSSAT crop simulation model (see figure 7-3); the GLOBIOM model developed by the International Institute of Applied Systems Analysis is linked to a globally gridded version of the EPIC model. Various models in the literature can produce substantially different projections of economic outcomes, suggesting substantial model uncertainty. Nine of the major partial equilibrium and computable general equilibrium models used for climate impact assessment were inter-compared (Nelson et al., 2014; von Lampe et al., 2014). A major new modelling project, MACSUR (<http://macsur.eu/>), is utilizing the various farm-level and regional partial equilibrium models developed in the earlier SEAMLESS project to assess climate change impacts in Europe.

Figure 7-3
Structure of the IMPACT modelling system developed by the International Food Policy Research Institute



Source: Rosegrant and IMPACT Development Team, 2012.

Box 7-5 describes a case study demonstrating application of the crop and economic models in Pakistan.

Box 7-5
Pakistan case study

AgMIP, funded by UK Aid, has been one of the first projects that has truly integrated climate change impact assessment and adaptation at the farm level. Most prior research projects have used a one-crop model with one or more climate change scenarios to estimate the potential impact of climate change on yield for one or more locations. In many cases proper management and local soil conditions were not sufficiently defined or were missing (White and Hoogenboom, 2010; White et al., 2011). In a majority of the cases, adaptation was also not considered and it was assumed that crop management practices for 2000 or 2010 were applicable to future crop production systems in 2050 or 2100. However, in reality, technology changes continuously as farmers adapt using new varieties and other management practices to improve the economic sustainability of their farming systems.

A comprehensive and integrated climate change assessment should be conducted at a country level for national programmes. However, the analysis can start at the farming systems level and then be scaled up. Although there is a tendency to run these analyses as a gridded scale (as shown in section 7.3.9), this does not address the uncertainty and variability associated with the individual operations of small-holder farmers. The following case study of the AgMIP regional integrated assessment, conducted by the AgMIP Pakistan project (Ahmad et al., 2015), is an example. Additional example case studies for representative countries in Sub-Saharan Africa and South Asia can be found in Rosenzweig and Hillel (2015).

Climate in Pakistan is very diverse, ranging from tropical to temperate, but with some arid conditions in the south. Weather extremes in the form of both floods and droughts are common and can affect a large portion of the population. For this case study, the province of Punjab, the largest province of Pakistan, was selected. It is considered one of the largest agricultural production systems in South Asia, covering 13.5 million hectares (ha). The rice-wheat cropping system is the bread basket of Punjab-Pakistan.

Using the protocols defined by AgMIP, as described in the *Handbook of Methods and Procedures* (discussed in box 7-3), an interdisciplinary team was formed in March 2012 that included meteorologists and climatologists from the Pakistan Meteorological Department (PMD) and scientists from the University of Agriculture (Faisalabad), Bahauddin Zakariya University (Multan), PMAS-Arid Agriculture University (Rawalpindi), and the COMSATS Institute of Information Technology (Vehari). The scientists had a range of specialties, including economics, extension, agronomy, crop modelling and computer science, and the main coordination was provided by the University of Agriculture.

Box 7-5 (cont.)
Pakistan case study

The rice-wheat cropping system spans five districts in Punjab-Pakistan and encompasses approximately 1.1 million ha. Rice is grown under flooded conditions by puddling the soil to force water to stand on the field. Rice is sown in nurseries, then transplanted during May and June and harvested from October to November. Wheat is planted following the harvest of rice, in some cases using the residual moisture from rice, from November through December. Some irrigation is applied during the wheat-growing season at critical growth stages to avoid extreme drought stress. Livestock also plays a critical role in this system, with fodder used as animal feed and farm yard manure returned to the field. In this study livestock was not dynamically modelled, but only used in the economic analyses. A simple representation of this farming system is shown in figure 7-4.

The crop models that were used in this study included the CSM-CERES-Wheat and CSM-CERES-Rice that are part of DSSAT Version 4.5 (Hoogenboom et al., 2010; Jones et al., 2003) and the APSIM model for wheat and rice (Keating et al., 2003). Using data that were collected in experiments conducted from 2000 to 2010, the models for wheat and rice were calibrated and evaluated. Both for wheat and rice there were three different cultivars. Following the calibration and evaluation, the models were also evaluated with the on-farm data (an example of the performance for rice for CSM-CERES-Rice and APSIM-Rice is shown in figure 7-5). Given that input information from individual farms was difficult to obtain, including local soil conditions, weather conditions and crop management, the results were very reasonable with a R^2 of 0.53 for CSM-CERES-Rice and 0.44 for APSIM-Rice, and a root mean squared error (RMSE) of 409 for CSM-CERES-Wheat and 440 for APSIM-Wheat.

The on-farm data used for model evaluation are one unique aspect of this case study. One hundred and fifty-five representative farms from the five districts were surveyed. Due to the heterogeneity of the small- hold farm population, each district was defined as its own stratum and two villages were selected from each district. In the survey, information related to planting date, cultivar, inputs for irrigation and fertilizer, yield and economics was requested. The average farm size was 4.5 ha, with the average yield of rice at 18,349 kg per farm (not per ha) and the average yield of wheat at 18,915 kg per farm. This information was then used for the model evaluation described previously (figure 7-5). Weather data from the nearest weather stations were provided by PMD.

Box 7-5 (cont.)

Pakistan case study

- Core Question 1: What is the sensitivity of the current agriculture management practices to climate change? This can be conducted by comparing System 1 and System 2.
- Core Question 2: What is the impact of climate change on future agricultural production? This can be addressed by comparing System 1 and System 3.
- Core Question 3: What is the impact of climate change on future agricultural production using adaptation management? This can be addressed by comparing System 3 and System 4.

In this analysis, interaction with stakeholders was critical. The stakeholders include not only farmers, but also policy makers and politicians, extension agents and various scientists with expertise in economics, plant breeding, irrigation, plant pathology, entomology and other related disciplines. For the Pakistan case study, two meetings were held with stakeholders to develop ‘story lines’ that define the future world and can be translated into quantitative information for modelling applications (i.e. RAPs). These relate not only to biophysical factors, but also to policy variables such as subsidies and price support, socioeconomic variables and others. The outcome of these discussions is shown in table 7-4 for an optimistic future scenario for the rice-wheat cropping system of Punjab.

To address the three core questions, simulations were conducted for each individual system, as described previously, using two simulation models for both crops. Daily weather data for 30 years, representing the base line, were provided for one location for each district by PMD. The crop models were then run for each of the 155 farms using the specific crop management information, soil inputs and 30 years of daily weather data to generate yield data for System 1. For the other three systems, PMD provided climate projection data for five CMIP5 GCMs, including CCSM4, GFDL-ESM2M, HadGEM2ES, MIROC5 and MIP-ESM-MR (Taylor, Stouffer and Meehl, 2012) using RCP8.5. For System 2, the same management was used as for System 1, but simulations were conducted using the climate data from each of the five GCMs. For System 3, the outcomes of the RAPs were used for crop management, while for System 4 different adaptation options were evaluated, including increasing the amount of nitrogen fertilizer applied, increasing planting or sowing density, decreasing the amount of irrigation applied and changing the planting date to an earlier date.

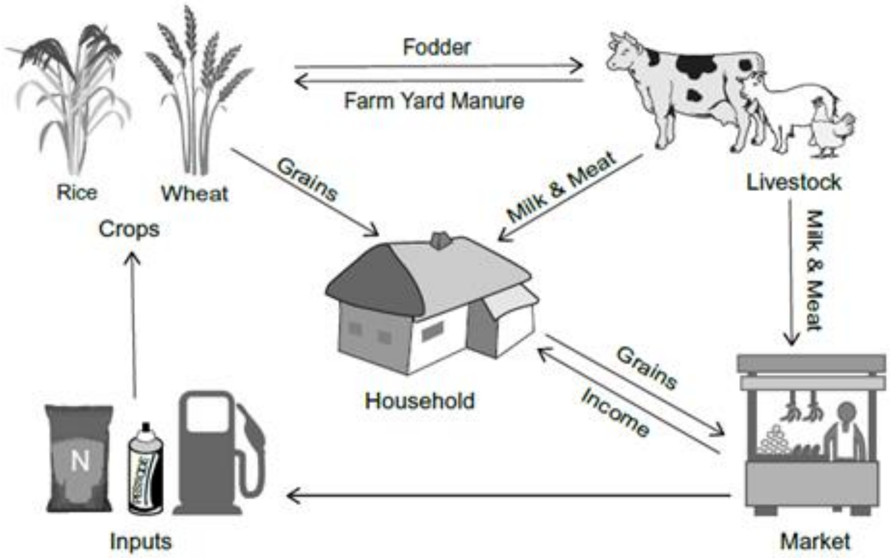
Box 7-5 (cont.)
Pakistan case study

Both the recorded yield data from the farm surveys and the simulated yield data from the crop models were used as input for the TOA-MD model. The outcome of the TOA-MD model is not a single number with respect to potential economic losses or gains, but a distribution. For instance, for Core Question 1, the reduction in wheat yield ranged from 6% to 19% for DSSAT and from 10% to 12% for APSIM, while for rice it ranged from 8% to 30% for DSSAT and from 14% to 19% for APSIM. Based on the economic analysis with TOA-MD, the share of famers worse off (‘losers’) under climate change ranged from 69% to 83% for DSSAT and from 72% to 76% for APSIM. The gainers, losers and net impact for both DSSAT and APSIM for all five GCMs for Core Question 1 are shown in figure 7-6. Using the RAPs for Core Question 2, the number of farmers who gained increased and who lost decreased, although the net impact is still negative (figure 7-7). Based on Core Question 3 (e.g. determining climate change impacts using adaptation scenarios based on an improvement in technology), the poverty rate is estimated to slightly decrease by 15–17% based on both the DSSAT and APSIM models, with the share of farmers implementing the adaptations mentioned above ranging from 69% to 74% for DSSAT and from 70% to 81% for APSIM).

As a final step, the rather detailed outcomes of the climate analyses, crop modelling analyses and TOA-MD analyses were summarized into a two-page document that can be quickly understood by politicians and decision makers at local, regional and national levels. This again is a new process that has rarely been adapted in previous climate change impact and analysis studies. The example for Pakistan is shown in figure 7-8.

Figure 7-4

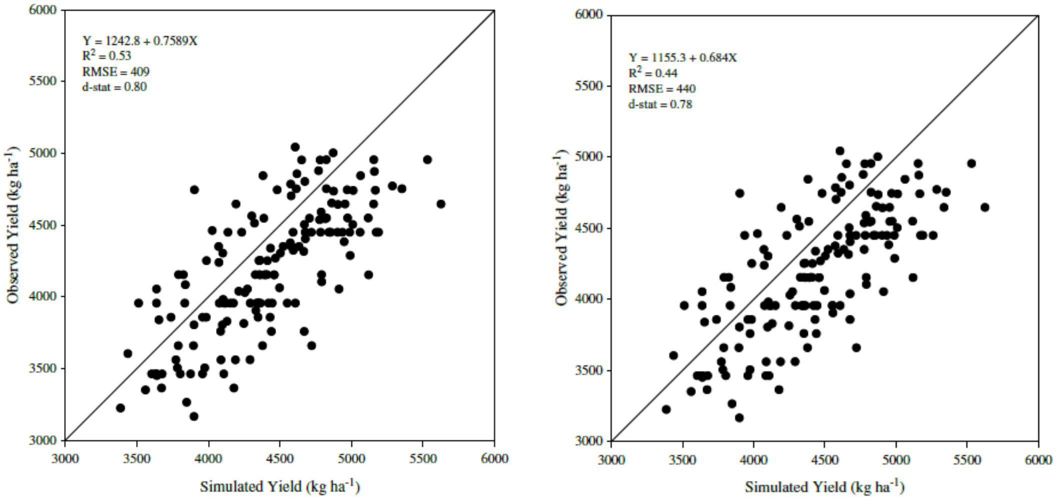
Rice-wheat farming system of Punjab, Pakistan



Source: Ahmad et al., 2015.

Figure 7-5

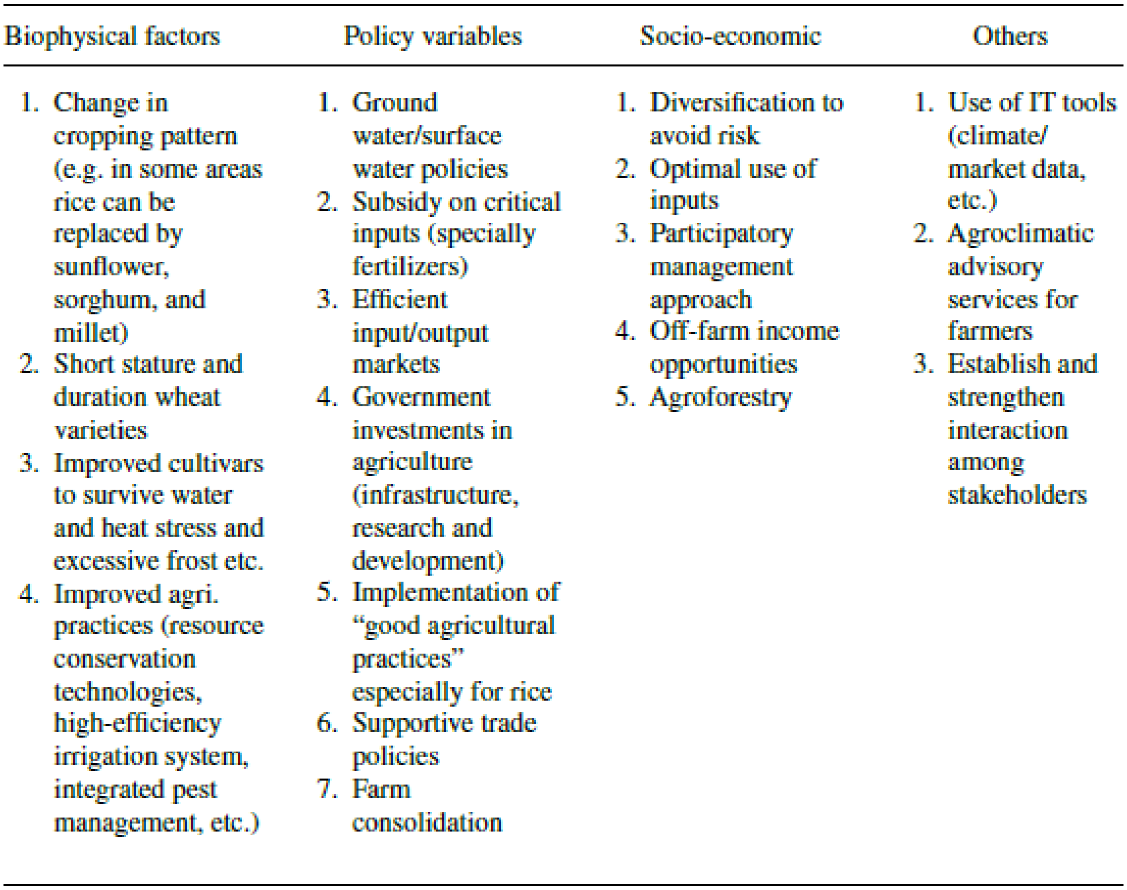
Comparison between observed and simulated yield for 155 farmers' rice fields for DSSAT (left) and APSIM (right)



Source: Ahmad et al., 2015.

Table 7-4

Key adaptation matrix under an optimistic scenario for the rice-wheat cropping system of Punjab



Biophysical factors	Policy variables	Socio-economic	Others
1. Change in cropping pattern (e.g. in some areas rice can be replaced by sunflower, sorghum, and millet) 2. Short stature and duration wheat varieties 3. Improved cultivars to survive water and heat stress and excessive frost etc. 4. Improved agri. practices (resource conservation technologies, high-efficiency irrigation system, integrated pest management, etc.)	1. Ground water/surface water policies 2. Subsidy on critical inputs (specially fertilizers) 3. Efficient input/output markets 4. Government investments in agriculture (infrastructure, research and development) 5. Implementation of "good agricultural practices" especially for rice 6. Supportive trade policies 7. Farm consolidation	1. Diversification to avoid risk 2. Optimal use of inputs 3. Participatory management approach 4. Off-farm income opportunities 5. Agroforestry	1. Use of IT tools (climate/ market data, etc.) 2. Agroclimatic advisory services for farmers 3. Establish and strengthen interaction among stakeholders

Source Ahmad et al., 2015

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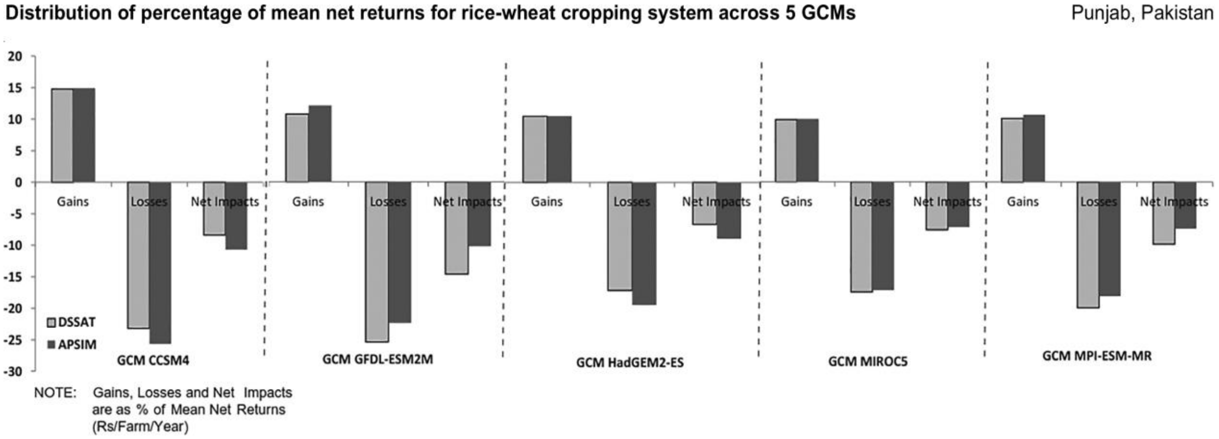
Figure 7-6

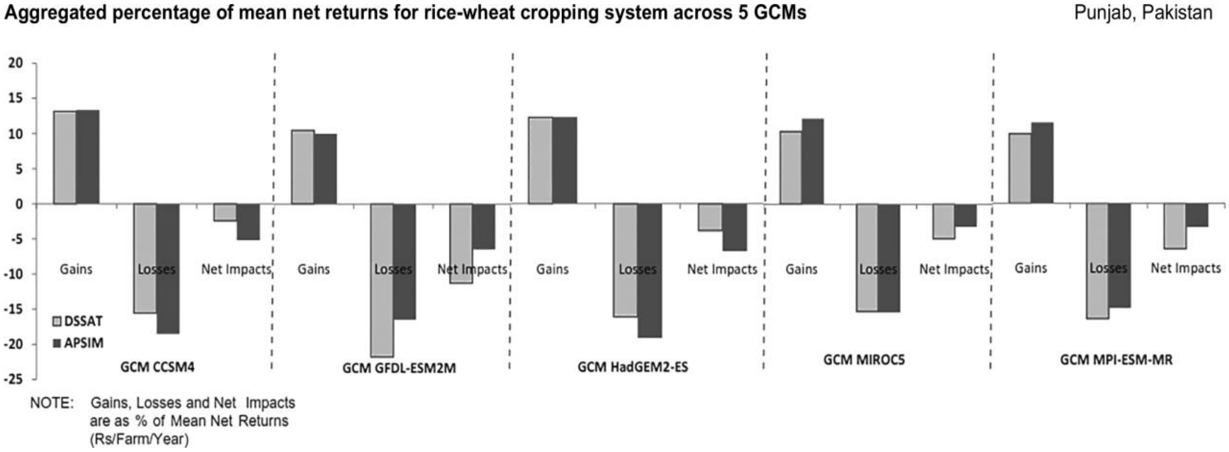
Distribution of gainers and losers (percentage) for five global climate models using DSSAT and APSIM crop models for the rice-wheat cropping system of Punjab, answering Core Question 1



Source: Ahmad et al., 2015.

Figure 7-7

Distribution of gainers and losers (percentage) for five global climate models using DSSAT and APSIM crop models for the rice-wheat cropping system of Punjab, answering Core Question 2



Source: Ahmad et al., 2015.

Figure 7-8

Policy brief for Punjab, Pakistan, based on the outcomes of Phase 1 of AgMIP

AgMIP The Agricultural Model Intercomparison and Improvement Project

Food Security in Punjab, Pakistan

Adapting rice-wheat farming to climate change

Harvesting rice in Pakistan.

Policy Brief
June 2014

Key Messages Punjab, Pakistan

Adaptations using different crop varieties and management practices can help reduce projected losses and poverty rates caused by increases in temperature and greater rainfall extremes.

CLIMATE

- **Climate change in the Pakistan Punjab** region is already occurring with **temperature increases of up to 1°C,** record-breaking floods, and drought.
- Temperatures are **projected to increase an average of 2°C** by 2050.
- **Heavy rainfall** and **increasing flooding** may occur during the wet seasons; **dry seasons could get drier.**

IMPACTS

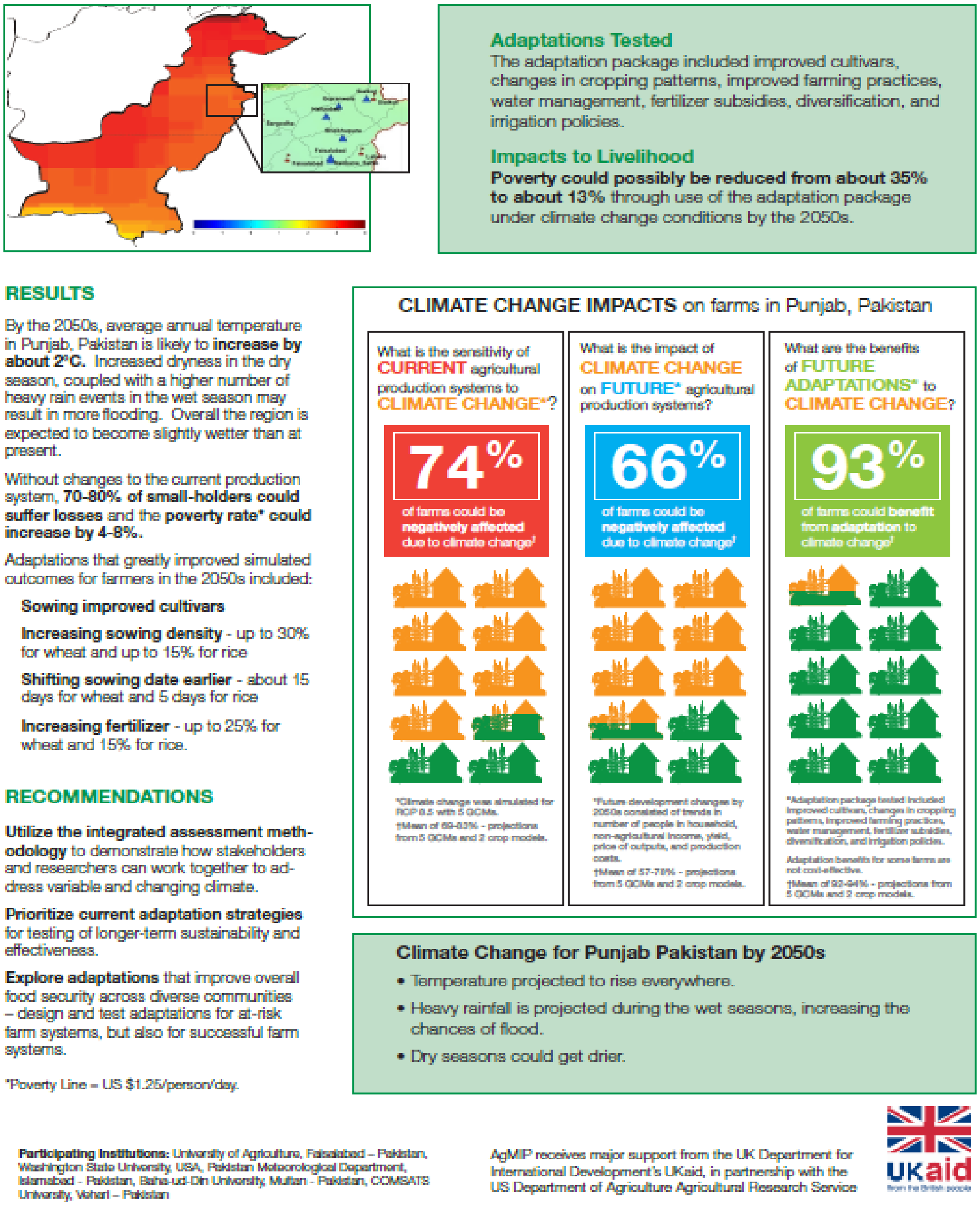
- **Major losses of irrigation water** for the Punjab area could result from Himalayan glacier melt.
- **Yields** trends of rice, wheat, and cotton **have recently plateaued,** partly due to changes in climate.
- **Rice yield losses** could range from **8-30%** and **wheat yield losses** could range from **6-19%** by 2050.
- Poverty might increase by about 6% due to climate change in the Punjab by 2050.

ADAPTATIONS

- The **adaptation package** evaluated consisted of new varieties, earlier sowing dates, increase in fertilizer, and higher sowing density.
- The models predict that the **majority of farmers** would likely **adopt** the simulated adaptation packages.
- **Additional adaptations could be tested** to understand how to mitigate the negative impacts of climate change.

Figure 7-9

Policy brief for Punjab, Pakistan, based on the outcomes of Phase 1 of AgMIP (courtesy of AgMIP)



Adaptations Tested

The adaptation package included improved cultivars, changes in cropping patterns, improved farming practices, water management, fertilizer subsidies, diversification, and irrigation policies.

Impacts to Livelihood

Poverty could possibly be reduced from about 35% to about 13% through use of the adaptation package under climate change conditions by the 2050s.

RESULTS

By the 2050s, average annual temperature in Punjab, Pakistan is likely to **increase by about 2°C.** Increased dryness in the dry season, coupled with a higher number of heavy rain events in the wet season may result in more flooding. Overall the region is expected to become slightly wetter than at present.

Without changes to the current production system, **70-80% of small-holders could suffer losses** and the **poverty rate* could increase by 4-8%.**

Adaptations that greatly improved simulated outcomes for farmers in the 2050s included:

Sowing improved cultivars

Increasing sowing density - up to 30% for wheat and up to 15% for rice

Shifting sowing date earlier - about 15 days for wheat and 5 days for rice

Increasing fertilizer - up to 25% for wheat and 15% for rice.

RECOMMENDATIONS

Utilize the integrated assessment methodology to demonstrate how stakeholders and researchers can work together to address variable and changing climate.

Prioritize current adaptation strategies for testing of longer-term sustainability and effectiveness.

Explore adaptations that improve overall food security across diverse communities – design and test adaptations for at-risk farm systems, but also for successful farm systems.

*Poverty Line = US $1.25/person/day.

CLIMATE CHANGE IMPACTS on farms in Punjab, Pakistan

What is the sensitivity of CURRENT agricultural production systems to CLIMATE CHANGE*?

74%

of farms could be **negatively affected** due to climate change†

*Climate change was simulated for RCP 8.5 with 5 GCMs.

†Mean of 69-83% - projections from 5 GCMs and 2 crop models.

What is the impact of CLIMATE CHANGE on FUTURE* agricultural production systems?

66%

of farms could be **negatively affected** due to climate change†

*Future development changes by 2050s consisted of trends in number of people in household, non-agricultural income, yield, price of outputs, and production costs.

†Mean of 57-78% - projections from 5 GCMs and 2 crop models.

What are the benefits of FUTURE ADAPTATIONS* to CLIMATE CHANGE?

93%

of farms could **benefit** from **adaptation** to climate change†

*Adaptation package tested included improved cultivars, changes in cropping patterns, improved farming practices, water management, fertilizer subsidies, diversification, and irrigation policies.

Adaptation benefits for some farms are not cost-effective.

†Mean of 92-94% - projections from 5 GCMs and 2 crop models.

Climate Change for Punjab Pakistan by 2050s

- Temperature projected to rise everywhere.
- Heavy rainfall is projected during the wet seasons, increasing the chances of flood.
- Dry seasons could get drier.

Participating Institutions: University of Agriculture, Faisalabad – Pakistan, Washington State University, USA, Pakistan Meteorological Department, Islamabad - Pakistan, Baha-ud-Din University, Multan - Pakistan, COMSATS University, Vehari – Pakistan

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UKaid
from the British people

Courtesy of AgMIP.

7.3.11. Information on datasets

Access to high-quality data is critical for any assessment and application study, including climate impact assessments, which will ultimately lead to new policies by decision makers. The amount and quality of the available data will affect the impact assessment, especially if time and funds are limited. Studies of the impacts of climate change on agriculture require a quantitative description of the study area, including current or baseline agricultural conditions –not only current climate data, but also information with respect to crop management, yield and socioeconomic information. Data are also needed for projecting future conditions in the absence of climate change, such as projected changes in agricultural technology and future prices and price support. Although specific data requirements will vary with the scope of the study and the method selected (this is discussed in more detail later), the type of data generally required and possible data sources are outlined in table 7-5. It is important to note that it is preferable to adopt a multi-disciplinary approach in which the discipline experts are responsible for obtaining the data. Overall this will strengthen the study and make the results and recommended outcomes more credible. In section 7.4 on integrated assessments, an AgMIP example is provided, in which national meteorologists, agricultural scientists, agronomists, economists, anthropologists and other scientists are successfully collaborating and have developed successful integrated assessments based on wide range of data.

Table 7-5
Summary of the datasets required and possible sources

Dataset	Possible sources	Comments
Experimental crop phenology, yield and yield components	At the local level, research and extension services of most agricultural universities or national research institutes of the Ministry of Agriculture	Necessary to calibrate the agricultural models; two years of data are acceptable; associated data on crop management is required.
Yield and typical management for the crops to be studied	At the local level, extension services or national statistic services of the Ministry of Agriculture	Annual data required to evaluate natural yield variability.
Climate data[a]	National Meteorological Service, National Climate Institutes, international organizations (e.g. World Meteorological Organization (WMO); UNFCCC; Climate Change, Agriculture and Food Security (CCAFS); others)	Preferably daily or monthly weather data are required to evaluate natural climate variability and to develop climate change scenarios.

Dataset	Possible sources	Comments
Soil characteristics	Ministry of Agriculture, international organizations (e.g. Food and Agriculture Organization of the United Nations (FAO); International Soil Reference and Information Centre (ISRIC))	Soil profile information, including texture to evaluate soil water holding capacity.
Production (both regional and national statistics)	At the regional level, agricultural yearbooks of the ministries of agriculture, international organizations	Time series required to evaluate natural production variability.
Crop management	At the local and regional levels, extension services of the ministries of agriculture, international organizations, stakeholder consultation	Include crop-sowing dates, crop varieties, labour, fertilizer and irrigation inputs.
Land use	Maps or digital images from the ministries of agriculture or the environment, satellite data from international organizations	Geographically explicit data are necessary to enable spatial extrapolation from sample sites across the study area.
General socioeconomic data	Ministry of Agriculture, international organizations, stakeholder consultation (including women)	Include the contribution of sample sites' agricultural production to total output of the study area, percentage of working labour in the agricultural sector.
Other	Stakeholder consultation (including women)	Additional data may be needed for specific studies (e.g. water irrigation requirements, rates of soil degradation and erosion).

a. See chapter 4.

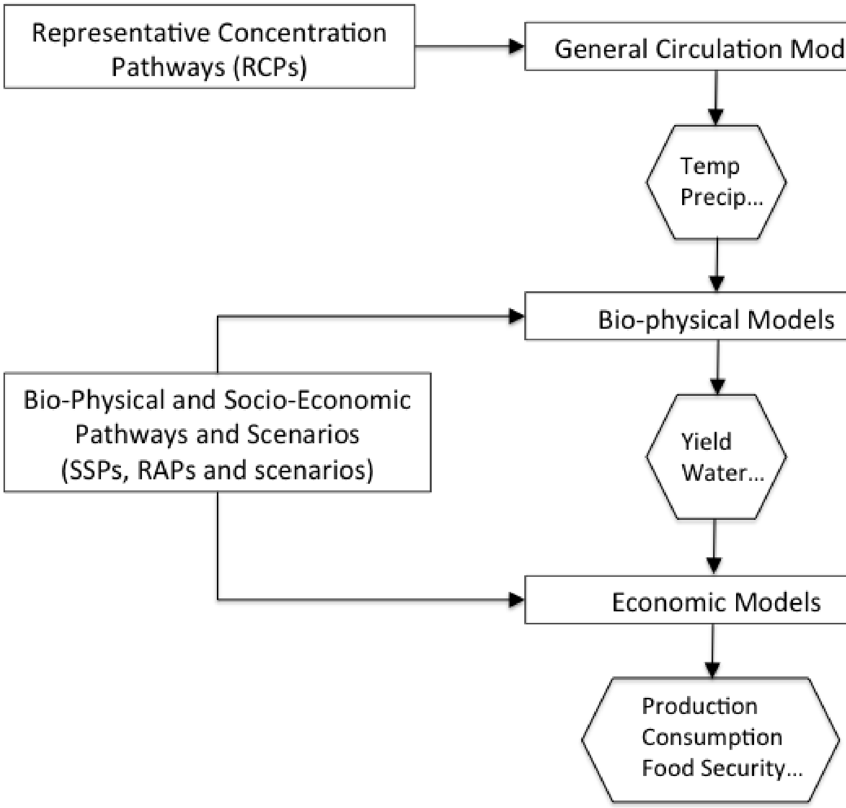
7.4. Integrated assessments

Global and regional food systems link farm production systems in various regions of the world to consumers through a web of inter-connected transportation, storage, processing, and distribution and marketing systems. In order to provide more complete assessments of climate impacts, regional and global integrated assessment approaches have been developed. These modelling systems link climate, crop, livestock, environmental and economic models at regional (subnational to national) and global scales, together with emissions scenarios and socioeconomic pathways and scenarios, to carry out climate impact assessments. An important limitation of these models, however, is that they focus on agricultural commodity (crop, livestock) supply and demand at a highly aggregated level, and are not able to represent in detail the food system beyond the farm that involves transport, storage, processing, distribution and marketing (Porter et al., 2014). Nor can these models as yet provide the detail on the consumption side needed to meaningfully represent all of the dimensions of how climate change could impact food security, including availability, access, utilization and stability (Antle, 2015).

Three types of climate and adaptation analyses can be found in the literature that can be described as answering three ‘questions’ about climate change impacts: (1) What impact would a change in climate today have on the current food system? (2) What impact could a change in climate have on the food system in the future, *without* adaptation to any changes in climate? Who would be most vulnerable to climate change without adaptation, and who might benefit from climate change? and (3) How could the food system perform in the future with climate change *and* adaptation? How would adaptation reduce vulnerabilities and help exploit any benefits of climate change?

Various models have been used to address these questions about possible climate impacts and adaptation. Most studies have utilized the modelling structure shown in figure 7-9, in which climate data from GCMs are used by biophysical models to simulate the productivity effects of climate change. These productivity impacts are then used as inputs to economic models that simulate economic outcomes. Some economic models also directly incorporate climate variables, thus bypassing the biophysical simulation models. Each of the model components in figure 7-9 is implemented using corresponding pathways and scenarios that define inputs into the models. These pathways and scenarios represent the key non-climate future conditions projected to exist in the future period being represented for the impact assessment, such as those described in chapters 2 and 3 (e.g. technological change, population growth, income growth). These factors define the socioeconomic setting in which the analysis is couched and thus can strongly influence the outcomes of the analysis.

Figure 7-10
General modelling structure of agricultural and food system impact assessments



Source: Wallach et al., 2015.

The general modelling structure illustrated in figure 7-9 can be elaborated in various ways, and the analysis can be carried out at various spatial and temporal scales. While in principle one large fully integrated model could be constructed that would incorporate a dynamic system of nested biophysical and socioeconomic processes at different spatial and temporal scales, no such 'super-model' is feasible given data and computational limitations. Instead, a number of different models representing biophysical processes (e.g. crop growth) and economic processes (e.g. market determination of prices, production, consumption and trade) are linked and simulated sequentially by passing outputs from one model to be used as inputs into another model in the logical sequence. Typically, the models are implemented for discrete time periods or 'time slices' and changes from one time slice to another are modelled rather than a continuous sequence of changes over time. Figure 7-3 presents the components of one of the major agricultural modelling frameworks known as IMPACT.

IMPACT and similar global modelling systems generate outcomes such as [data on] food production and consumption at the national level or in multi-country regions, and are thus relevant to food availability at those scales. To achieve higher-resolution outcomes for analysis of outcomes such as poverty and food security, several approaches have been developed. One approach is to link a global model to nationally disaggregated data (Hertel, Burke and Lobell, 2010). Alternatively, AgMIP has developed a coordinated global and regional approach to integrated assessment of agricultural effects and adaptation (Rosenzweig et al., 2013; Antle et al., 2015). In this approach (figure 7-1), climate projections of temperature and precipitation from GCMs are down-scaled and linked to globally gridded biophysical models that simulate crop and livestock productivity effects, as in the IMPACT approach. In addition, global socioeconomic pathways and scenarios are used to construct projections of other inputs needed for global agricultural economic models, such as population growth, productivity growth and rates of urbanization. These global models simulate production, consumption, trade and land use for multi-national or national regions as well as market equilibrium prices. To obtain estimates of effects that are less highly aggregated (e.g. specific to geographic regions or socioeconomic groups), the prices and yields from the global economic models are used as inputs into regional economic models. These regional models can simulate outcomes such as the regional distribution of production, income and poverty rates, and can be used to construct food security indicators.

7.4.1. Integration with other sectors

When assessing the impact of climate change of the agriculture sector, it is important to consider how changes in other sectors may also contribute to impacts in the agriculture sector (table 7-4). For example, coastal impacts may also have impacts on the agriculture sector, with increasing sea levels impacting the availability of land for agriculture or raising the salinity of agricultural lands.

While impact and adaptation planning are discussed at the sector-specific level, it is important to consider the interrelationships between sectors and how these may influence overall risk prioritization and adaptation planning. Such a cross-sector assessment is referred to as ‘integration’. The aim of integration is to understand the interrelationships between sector-specific risks to set impact and adaptation priorities. This may be important for policy makers and other stakeholders to understand how a sector, community, region or nation could be affected in total by climate change, and what the total economic impact may be. It may also be important to know how different sectors, regions or populations compare in terms of relative vulnerability to help set priorities for adaptation.

There are essentially two approaches to integrating adaptation in agriculture, forestry and fisheries. The first is to use integrated assessment models, such as those outlined in box 7-1 that explicitly take a spatially integrated perspective. The second approach is to seek to cross-compare the results from a number of geographically focused, or crop-specific assessments, into a coherent view of adaptation priorities and actions. Seeking such a blended approach is often the optimal approach and, as such, careful thought has to be given to the methods for integrating their results – including multi-criteria analysis or economic-based tools.

Chapter 9 in these training materials provides further details about integrating impact assessment and adaptation outcomes.

7.5. References

Ahmad A, Ashfaq M, Rasul G, Wajid SA, Khaliq T, Rasul F, Saeed U, ur Rahman MH, Hussain J, Baig IA, Naqvi SAA, Bokhari SAA, Ahmad S, Naseem W, Hoogenboom G and Valdivia R. 2015. Impact of climate change on the rice-wheat cropping system of Pakistan. *In:* C Rosenzweig and D Hillel (eds.). *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 2.* London: Imperial College Press.

Alexandratos N. 2005. Countries with rapid population growth and resources constraints: Issues of food, agriculture and development. *Popul. Dev. Rev*. 31: pp.237–258.

Allen RG., Pereira LS, Raes D and Smith M. 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper. FAO, Rome, Italy.

Antle JM. 2011. Parsimonious multi-dimensional impact assessment. *American Journal of Agricultural Economics.* 93: pp.1292–1311.

Antle JM. 2015. Climate Change, Vulnerability and Food Security. *Choices.* 2nd Quarter 2015 30(2). http://www.choicesmagazine.org/choices-magazine/theme-articles/climate-change-and-agriculture-revisiting-the-evidence-and-potential-solutions/climate-change-vulnerability-and-food-insecurity Antle JM and Valdivia RO. 2011. *The Tradeoff Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD), Version 5.0*. See website for more information <http://tradeoffs.oregonstate.edu/>.

Antle JM, Capalbo SM, Elliott ET and Paustian KH. 2004. Adaptation, spatial heterogeneity, and the vulnerability of agricultural systems to climate change and CO_2 fertilization: An integrated assessment approach. *Climatic Change.* 64(3): pp.289–315.

Antle JM, Valdivia RO, Crissman CC, Stoorvogel J and Yanggen D. 2005. Spatial heterogeneity and adoption of soil conservation investments: Integrated assessment of slow formation terraces in the Andes. *Journal of International Agricultural Trade Development*. 1(1): pp.29–53.

Antle JM, Valdivia RO, Boote KJ, Janssen S, Jones JW, Porter CH, Rosenzweig C, Ruane AC and Thorburn PJ. 2015. AgMIP's trans-disciplinary agricultural systems approach to regional integrated assessment of climate impact, vulnerability and adaptation. *In:* C Rosenzweig and D Hillel (eds.). *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1.* London: Imperial College Press.

Badini O, Stöckle CO and Franz EH. 1997. Application of crop simulation modeling and GIS to agroclimatic assessment in Burkina Faso. *Agriculture, Ecosystems & Environment.* 64: pp.233–244.

Barnett J and O'Neill S. 2009. Maladaptation: Editorial. *Global Environmental Change*. 20: pp.211–213.

Benioff R and Warren J (eds.). 1996. *Steps in Preparing Climate Change Action Plans: A Handbook*. Washington DC: U.S. Country Studies Program.

Boogaard HL, van Diepen CA, Rötter RP, Cabrera JMCA and van Laar HH. 1998. *User's Guide for the WOFOST 7.1 Crop Growth Simulation Model and WOFOST Control Center 1.5*. Technical Document 52. DLO-Winand Staring Centre, Wageningen.

Carter TR and Saarikko RA. 1996. Estimating regional crop potential in Finland under a changing climate. *Agricultural and Forest Meteorology*. 79(4): pp.301–313.

Claessens L, Antle JM, Stoorvogel JJ, Valdivia RO, Thornton PK and Herrero M. 2012. A method for evaluating climate change adaptation strategies for small-scale farmers using survey, experimental and modelled data. *Agricultural Systems.* 111: pp.85–95.

Deschenes O and Greenstone M. 2007. The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *The American Economic Review.* 97: pp.354–385.

Deschenes O and Kolstad C. 2011. Economic impacts of climate change on California agriculture. *Climatic Change.* 109: pp.365–386.

Easterling WE, Aggarwal PK, Batima P, Brander KM, Erda LL, Howden SM, Kirilenko A, Morton J, Soussana JF, Schmidhuber J and Tubiello FN. 2007. Food, fibre and forest products. *In:* ML Parry, OF Canziani, JP Palutikof, PJ van der Linden and CE Hanson (eds.). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. pp.273–313.

Elliott J and Müller C. 2015. The AgMIP GRIDded Crop Modelling Initiative (AgGRID) and the Global Gridded Crop Model Intercomparison (GGCMI). *In:* C Rosenzweig and D Hillel (eds.). *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1*. London: Imperial College Press. pp.175–189.

FAO (Food and Agriculture Organization of the United Nations). 2004. *FAOCLIM 2: World-Wide Agroclimatic Data*. Available at <http://www.fao.org/nr/climpag/pub/en1102_en.asp>.

FAO. 2009. FAO’s Director-General on how to feed the world in 2050. *Population and Development Review.* 35(4): pp.837–839.

FAO. 2011. *Framework Programme on Climate Change Adaptation*. Available at <http://www.fao.org/docrep/014/i2316e/i2316e00.pdf>.

Fisher AC, Hanemann WM, Roberts MJ and Schlenker W. 2012. The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather: Comment. *American Economic Review*. 102(7): pp.3749–3760.

Fleischer A, Mendelsohn R and Dinar A. 2011. Bundling agricultural technologies to adapt to climate change. *Technological Forecasting and Social Change.* 78: pp.982–990.

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N and Snyder PK. 2005. Global consequences of land use. *Science*. 309: pp.570–574.

Hansen JW and Jones JW. 2000. Scaling-up crop models for climate variability applications. *Agricultural Systems*. 65: pp.43–72.

Hazell P and Wood S. 2007. Drivers of change in global agriculture. *Philosophical Transactions of The Royal Society B: Biological Sciences.* 363(1491): pp.495–515.

Hertel TW, Burke MB and Lobell DB. 2010. The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change.* 20: pp.577–585.

Holden NM. 2001. *Agro-Meteorological Modeling – Principles, Data and Applications*. Dublin: Agmet.

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Boote KJ, Hunt LA, Singh U, Lizaso JI, White JW, Uryasev O, Ogoshi R, Koo J, Shelia V and Tsuji GY. 2014. *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.6* Available at <http://dssat.net/>.

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Boote KJ, Hunt LA, Singh U, Lizaso JI, White JW, Uryasev O, Royce FS, Ogoshi R, Gijsman AJ and Tsuji GY. 2010. *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5* [CD-ROM]. University of Hawaii, Honolulu, Hawaii.

Iglesias A and Quiroga S. 2007. Measuring the risk of climate variability to cereal production at five sites in Spain. *Climate Research*. 34: pp.45–57.

Iglesias A, Mougou R, Moneo M and Quiroga S. 2011. Towards adaptation of agriculture to climate change in the Mediterranean. *Regional Environmental Change*. 11: pp.159–166.

Iglesias A, Rosenzweig C and Pereira D. 2000. Agricultural impacts of climate in Spain: Developing tools for a spatial analysis. *Global Environmental Change*. 10: pp.69–80.

Iglesias A, Garote L, Flores F and Moneo M. 2007a. Challenges to manage the risk of water scarcity and climate change in the Mediterranean. *Water Resources Management*. 21(5): pp.227–288.

Iglesias A, Avis K, Benzie M, Fisher P, Harley M, Hodgson N, Horrocks L, Moneo M and Webb J. 2007b. *Adaptation to Climate Change in the Agricultural Sector.* Report to the European Commission Directorate-General for Agriculture and Rural Development.

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ and Ritchie JT. 2003. DSSAT cropping system model. *European Journal of Agronomy*. 18: pp.235–265.

Kaminski J, Kan I and Fleischer A. 2013. A structural land-use analysis of agricultural adaptation to climate change: A proactive approach. *American Journal of Agricultural Economics.* 95: pp.70–93.

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freeburn DM and Smith CJ. 2003. An overview of APSIM: A model designed for farming system simulation. *European Journal of Agronomy*. 18: pp.267–288.

Kelly DL, Kolstad CD and Mitchell GT. 2005. Adjustment costs from environmental change. *Journal of Environmental Economics and Management.* 50: pp.468–495.

Lepers E, Lambin EF, Janetos AC, de Fries R, Achard F, Ramankutty N and Scholes RJ. 2004. A synthesis of information on rapid land-cover change for the period 1981–2000. *BioScience*. 55: pp.115–124.

Lobell DB and Burke MB. 2010. On the use of statistical models to predict crop yield responses to climate change. *Agricultural and Forest Meteorology*. 150(11): pp.1443–1452.

Masikati P, Homann-Kee Tui S, Descheemaeker K, Crespo O, Walker S, Lennard CJ, Claessens L, Gama AC, Famba S, van Rooyen AF and Valdivia RO. 2015. Crop-livestock intensification in the face of climate change: Exploring opportunities to reduce risk and increase resilience in southern Africa by using an integrated multi-modeling approach. *In:* C Rosenzweig and D Hillel (eds.). *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 2.* London: Imperial College Press. pp.159–198.

Mendelsohn R and Dinar A. 2009. *Climate Change and Agriculture.* Washington, DC: World Bank.

Mendelsohn R, Nordhaus W and Shaw D. 1994. The impact of global warming on agriculture: A Ricardian analysis. *American Economic Review.* 84(4): pp.753–771.

Mérel P and Howitt R. 2014. Theory and application of positive mathematical programming in agriculture and the environment. *Annual Review of Resource Economics.* 6: pp.451–470.

Mu JE, McCarl BA and Wein AM. 2013. Adaptation to climate change: Changes in farmland use and stocking rate in the US. *Mitigation and Adaptation Strategies for Global Change*. 18: pp.713–730.

Nelson GC, Valin H, Sands RD, Havlik P, Ahammad H, Deryng D and Willenbockel D. 2014. Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences.* 111(9): pp.3274–3279.

Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, Zhu T, Ringler C, Msangi S, Palazzo A and Batka M. 2009. *Climate Change: Impact on Agriculture and Costs of Adaptation.* Intl Food Policy Res Inst.

Ortiz-Bobea A and Just RE. 2013. Modeling the structure of adaptation in climate change impact assessment. *American Journal of Agricultural Economics.* 95(2): pp.244–251.

Parry M, Rosenzweig C and Livermore M. 2005. Climate change, global food supply and risk of hunger. *Philosophical Transactions of the Royal Society.* 360: pp.2125–2138.

Parry ML, Canziani O, Palutikof JP, Hanson C and van der Linden P (eds.) 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.

Parry ML, Rosenzweig C, Iglesias A, Livermore M and Ficher G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environment Change*. 14: pp.53–67.

Pinto E, Kay RC and Travers A. 2008. Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to, Climate Change. Bonn: UNFCCC Secretariat. Available at <http://unfccc.int/files/adaptation/nairobi_workprogramme/compendium_on_methods_tools/application/pdf/20080307_compendium_m_t_complete.pdf>.

Porter JR and Semenov MA. 2005. Crop responses to climatic variability. *Philosophical Transactions of the Royal Society B*. 360(1463): pp.2021–2035.

Porter JR, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, Lobell DB and Travasso MI. 2014. Food security and food production systems. *In:* CB Field, VR Barros, DJ Dokken, KJ Mach, MD Mastrandrea, TE Bilir, M Chatterjee, KL Ebi, YO Estrada, RC Genova, B Girma, ES Kissel, AN Levy, S MacCracken, PR Mastrandrea and LL White (eds.). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press. pp.485–533.

Quiroga S and Iglesias A. 2009. A comparison of the climate risks of cereal, citrus, grapevine and olive production in Spain. *Agricultural Systems*. 101: pp.91–100.

Radeloff V, Nelson E, Plantinga A, Lewis D, Helmers D, Lawler J, Withey J, Beaudry F, Martinuzzi S and Butsic V. 2012. Economic-based projections of future land use in the conterminous United States under alternative policy scenarios. *Ecological Applications.* 22: pp.1036–1049.

Rosegrant MW and IMPACT Development Team. 2012. *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model Description.* Washington, DC: International Food Policy Research Institute.

Rosenzweig C and Hillel D (eds.). 2015. *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments (in 2 parts).* London: Imperial College Press.

Rosenzweig C and Iglesias A (eds.). 1994. *Implications of Climate Change for International Agriculture: Crop Modeling Study*. EPA 230-B-94-003. Washington DC: U.S. Environmental Protection Agency.

Rosenzweig C and Iglesias A. 1998. The use of crop models for international climate change impact assessment. *In:* GY Tsuji, G Hoogenboom and PK Thornton (eds.). *Understanding Options for Agricultural Production*. Dordrecht: Kluwer Academic Publishers.

Rosenzweig C, Iglesias A, Fisher G, Liu Y, Baethgen W and Jones JW. 1999. Wheat yield functions for analysis of landuse change in China. *Environmental Modeling and Assessment*. 4: pp.128–132.

Rosenzweig C, Jones JW, Hatfield JL, Antle JM, Ruane AC and Mutter CZ. 2015. The agricultural model intercomparison and improvement project: Phase I activities by a global community of science. *In:* C Rosenzweig and D Hillel (eds.). *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison* *and Improvement Project Integrated Crop and Economic Assessments, Part 1.* London: Imperial College Press. pp.3–24.

Rosenzweig C, Strzepek KM, Major DC, Iglesias A, Yates DN, McCluskey A and Hillel D. 2004. Water resources for agriculture in a changing climate: International case studies. *Global Environmental Change*. 14: pp.345–360.

Rosenzweig C, Jones JW, Hatfield JL, Ruane AC, Boote KJ, Thorburn P, Antle JM, Nelson GC, Porter C, Janssen S, Asseng S, Basso B, Ewert F, Wallach D, Baigorria G and Winter JM. 2013. The agricultural model intercomparison and improvement project (AgMIP): Protocols and pilot studies. *Ag. For. Meteor*. 170: pp.166–182.

Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N, Neumann K, Piontek F, Pugh TAM, Schmid E, Stehfest E, Yang H and Jones JW. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences.* 111(9): pp.3268–3273.

Rotter RP, Carter TR, Olesen JE and Porter JR. 2011. Crop-climate models need an overhaul. *Nature Climate Change*. 1: pp.175–177.

Schlenker W, Hanemann WM and Fisher AC. 2005. Will U.S. agriculture really benefit from global warming? Account for irrigation in the hedonic approach. *The American Economic Review*. 95(1): pp.395–406.

Schlenker W, Hanemann WM and Fisher AC. 2006. The impact of global warming on U.S. agriculture: An econometric analysis of optimal growing conditions. *The Review of Economics and Statistics*. 88(1): pp.113–125.

Seo SN. 2010. A microeconometric analysis of adapting portfolios to climate change: Adoption of agricultural systems in Latin America. *Applied Economic Perspectives and Policy*. 32(3): pp.489–514.

Seo SN and Mendelsohn R. 2008. An analysis of crop choice: Adapting to climate change in South American farms. *Ecological Economics*. 67: pp.109–116.

Seo SN, Mendelsohn R, Dinar A and Kurukulasuriya P. 2009. Adapting to climate change mosaically: An analysis of African livestock management by agro-ecological zones. *The BE Journal of Economic Analysis & Policy*. 9(2): pp.1935–1682.

Sharpley AN and Williams JR. 1990. EPIC – Erosion/Productivity Impact Calculator: 1. Model Documentation. U.S. Department of Agriculture Technical Bulletin No. 1768.

Steduto P, Hsiao RC, Fereres E and Raes D. 2012. Crop Yield Response to Water. FAO Irrigation and Drainage Paper 66. FAO, Rome, Italy.

Supit I, Hooijer AA and van Diepen CA (eds.). 1994. *System Description of the WOFOST 6.0 Crop Simulation Model Implemented in CGMS*. *Volume 1: Theory and Algorithms.* EUR 15956. Luxembourg: Office for Official Publications of the European Communities.

Taylor KE, Stouffer RJ and Meehl GA. 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society.* 93(4): pp.485–498.

Tsuji GY, Hoogenboom G and Thornton PK (eds.). 1998. *Understanding Options for Agricultural Production. Systems Approaches for Sustainable Agricultural Development.* Dordrecht: Kluwer Academic Publishers.

UNFCCC. 2009. *Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to Climate Change*. Available at <http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5457.php>.

Valdivia R, Stoorvogel J and Antle JM. 2012. Economic and environmental impacts of climate change and socio-economic scenarios: A case study of a semi-subsistence agricultural system. *The International Journal of Climate Change Impacts and Responses*. 3(2): pp.157–175.

Valdivia RO, Antle JM, Rosenzweig C, Ruane AC, Vervoort J, Ashfaq M, Hathie I, Tui SH-K, Mulwa R, Nhemachena C, Ponnusamy P, Rasnayaka H and Singh H. 2015. Representative agricultural pathways and scenarios for regional integrated assessment of climate change impact, vulnerability and adaptation. *In:* C Rosenzweig and D Hillel (eds.). *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1.* London: Imperial College Press. pp.101–145.

van der Mensbrugghe D. 2013. *The ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model: Version 8.0* (Technical Report). Rome: Food and Agricultural Organization of the United Nations.

van Wijk M, Rufino M, Enahoro D, Parsons D, Silvestri S, Valdivia R and Herrero M. 2014. Farm household models to analyse food security in a changing climate: A review. *Global Food Security*. 3: pp.77–84.

von Lampe M, Willenbockel D, Ahammad H, Blanc E, Cai Y, Calvin K, Fujimori S, Hasegawa T, Havlik P, Heyhoe E, Kyle P, Lotze-Campen H, Mason d'Croz D, Nelson GC, Sands RD, Schmitz C, Tabeau A, Valin H, van der Mensbrugghe D and van Meijl H. 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics.* 45: pp.3–20.

Wallach D, Mearns LO, Rivington M, Antle JM and Ruane AC. 2015. Uncertainty in agricultural impact assessment. *In:* C Rosenzweig and D Hillel (eds.). *Handbook* *of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1.* London: Imperial College Press. pp.261–277.

White JW and G Hoogenboom. 2010. Crop response to climate: Ecophysiological models. *In*: D Lobell and M Burke (eds.). *Climate Change and Food Security. Adapting Agriculture to a Warmer World. Advances in Global Change Research*. Dordrecht: Springer Science. pp.59–83.

White JW, Hoogenboom G, Kimball BA and Wall GW. 2011. Methodologies for simulating impacts of climate change on agricultural production. *Field Crops Research.* 124(3): pp.357–368.

Wu J, Adams RM, King CL and Tanaka K. 2004. From microlevel decisions to landscape changes: An assessment of agricultural conservation policies. *American Journal of Agricultural Economics.* 86(1): pp.26–41.

Appendix 7-1: Drivers of change in agriculture

Drivers of change

Effects of current climate variability

In many regions of the world, such as Africa, Southern and Central America, and South and Southeast Asia and the Pacific, climates are extremely variable from year to year, and recurrent drought and flood problems often affect entire countries over multi-year periods. These often result in serious socioeconomic problems.

Agriculture is strongly dependent on water resources and climatic conditions, particularly in the regions of the world that are particularly sensitive to climatic hazards, such as Africa, South and Central America, Asia and the Pacific. Some countries in these regions, where economic and social situations are often unstable, are extremely vulnerable to changes in environmental factors. It is especially the case in countries where technological buffering to droughts and floods is less advanced, and where the main physical factors affecting production (soils, terrain and climate) are less suited to farming. Crop production is consequently extremely sensitive to large year-to-year weather fluctuations. Crop diseases or pest infestations are also weather dependent and tend to cause more damage in countries with lower technological levels.

Drivers of agricultural response to climate change

Estimation of future agricultural responses to climate change is usually based on scenarios of future climate change through the methods and approaches outlined in chapter 3. As outlined below, a number of scenarios are often produced to reflect inherent uncertainties of predicting future conditions.

Agriculture is a complex sector involving different driving parameters (environmental, economic and social). It is now well recognized that crop production is very sensitive to climate change (Easterling et al., 2007), with different effects according to region. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) Working Group II estimates a general climate change driven reduction of potential crop yields and a decrease in water availability for agriculture and populations in many parts of the developing world (table 7-6).

The main drivers of agricultural responses to climate change are biophysical effects (table 7-7) and socioeconomic factors (table 7-8). Crop production is affected biophysically by changing meteorological variables, including rising temperatures, changing precipitation regimes and increasing levels of atmospheric carbon dioxide (CO_2). Biophysical effects of climate change on agricultural production depend on the region and the agricultural system, and the effects vary through time.

Table 7-6

Climate change and related factors relevant to agricultural production and food security

Climate factor	**Direction of change**	**Consequences and factors that interact with agricultural production and food security**
Sea level rise	Increase	Sea level intrusion in coastal (agricultural) areas and salinization of water supply
Precipitation intensity/run-off	Intensified hydrological cycle, so generally increases, but with regional variations	Changed patterns of erosion and accretion; changed storm impacts; changed occurrence of storm flooding and storm damage, water logging, increase in pests
Heat stress	Increases in heat waves	Damage to grain formation, increase in some pests
Drought	Poorly known, but significant increased temporal and spatial variability expected	Crop failure, yield decrease, competition for water
Atmospheric CO_2	Increase	Increased crop productivity but also increased weed productivity and therefore competition with crops

Sources: Adapted from Parry et al., 2004 and Easterling et al., 2007.

Table 7-7

Characterization of agronomic impacts, adaptive capacity and sector outcomes

Biophysical impact	**Uncertainty level**	**Expected intensity of negative effects**	**Adaptive capacity**	**Socioeconomic and other secondary impacts**
Changes in crop growth conditions	Medium	High for some crops and regions	Moderate to high	Changes in optimal farming systems, relocation of farm processing industry, increased economic risk, loss of rural income, pollution due to nutrient leaching, biodiversity decrease
Changes in optimal conditions for livestock production	High	Medium	High for intensive production systems	Changes in optimal farming systems, loss of rural income
Changes in precipitation and availability of water resources	Medium to low	High for developing countries	Moderate	Increased demand for irrigation, decreased yield of crops, increased risk of soil salinization, increased water shortage, loss of rural income

Biophysical impact	**Uncertainty level**	**Expected intensity of negative effects**	**Adaptive capacity**	**Socioeconomic and other secondary impacts**
Changes in agricultural pests	High to very high	Medium	Moderate to high	Pollution due to increased use of pesticides, decreased yield and quality of crops, increased economic risk, loss of rural income
Changes in soil fertility and erosion	Medium	High for developing countries	Moderate	Pollution by nutrient leaching, biodiversity decrease, decreased yield of crops, land abandonment, increased risk of desertification, loss of rural income

Table 7-8
Characterization of aggregated farming system impacts, adaptive capacity and sector outcomes

Socioeconomic impact	**Uncertainty level**	**Expected intensity of negative effects**	**Autonomous adaptation (private coping capacity)**	**Other impacts**
Changes in optimal farming systems	High	High for areas where current optimal farming systems are extensive	Moderate	Changes in crop and livestock production activities, relocation of farm processing industry, loss of rural income, pollution due to nutrient leaching, biodiversity decrease
Relocation of farm processing industry	High	High for some food industries requiring large infrastructure or local labour	Moderate	Loss of rural income, loss of cultural heritage
Increased (economic) risk	Medium	High for crops cultivated near their climatic limits	Low	Loss of rural income
Loss of rural income and cultural heritage	High	(Not characterized)	Moderate	Land abandonment, increased risk of desertification, welfare decrease in rural societies, migration to urban areas, biodiversity decrease

Socioeconomic factors influence responses to changes in crop productivity, with price changes and shifts in comparative advantage. The final response depends on the adaptation strategies in each region and agricultural system. The combination of biophysical and socioeconomic effects can result in:

- Changes in the mix of crops grown, and hence in the type of farming and rural land use;
- Changes in production, farm income and rural employment;
- Changes in rural income, contribution to national gross domestic product (GDP) and agricultural export earnings.

Non-climate drivers

Non-climate drivers, including land use, land degradation, geological processes, urbanization and pollution, affect the agricultural sector directly and indirectly through their effects on climate. These drivers can operate either independently or in association with each other (Lepers et al., 2004).

Hazell and Wood (2007) take a useful approach in looking at non-climate drivers of change to the agriculture sector over the following three distinct scales:

- ***Global-scale drivers***: drivers that affect agriculture worldwide, but to varying degrees. These drivers include, but are not limited to, international trade and globalization of markets, Organisation for Economic Co-operation and Development (OECD) agriculture policies, rapid globalization of science and knowledge access facilitated by expanding global communications options. These options can serve to accelerate the flow of information, technology and products relevant to agricultural development;
- ***Country-scale drivers***: drivers that affect all agriculture within a country, although factors such as poor infrastructure and market access may lead to spatially differentiated impacts. Key drivers include income and urbanization, changing market chains and shifts in public policy;
- ***Local-scale drivers***: drivers that are specific to each local geographical area and different types of agricultural production system. Relevant drivers include poverty, population pressure, health, technology design, property rights, infrastructure and market access and non-farm opportunities.

The above discussion of non-climate drivers reflects the critical role of the economy, from local to global scales, in driving agricultural systems and practices. In addition to these primary economic drivers, a range of key environmental drivers including volcanic activity, earthquakes and tsunamis, pollution and invasive species have significant influence on agricultural systems.

Appendix 7-2: Potential impacts

Climate change affects all agricultural sectors in a multitude of ways that vary region by region, because it reduces the predictability of seasonal weather patterns and increases the frequency and intensity of extreme weather events such as floods, cyclones and heat waves (FAO, 2011). The impacts of climate change on the agriculture sector (table 7-9) are well documented through a range of organizations, including the Intergovernmental Panel on Climate Change (IPCC) and Food and Agriculture Organization of the United Nations (FAO), and peer-reviewed literature. This section presents the key impacts on agricultural crops and livestock, forestry and fisheries subsectors to closely align to the updated findings of IPCC Fourth Assessment Report (AR4).

Table 7-9
Likely direction of change for broad impact areas in agriculture

Biophysical impact	**Direction of change**	**Level of confidence**
Optimal location of crop zones	Not consistent	High
Crop productivity	Not consistent	High
Irrigation requirements	Increase	High
Soil and salinity erosion	Increase	Medium
Damage by extreme weather events	Increase	Medium
Environmental degradation	Increase	Medium
Pests and diseases	Increase	Medium

Source: Adapted from Easterling et al., 2007.

Agricultural crops and livestock

Impacts on agricultural crops at the global scale might be relatively small during the first half of the twenty-first century; however, impacts will become progressively more profound in the latter half of the century (Easterling et al., 2007). It is projected that crop production in mainly low-latitude developing countries will suffer more, and earlier, than the mainly mid- to high-latitude countries, due to a combination of adverse agroclimate, socioeconomic and technological conditions (Alexandratos, 2005). Similarly, pastures and livestock production systems occur under most climates and range from extensive pastoral systems with grazing herbivores to intensive systems based on forage and grain crops, where animals are usually kept indoors in a more controlled environment (Easterling et al., 2007). Climate change has direct effects on livestock productivity as well as indirectly through changes on the availability of fodder and pastures (FAO, 2011).

Impacts on pasture and livestock production will be due to increases in carbon dioxide (CO2) concentration in the atmosphere, in conjunction with changes in rainfall and temperature that are likely to have significant implications for grasslands and rangelands, with production increases in humid temperate grasslands, but decreases in arid and semi-arid regions (Easterling et al., 2007). Specific impacts for food crops, pastures and livestock per region are presented table 7-10 and table 7-11.

Table 7-10
Summary of selected conclusions for the agriculture sector, by warming increment

Temperature change	Sub-sector	Region	Finding
+1°C to +2°C	Food crops	Mid to high latitudes	• Cold limitation alleviated for all crops • Adaptation of maize and wheat increases yield 10–15%, no change in rice yield, regional variation is high
	Pastures and livestock	Temperate	• Cold limitation alleviated for pastures, seasonal increased frequency of heat stress for livestock
	Food crops	Low latitudes	• Wheat and maize yields reduced below baseline levels, rice is unchanged • Adaptation of maize, wheat, rice maintains yields at current levels
	Pastures and livestock	Semi-arid	• No increase in net primary productivity, seasonal increased frequency of heat stress for livestock
	Prices	Global	• Agricultural prices: –10% to –30%
+2°C to +3°C	Food crops	Global	• 550 ppm CO_2 (approximately equal to +2°C): 17% increase in C3 crop yield (increase is offset by temperature increase of 2°C assuming no adaptation and 3°C with adaptation)
	Prices	Global	• Agriculture prices: –10% to +10%
	Food crops	Mid to high latitudes	• Adaptation increases all crops above baseline yield
	Fisheries	Temperate	• Positive effect on trout in winter, negative in summer
	Pastures and livestock	Temperate	• Moderate production loss in swine and confined cattle
	Fibre	Temperature	• Yields decrease by 9%
	Pastures and livestock	Semi-arid	• Reduction in animal weight and pasture production, and increased heat stress for livestock

Temperature change	Sub-sector	Region	Finding
	Food crops	Low latitudes	• Adaptation maintains yields of all crops above baseline, yields drop below baseline for all crops without adaptation
+3°C to +5°C	Prices and trade	Global	• Reversal of downward trend in wood prices • Agriculture prices: +10% to +40% • Cereal imports of developing countries to increase by 10–40%
	Forestry	Temperate Tropical	• Increase in fire hazard and insect damage • Massive Amazonian deforestation possible
	Food crops	Low latitudes	• Adaptation maintains yields of all crops above baseline; yield drops below baseline for all crops without adaptation
	Pastures and livestock	Tropical	• Strong production loss in swine and confined cattle
	Food crops	Low latitudes	• Maize and wheat yields reduced below baseline regardless of adaptation, but adaptation maintains rice yields at baseline levels
	Pastures and livestock	Semi-arid	• Reduction in animal weight and pasture growth, increased animal heat stress and mortality

Source: Easterling et al., 2007.

Table 7-11

Summary of selected findings for the agriculture sector, by time increment

Time slice	Sub-sector	Location	Finding
2020	Food crops	United States	• Extreme events (e.g. increased heavy precipitation) cause crop losses to 3 billion United States dollars (USD) by 2030 with respect to current levels
	Small-hold farming and fishing	Low latitudes, especially East and South Africa	• Decrease in maize yields, increased risk of crop failure, high livestock mortality
	Small-hold farming and fishing	Low latitudes, especially South Asia	• Early snow melt causing spring flooding and summer irrigation shortage
	Forestry	Global	• Increased export of timber from temperate to tropical countries • Increase in share of timber production from plantations • Timber production: +5% to +15%

Time slice	**Sub-sector**	**Location**	**Finding**
2050	Fisheries	Global	- Marine primary production: +0.7% to +8.1%, with large regional variation
	Food crops	Global	- With adaptation, yields of wheat, rice and maize above baseline levels in mid- to high-latitude regions and at baseline levels in low latitudes
	Forestry	Global	- Timber production: +20% to +40%
2080	Food crops	Global	- Crop irrigation water requirement increases 5–20%, with range due to significant regional variation
	Forestry	Global	- Timber production: +20% to +60% with high regional variation
	Agriculture sector	Global	- Stabilization at 550 ppm CO_2 ameliorates 70–100% of agricultural cost caused by unabated climate change

Source: Easterling et al., 2007.

Appendix 7-3: Agriculture adaptation

Historically, agriculture has shown a considerable ability to adapt to changing conditions, whether from alterations in resource availability, technology or economics. Many adaptations occur autonomously and without the need for conscious response by farmers and agricultural planners. However, it is likely – at least in some parts of the world and, especially, in developing countries – that the rate and magnitude of climate change will exceed that of normal change in agriculture. Consequently, specific technologies and management styles will need to be adopted to avoid the most serious effects. As much as possible, response adjustments need to be identified along with their costs and benefits. There is much to be gained from evaluating the capability that exists in currently available technology and the potential capability that can developed in the future.

Although most adaptation to climate change will ultimately be characterized by responses at the farm level, encouragement of response by policy affects the speed and extent of adoption. The time required to implement adaptation measures varies considerably, depending on the scale, cost, resources and capacities required to implement the measure and the barriers that need to be overcome. Two broad types of adaptation are considered here: farm-based adaptation and policy adaptation. Farm-based adaptation includes changes in crops or crop management. Table 7-12 outlines examples of farm-based adaptation measures that can be evaluated with the tools mentioned in this chapter. All measures may contribute to adaptation to climate change, but in many cases they may have unintended negative (‘maladaptive’) effects that need to be carefully evaluated, such as adaptive measures that may be viewed as effective in the short term, but limit future adaptive choices (Barnett and O’Neill, 2009). Policy-based adaptation can create synergy with farmers’ responses, particularly in countries where education of the rural population is limited. Research to test the robustness of alternative farming strategies and development of new crop varieties are also among policy-based measures with the potential for being effective.

Iglesias et al. (2011, 2007a) present an assessment in terms of potential benefits, technical feasibility and potential costs for a number of potential adaptation options explored, not just for dealing with climate change risks, but also to allow for the exploitation of possible opportunities. Table 7-13 provides an assessment of potential adaptation options to respond to identified risks and opportunities, reporting on level of implementation, option category and information about timescale (urgency), technical difficulty, potential cost and potential benefits for each potential adaptation option. The discussion of the table is divided broadly into the risks, measures and opportunities identified: zoning and crop productivity, floods, drought, water scarcity and irrigation, water quality, soils quality and desertification, glaciers and permafrost, sea level rise, pests and diseases, and livestock. The table synthesizes results in a simple quantitative ratio of the effort (average of time scale, potential cost and technical difficulty) to benefit (potential benefit) of different adaptation measures for all risks and opportunities identified.

Table 7-12
Example farm-based adaptation measures, actions to implement them and potential results

Measure	Action	Potential result
Choice of crop	Use of drought or heat-resistant varieties	Reduced risk of yield loss and reduced irrigation requirements
	Use of pest-resistant varieties	Reduced crop loss when climate conditions are favorable for increased weeds and pests
	Use of quicker (or slower) maturing varieties	Ensures maturation in growing season shortened by reduced moisture or thermal resources, maximization of yields under longer growing seasons
	Altering mix of crops	Reduced production variability
Tillage and time of operations	Change planting date	Match altered precipitation patterns
	Terracing, ridging	Increased moisture availability to plants
	Land levelling	Spread of water and increase in infiltration
	Reduced tillage	Reduced loss of soil organic matter, reduced soil erosion and reduced loss of nutrients
	Deep plowing	Break up of impervious layers or hardpan soils to increase infiltration
	Change fallow and mulching practices	Retained moisture and organic matter
	Alter cultivations	Reduced weed infestation
	Switch seasons for cropping	Avoid effects of increased summer drought (e.g. by switching from spring to winter crops)
Crop husbandry	Alter row and plant spacing	Increase root extension to soil water
	Intercropping	Reduce yield variability, maximize use of moisture
Irrigation and water harvesting	Introduce new irrigation schemes to dryland areas	Avoid losses due to drought
	Improve irrigation efficiency	Avoid moisture stress
	Water harvesting	Increase moisture availability

Measure	**Action**	**Potential result**
Input of agrochemicals	Vary amounts of fertilizer application	Increase nitrogen to improve yield if more water is available; or decrease nitrogen to minimize input costs
	Alter time of application	Match applications to, for example, altered patterns of precipitation
	Vary amount of chemical control	Avoid pest, weed and disease damage

Source: Iglesias et al., 2007b.

Table 7-13
Adaptation measures to climate change risks and opportunities

Risk /measure	**Level (1)**	**Category (2)**	**Time-scale (3)**	**Technical difficulty (4)**	**Potential cost (5)**	**Potential benefits (6)**
All risks						
Implement regional adaptation plans	P	MA	LT	H	M	H
Advisory services	P	MA	MT	M	M	H
Research: technology and biotechnology	P	MA	LT	H	H	H
Research: water-use efficiency	P	MA	MT	M	M	H
Research: management and planning	P	MA	ST	M	L	H
Insurance	P	MA	MT	M	H	H
1. Disruption of zoning areas and decreased crop productivity						
Change in crops and cropping patterns	F	MA	ST	L	M	M
Changing cultivation practices	F	MA	MT	M	M	M
Increased input of agrochemicals	F	MA	ST	L	M	L

Risk /measure	**Level (1)**	**Category (2)**	**Time-scale (3)**	**Technical difficulty (4)**	**Potential cost (5)**	**Potential benefits (6)**
Introduce new irrigation areas	P	MA	LT	H	H	H
Develop climate change – resilient crops	P	T	LT	H	H	M
Livelihood diversification	P	MA	MT	M	H	M
Relocation of farm-processing industry	P	MA	LT	H	H	H
2. Increased risk of floods						
Create/restore wetlands	F	I	LT	H	H	M
Enhance floodplain management	F	MA	MT	H	H	H
Improve drainage systems	F	I	LT	M	L	M
Reduce grazing pressures to protect against soil erosion	F	MA	MT	M	H	L
Addition of organic material into soils	F	MA	ST	L	M	L
Incentive farmers for being ‘custodians’ of floodplains	P	MA	LT	M	H	H
Hard defences	P	I	LT	H	H	H
Increase rainfall interception capacity (reservoirs)	P	I	MT	M	M	H
3. Increased risk of drought and water scarcity **4. Increased need of supplemental irrigation**						
Introduce drought-resistant crops	F	MA	LT	H	M	M
Shift crops from vulnerable areas	F	MA	LT	H	H	M

Risk /measure	Level (1)	Category (2)	Time-scale (3)	Technical difficulty (4)	Potential cost (5)	Potential benefits (6)
Improve soil-moisture retention capacity	F	T	MT	M	M	L
Increase irrigation water-use efficiency	F	T	MT	M	M	H
Small-scale water reservoirs on farmland	F	I	MT	M	M	H
Advanced irrigation systems	F	T	MT	M	H	H
Improve reservoir capacity	P	I	LT	H	H	H
Water reutilization	P	I	MT	H	H	H
Improve water charging and trade	P	MA	LT	H	H	H
Introduce water audits	P	MA	LT	H	L	H
Renegotiation of groundwater abstraction agreements	P	MA	LT	H	H	H
Set clear water-use priorities	P	MA	LT	H	L	H
5. Deterioration of water quality						
Improve nitrogen-fertilization efficiency	F	MA	ST	L	L	L
Aerate plowing equipment	F	T	MT	L	M	L
Develop less-polluting inputs	P	T	LT	M	L	H
6. Deterioration of soils quality and desertification						
Introduce precision agriculture	F	MA	LT	M	H	M
Soil carbon management and zero tillage	F	T	MT	M	M	M

Risk /measure	Level (1)	Category (2)	Time-scale (3)	Technical difficulty (4)	Potential cost (5)	Potential benefits (6)
7. Loss of glaciers and alteration of permafrost						
Water capture and storage systems	P	I	LT	M	H	H
Increased maintenance and structure of buildings and infrastructure	P	I	LT	M	H	M
8. Sea level rise intrusion in coastal agricultural areas						
Alternative crops	F	MA	MT	M	M	L
Improve drainage systems	F	I	LT	M	H	H
Hard defences	P	I	LT	H	H	H
Management of saltwater intrusion	P	MA	LT	H	H	H
Set aside land for buffer zones	P	MA	LT	H	H	H
9. Increased risk of agricultural pests, diseases and weeds						
Additional pesticide application	F	MA	ST	L	L	L
Introduce pest-resistant varieties	F	MA	ST	M	H	M
Use of natural predators	F	MA	ST	M	M	L
Vaccinate livestock	F	MA	ST	L	M	L
Improve monitoring	P	I	LT	H	M	H
Develop sustainable pesticides strategy	P	MA	LT	M	M	L
10. Deterioration of livestock conditions						
Change to more heat-tolerant species/breeds	F	MA	LT	H	M	M

Risk /measure	**Level (1)**	**Category (2)**	**Time-scale (3)**	**Technical difficulty (4)**	**Potential cost (5)**	**Potential benefits (6)**
Change the grazing regime	F	MA	ST	L	L	L
Change the pasture composition	F	MA	ST	L	L	L
Supplemental feeding to grazing	F	MA	ST	L	M	L
Change the time of operations and breeding	F	MA	MT	H	M	M
Increase shelter and heat protection	F	I	LT	M	H	M
All opportunities						
Implement regional adaptation plans	P	MA	LT	H	M	H
Advisory services	P	MA	MT	M	M	H
Research: technology and biotechnology	P	MA	LT	H	H	H
Research: water-use efficiency	P	MA	MT	M	M	H
Research: management and planning	P	MA	ST	M	L	H
Change to more productive varieties	F	T	MT	M	M	M
Improve crop diversification	F	T	LT	M	M	M
Extend livestock farming to new areas	F	T	MT	M	H	M
Increase stocking rate	F	MA	ST	L	M	L
Decrease heating in glasshouses	F	T	ST	L	L	H
Introduce ground heat sources	F	T	ST	M	M	M

LEGEND: (1) farm level (F) or policy level (P); (2) technical (T), management (MA) or infrastructural (I); (3) short term (ST), medium term (MT) or long-term (LT); (4) (5) (6) low (L), medium (M) or high (H).