Climate change and agriculture

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Contents

1. Overview

1.1. Context of National Communications

Sustainable development includes social, economic, and environmental dimensions. Climate change modifies all these dimensions and therefore alters the potential development pathways. In particular, the effects of climate change in agriculture determine future of food security and ultimately influence the inequitable North/South divide. Developing Countries prepare National Communications to the UNFCCC in accordance with Article 12 of the Convention. The National Communications are compiled from detailed studies on a sectoral basis and provide a framework for analyzing the vulnerability and adaptation measures of each country.

According to the IPCC Third Assessment Report (IPCC, 2001), climate change is already happening, and will continue to happen even if global greenhouse gas emissions are curtailed. Many studies document the implications of climate change for agriculture and pose a reasonable concern that climate change is a threat to poverty and sustainable development, especially in developing countries (non-annex I countries). The definition of the key vulnerable production sectors and regions and the design, evaluation, and the implementation of adaptation measures for agriculture define the overall future vulnerability of rural populations. This chapter focuses on the methods for making these evaluations, providing examples of application in developing countries and an overview of previous knowledge. The merits of each approach vary according to the level of impact being studied, and they may frequently be mutually supportive. For example, simple agro-climatic indices often provide the necessary information on how crops respond to varying rainfall and temperature in wide geographical areas; crop-specific models are use to test alternative management that can in turn be used as a component for an economic model that analyses regional vulnerability or national adaptation strategies. Therefore, a mix of approaches is often the most rewarding.

1.2. Effects of current climate variability

Climate is an essential component of the natural capital. In many regions of the world, such Africa, Southern and Central America, and South and Southeast Asia, climates are extremely variable from year to year, and recurrent drought and flood problems often affect entire countries over multiyear periods. These often result in serious social problems. The observed temperature increase over the last century is affecting the region (IPCC, 2001). The persistent drying trend in parts of Africa over the last decades has affected food production, including freshwater fisheries, industrial and domestic water supplies, and hydropower generation (Benson and Clay, 1998; 2000; Iglesias and Moneo, 2005; Iglesias et al., 2006).

Agriculture is strongly dependent on water resources and climatic conditions, particularly in regions of the world that are particularly sensitive to climatic hazards, such as Africa, South and Central America and Asia. Some countries in these regions, where economical 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, 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 damages in countries with lower technological levels.

1.3. Drivers of agricultural response to climate change

Future agricultural responses to climate change are based on scenarios. It is crucial to understand that there is large uncertainty in the climate scenarios used for the analyses. The scenarios are essential for evaluating possible futures but they do not represent conditions that will actually occur. Nevertheless, conditions similar to the scenarios are possible, and as such they should be used to explore possible adaptive measures.

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 (McCarthy et al., 2001), with different effects according to region. The IPCC analysis on climate change impacts (Third Assessment Report) estimates a general reduction of potential crop yields and a decrease in water availability for agriculture and population in many parts of the developing world (see Table 1).
The main drivers of agricultural responses to climate change are biophysical effects (see Table 2) and socioeconomic factors (see Table 3). Crop production is affected biophysically by changing meteorological variables, including rising temperatures, changing precipitation regimes, and increasing levels of atmospheric carbon dioxide. Biophysical effects of climate change on agricultural production depend on the region and the agricultural system, and the effects vary through time.

Table 1. 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/runoff	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.

Source: Iglesias (2005), elaborated from data and information of the IPCC (2001); Parry et al. (1999); Parry et al. (2004).
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 GDP, and agricultural export earnings.

Table 2. 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 by nutrient leaching. Biodiversity.
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 the 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.
Changes in agricultural pests	High to very high	Medium	Moderate to high	Pollution by 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. Decreased yield of crops. Land abandonment. Increased risk of desertification. Loss of rural income.

Source: Iglesias (2005).

Table 3. 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 by nutrient leaching. Biodiversity.
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.

Source: Iglesias (2005).

1.4. Previous studies

Several hundred studies on climate changes on agriculture have been completed. They provide a first indication of the impact types to expect, and thus the most effective analysis methods to implement. Potential impacts on world food supply have been estimated for several climate change and socioeconomic scenarios (Figure 1). Some regions may improve their agricultural production whereas others will suffer from yield losses, and so a reorganization of the agricultural production areas may be required. In a particular region, crops are expected to be differently affected, leading to the need for adaptations in supporting industries and markets, farm-level strategies, and rural development schemes.

Although Figure 1 shows that global production appears stable (additional quantitative data are provided by Parry et al., 2004), regional differences in crop production are likely to grow stronger through time, leading to a significant polarization of effects, with substantial increases in prices and risk of hunger amongst the poorer nations. The most serious effects are at the margins (vulnerable regions and groups). Individuals particularly vulnerable to environmental change are those with relatively high exposures to changes, high sensitivities to changes, low coping and adaptive capacities, and low resilience and recovery potential. Adaptation is necessary, but adaptation has limits (technology and biotechnology, political and cultural).

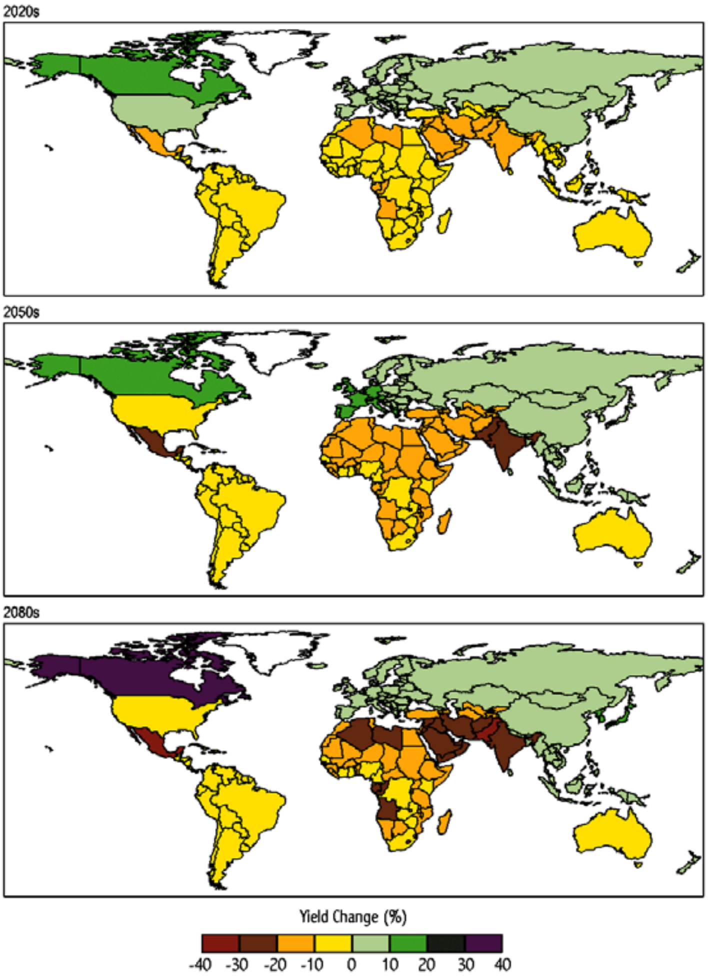


Figure 1. Percentage change in average crop yields for the HadCM2 climate change scenario. Source: Parry et al. (2004).

2. Adaptation

2.1. Stakeholder choices for agricultural adaptation

Historically agriculture has shown a considerable ability to adapt to changing conditions, whether these have stemmed 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, especially in developing countries, that the rate and magnitude of climate change will exceed that of normal change in agriculture and that specific technologies and management styles will need to be adopted to avoid the most serious of effects. As far as possible the 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.

While most adaptation to climate change will ultimately be characterised by responses at the farm level, encouragement of response by policy affects the speed and extent of adoption. Most major adaptations may require 10 to 20 years to implement. 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 4 outlines examples of farm based adaptation measures that can be evaluated with the tools provided in this manual. All measures may contribute to adapt to climate change but in many cases may have other negative effects, such as environmental damage. Policy based adaptation creates synergies with the farmers' responses particularly in countries where education of the rural population is limited. Agricultural research to test the robustness of alternative farming strategies and development of new crop varieties are also among the policy based measures with a potential for being effective in the future.

Table 4. Adaptation measures, actions to implement them, and potential results (Iglesias, 2005)

Measure	Action	Potential result
Choice of crop	Drought of heat resistant	Reduction of risk of yield loss and reduction of irrigation requirements
	Pest resistant	Reduce crop loss when climate conditions are favourable for increased weeds and pests
	Quicker (or slower) maturing varieties	Ensure maturation in growing season shortened by reduced moisture or thermal resources; maximization of yields under longer growing seasons
	Altered mix of crops	Reduction of overall production variability
Tillage and time of operations	Change planting date	Match altered precipitation patterns
	Terracing, ridging	Increase moisture availability to plants
	Land levelling	Spread water and increase infiltration
	Reduced tillage	Reduction of soil organic matter losses, soil erosion, and nutrients
	Deep ploughing	Break up impervious layers or hardpan, to increase infiltration
	Change fallow and mulching practices	Retain moisture and organic matter
	Alter cultivations	Reduce weed infestation
	Switch seasons for cropping	Change from spring to winter crops to avoid increased summer drought
Crop husbandry	Alter row and plant spacing	Increase root extension to soil water
	Intercropping	Reduce yield variability, maximise 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
Input of agro-chemicals	Vary amounts of fertilizer application	Increase nitrogen to improve yield if more water is available; or decrease to minimise input costs
	Alter time of application	Match applications to (e.g.) altered pattern of precipitation
	Vary amount of chemical control	Avoid pest, weed, and disease damage

2.2. Adaptation of vulnerable areas

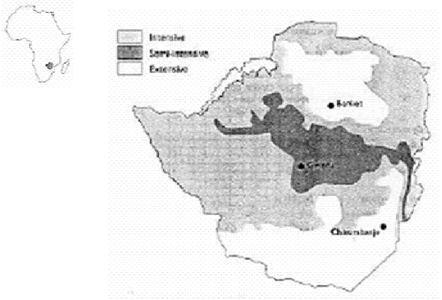
The adaptation capacity of the agriculture sector in developing countries is challenged in particular, because climate change comes in conjunction with high development pressure, increasing populations, water management that is already regulating most of available water resources, and agricultural systems that are often not adapted (anymore) to local conditions. Evidence for limits to adaptation of socioeconomic and agricultural systems in many regions can be documented in recent history. For example, water management schemes were not able to cope with sustained droughts or floods in the late 1990s and early 2000s in many countries, causing severe damage to agriculture and to vulnerable populations. Effective measures to cope with long-term drought and water scarcity are limited and difficult to implement because of the variety of the stakeholders involved and the lack of adequate means to negotiate new policies. The following steps may be taken as an example to evaluate how agricultural adaptation can be assessed: problem definition, evaluation of the biophysical impacts, stakeholder adaptation. Box 1 shows the result of the process as an example in Zimbabwe.

Box 1. Vulnerability and adaptation of maize production to climate change in Zimbabwe

1. Define problem. Maize is the primary crop food in Zimbabwe, occupies about half of the total agricultural cropland, and is grown by all the farming sectors (about two-thirds by communal farmers and one-third by commercial farmers).

Agroclimatic zones

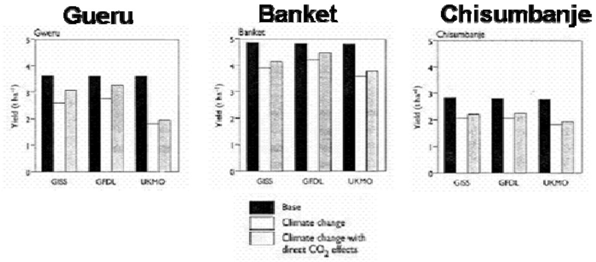
Source: Muchena and Iglesias, 1994



2. Assess biophysical and socioeconomic impacts. All scenarios considered cause decreases in maize production.

Impacts of climate change: CERES-Maize model

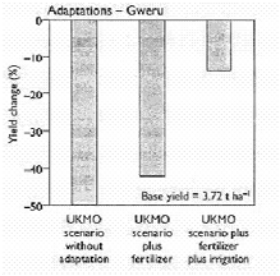
Source: Muchena and Iglesias, 1994



3. Assess adjustments and adaptation strategies. Stakeholders proposed increased agricultural inputs and technology as strategies to decrease the risk of production under current and future climate.

Adaptation strategies in Gueru: CERES-Maize model

Source: Muchena and Iglesias, 1994



Increased inputs and improve management:

- **Fertilizer**
- **Fertilizer and irrigation**

Source: Muchena and Iglesias, 1994.

3. Methods and tools

3.1. General considerations

The methods for assessing climate impacts in crop production and evaluation of adaptation strategies are extensively developed and used widely 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 difficult to model. The tools presented in this chapter are adequate to be used with modified mean climate conditions. To evaluate changes in the frequency and intensity of extreme events such as drought or floods, it is important to include a combination of empirical yield responses based on statistical data and modeling approaches. In all cases, the challenge for interpreting the results is derived from the use of uncertain climate change scenarios.

A number of different approaches to the assessment of the impacts of climate change on agriculture have been developed from many studies conducted to date. Approaches used to assess biophysical impacts include:

- Agroclimatic indices and geographic information systems (GIS)
- Statistical models and yield functions
- Process-based models.

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 U.S. Country Studies Program (Benioff et al., 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 different methods yields information on different types of impacts (see Table 5). For example, simple agroclimatic indices can be used to analyze large-area shifts of cropping zones, whereas process-based crop growth models should be used to analyze changes in 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 approach 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 are visualized in the form of maps. This simple regional approach is essential for integrating climate change, crop production, water demand indices, and socioeconomic indices at the regional scale, thus providing a first-order evaluating tool to analyze possible adaptation strategies.

A site-specific approach involves local studies that analyze 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.

Since economic sectors vary greatly among different 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.

Table 5. Summary of the characteristics of the main agricultural models

Type of model	Description and use	Strengths	Weaknesses
Agroclimatic indices and GIS	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.
Statistical models and yield functions	Based on the empirical relationship between observed climate and crop responses. Used in yield prediction for famine early warning and commodity markets.	Present-day crop and climatic variations are well described.	Do not explain causal mechanisms. May not capture future climate crop relationships or CO_2 fertilization.
Process-based crop models	Calculate crop responses to factors that affect growth and yield (i.e., climate, soils, and management). Used by many agricultural scientists for research and development.	Process based, widely calibrated, and validated. Useful for testing a broad range of adaptations. Test mitigation and adaptation strategies simultaneously. Available for most major crops.	Require detailed weather and management data for best results.
Economic tools	Calculate land values, commodity prices, and economic outcomes for farmers and consumers based on crop production data.	Useful for incorporating financial considerations and market-based adaptations.	Not all social systems, households, and individuals appropriately represented. Climate-induced alterations in availability of land and water not always taken into account. Focus on profit and utility-maximizing behavior. Models are complex and require a lot of data.
Household and village models	Description of coping strategies for current conditions by household and village as the unit of response.	Useful in semi-commercial economies.	Not generalizable; Do not capture future climate stresses, if different from current.

3.2. Agroclimatic indices and GIS

Simple agroclimatic indices combined with GIS have been used to provide an initial evaluation of both global agricultural climate change impacts and shifts in agricultural suitable areas in particular regions. The agroclimatic indices are based on simple relationships of crop suitability or potential to climate (e.g., identifying the temperature thresholds of a given crop or using accumulated temperature over the growing season to predict crop yields; e.g., 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 et al., 1997) has provided understanding of the relationships between the weather, soils, and agricultural production systems and the complexities associated with their variability. Carter and Saarikko (1996) describe basic methods for agroclimatic spatial analysis.

3.3. 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). However, 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 for being 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, e.g., in Spain (Iglesias et al., 1999), China (Rosenzweig et al., 1999) and globally (Parry et al., 2004).

3.4. Process-based crop models

Process-based models use simplified functions to express the interactions between crop growth and the major environmental factors that affect crops (i.e., climate, soils, and management), and many have been used in climate impact assessments. Most were developed as tools in agricultural management, particularly for providing information on the optimal amounts of input (such as fertilizers, pesticides, and irrigation) and their optimal timing. Dynamic crop models are now available for most of the major crops. In each case, the aim is to predict the response of a given crop to specific climate, soil, and management factors governing production. Crop models have been used extensively to represent stakeholders management options (Rosenzweig and Iglesias, 1998).

The ICASA/IBSNAT dynamic crop growth models (International Consortium for Application of Systems Approaches to Agriculture – International Benchmark Sites Network for Agrotechnology Transfer) are structured as a decision support system to facilitate simulations of crop responses to management (DSSAT). The ICASA/IBSNAT models have been used widely for evaluating climate impacts in agriculture at different levels ranging from individual sites to wide geographic areas (see Rosenzweig and Iglesias, 1994, 1998, for a full description of the method). This type of model structure is particularly useful in evaluating the adaptation of agricultural management to climate change. The DSSAT software includes all ICASA/IBSNAT models with an interface that allows output analysis.

The WOFOST model suite is generic and includes model parameters for certain crops (Supit et al., 1994; Boogaard et al., 1998). There are several versions of the models, which are under continuous development at the University of Wageningen.

The EPIC model (Erosion Productivity Impact Calculator; 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.

CROPWAT is an empirical irrigation management model developed by the United Nations Food and Agriculture Organization (FAO) to calculate regional crop water and irrigation requirements from climatic and crop data (CROPWAT, 1995, 2004). Net irrigation demand (balance between the crop evapotranspiration and the water available for the crop) can be calculated for more than 1,000 sites around the world included in the FAOClim database (FAO, 2004). The model can be adjusted to include irrigation efficiency for each region.

Table 6 summarizes the main crop models that have been used for evaluating impacts and adaptation to climate change. Rosenzweig and Iglesias (1998) provide more complete guidelines for using crop models in adaptation studies.

Box 2 provides more information on DSSAT as an example of a crop-specific family of models, and Box 3 provides more information on WOFOST as an example of a generic model.

Table 6. Crop models

Crop	Model
Crop specific	ICASA/IBSANT crop specific models included in the DSSAT software (including all CERES and GRO models listed under each crop)
Generic	WOFOST provides a family of generic models with specific parameters for maize, wheat, sugar beet, and more (not listed under each crop since are not crop specific)
General model	EPIC
Water irrigation requirements for all crops	CROPWAT
Alfalfa	ALSIM, ALFALFA
Barley	CERES-Barley
Cotton	GOSSYM, COTCROP, COTTAM
Dry beans	BEANGRO
Maize	CERES-Maize, CORNF, SIMAIZ, CORNMOD, VT-Maize, GAPS, CUPID
Peanuts	PNUTGRO
Pearl millet	CERES-Millet, RESCAP
Potatoes	SUBSTOR
Rice	CERES-Rice, RICEMOD
Sorghum	CERES-Sorghum, SORGF, SORKAM, RESCAP
Soybeans	SOYGRO, GLYCIM, REALSOY, SOYMOD
Sugarcane	CANEMOD
Wheat	CERES-Wheat, TAMW, SIMTAG, AFRCWHEAT, NWHEAT, SIRIUS, SOILN-Wheat

Box 2. Description of the DSSAT crop models

Description: The DSSAT models use simplified functions to predict the growth of crops as influenced by the major factors that affect yields, i.e., genetics, climate (daily solar radiation, maximum and minimum temperatures, and precipitation), soils, and management. Models are available for many crops (see Table 7.5); these have been validated over a wide range of environments and are not specific to any particular location or soil type. Modeled processes include phenological development, growth of vegetative and reproductive plant parts, extension growth of leaves and stems, senescence of leaves, biomass production and partitioning among plant parts, and root system dynamics. The models include subroutines to simulate the soil and crop water balance and the nitrogen balance.

Variables: The primary variable influencing each phase of plant development is temperature. Potential dry matter production is a function of intercepted radiation; the interception by the canopy is determined by leaf area. The dry matter allocation to different parts of the plant (grain, leaves, stem, roots, etc.) is determined by phenological stage and degree of water stress. Final grain yield is the product of plant population, kernels per plant, and kernel weight. To account for the effect of elevated carbon dioxide on stomatal closure and increased leaf area index, a ratio of transpiration under elevated CO_2 conditions to that under ambient conditions is added.

(i) Inputs

Type of data	Requirements	Source of data
Current climate	Daily maximum and minimum temperatures and solar radiation for at least a 20-year period.	National meteorological or research institutions. Daily data may be simulated from monthly averages when not available.
Modified climate (climate change scenarios)	Modified daily maximum and minimum temperatures, precipitation, and solar radiation for a period of the same length as the current climate.	National meteorological or research institutions.
Crop management	Crop variety, sowing date and density, fertilizer and irrigation inputs (dates and amounts).	Agricultural research institutions.
Soils	Soil albedo and drainage, and a description of the different layers of the soil profile (texture, water holding capacity, organic matter, and nitrogen).	Agricultural or hydrological research institutions.
Economics (optional)	Cost of labor and price of unit production.	Agricultural statistics.

Outputs: Variables included in the summary output file are the main phenological events, yield and yield components.

For more information: Rosenzweig and Iglesias, 1994 and 1998.

Box 3. Description of WOFOST

Description: WOFOST originated in the framework of an interdisciplinary study on potential world food production by the Centre for World Food Studies (CWFS) in cooperation with the Wageningen Agricultural University. Related models are the successive SUCROS models (Simple and Universal CROP growth Simulator), ARID CROP, Spring wheat, MACROS, and ORYZA1. WOFOST version 6.0 is a mechanistic model that explains crop growth on the basis of photosynthesis and respiration, and how these processes are affected by environmental conditions. The crop growth model is generic, and includes model parameters for wheat, grain maize, barley, rice, sugar beet, potato, field bean, soybean, oilseed rape, and dunflower.
Inputs: Meteorological data (rain, temperature, windspeed, global radiation, air humidity) are needed as input. Other input data include volumetric soil moisture content at various suction levels, and other data on saturated and unsaturated water flow. Also data on site-specific soil and crop management are required. The time step for simulation is one day. WOFOST 6.0 includes an option to use average (monthly) weather data. Daily rainfall data are generated using a built-in mathematical generator.
Outputs: The model describes crop growth as biomass accumulation in combination with phenological development.

For more information: Supit et al., 1994; Boogaard et al., 1998.

3.5. Calibration and validation of the crop models

Crop models are assisting tools for assessing the vulnerability and adaptation to climate change: the stakeholder participation is essential. A mandatory first step is that technical stakeholders need assemble field agricultural data for calibration and validation of the crop models. Subsequently, regional stakeholders evaluate the representativeness of the agricultural model results for spatial upscalling of the model results.

In all agricultural models, the procedure involves the adjustment of coefficients that describe crop characteristics and response to environmental conditions. Table 7 summarizes the steps involved in the calibration and validation of the agricultural models with specific references relevant to the DSSAT models as an example. 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 orientative coefficients for each crop for the most commonly used varieties, based on numerous previous and referenced field experiments, is included in the software. The few “genetic coefficients” that describe each variety only attempt to represent the phenology or time of developmental phases (i.e., juvenile stage, flowering, physiological maturity, etc.) and the accumulation of dry mater in the different organs (i.e., roots, vegetative parts, and grain). The limited number of coefficients do not attempt to represent the very large number of characteristics of each crop variety, such as response to pests and diseases.

An enclosed document describes the calibration and validation process in more detail (Iglesias, 2006).

Table 7. Summary of the steps for the calibration and validation of the crop models

Step	Concept / Procedure	Example
1. Calibration of crop phenology	The crop developmental stage determines how the biomass is accumulated and to which organ of the plant is directed Adjust the simulated dates on flowering and physiological maturity to field data	In the 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 the development of the crop can be adjusted to the development in the field.
2. Calibration of grain production	The adequate rate and quantity of biomass accumulation determines final crop productivity Adjust the simulated grain yield to field data	In the 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)
3. Validation of the calibrated model	Ensure that the adjustment of crop model results with one experimental field dataset to represent a wider agricultural area Test if the simulated crop flowering and maturity dates and grain yield represent farmers' results	Well calibrated models should always simulate correctly the dates of crop maturity. Simulated yields may be higher than the ones observed in the farms, but they should represent the geographic variation of farm yields arising from different soils or management conditions.

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3.6. Economic tools

Economic models are designed to estimate the potential impacts of climate change on production, consumption, income, gross domestic product (GDP), employment, and farm value. These may be only partial indicators of social welfare, however. Not all social systems, households, and individuals (for example, smallholder farmers) may be appropriately represented in models that are based on producer and consumer theory. Many of the economic models used in impact analyses to date do not account for the climate-induced alterations in the availability of land and water for irrigation, although such important considerations can be included. Studies and models based on market-oriented economies assume profit and utility maximizing behavior.

Several types of economic approaches have been used for agricultural impact assessment. The most useful of these are simple economic forecasting approaches (e.g., Benioff et al., 1996), which are forecasts based on a structured framework of available economic (production, consumption, and governing policies) and agricultural (production techniques and alternative crops) information. These are generally simple techniques that can be used in most climate impact studies.
The following approaches can also be used, although they are relatively complicated and may be difficult, time-consuming, or expensive to apply.

Economic cross-sectional models. One form of economic analysis is the use of spatial analogues, that is, cropping patterns in areas with climates similar to what may happen under climate change. This Ricardian approach has been used in a number of applications (e.g., Mendelsohn et al., 1994, 1999). Economic models can be based on statistical relationships between climate variables and economic indicators. An advantage of the approach is that farmer adaptation to local climate conditions is implicitly considered. Among the disadvantages are that food prices and domestic farm output prices are considered constant, and key factors that determine agricultural production, such as water availability and carbon fertilization, are not generally considered.

Microeconomic models (farm level). These are models based on the goal of maximizing economic returns to inputs. They are designed to simulate the decision-making process of a representative farmer regarding methods of production and allocation of land, labor, existing infrastructure, and new capital. These farm models have most often been developed as tools for rural planning and agricultural extension, simulating the effects of changes in inputs (e.g., fertilizers, irrigation, credit, management skills) on farm strategy (e.g., cropping mix, employment). They tend to be optimizing economic models using linear programming and require quite specific data and advanced analytic skills. Many take a range of farm types that is representative of those existing in a region and, for each of these types, simulate the mix of crops and inputs that would maximize farm income under given conditions. These conditions can be varied (variation of weather, prices of crops, and fertilizers) and the appropriate farm response modeled. Changes of climate, instead of variations of weather, can be input, and the farm-level response in output and income is then simulated.

Household and village models. In semi-commercial economies, it may be more appropriate to focus on the household or village as the unit of response. Here the objective may be to secure a minimum level of income rather than to maximize income, and the focus of analysis should be on the strategies developed to reduce the negative effects of crop yield changes rather than increase the positive ones. Frequently referred to as coping strategies, these have been analyzed in particular detail in the context of risk of hunger (often related to drought). As with farm models, those climate impact assessments that have included successful analyses on responses at the household and village level have tended to borrow from existing studies, adapting them to consider changes in climate rather than variations of weather. For specific examples of their use in climate impact assessment in Kenya and India, see Akong’a et al. in Parry et al. (1998) and Jodha in Gadgil et al. (1988). For a more general discussion, see Downing (1991).

Macroeconomic models. These can be models of a regional, national, or global agricultural economy. For climate change purposes, the models allocate domestic and foreign consumption and regional production based on given perturbations of crop production, water supply, and demand for irrigation derived from biophysical techniques. Population growth and improvements in technology are set exogenously. These models measure the potential magnitude of climate change impacts on the economic welfare of both producers and consumers of agricultural goods. The predicted changes in production and prices from agricultural sector models can then be used in general equilibrium models of the larger economy. Adams et al. (1990) and Fischer et al. (2002) provide key examples of the use of macroeconomic models.

3.7. 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 the use of sensitivity scenarios combined with agricultural models (for example, increase in temperature from 0^{o} to 3^{o}C and changes in precipitation from -30 to +30 percent) provides and idea of the tolerable thresholds of change for a particular system.

One method that shows to be effective for generating climate change possible 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 sites) and divide them into two periods: for example 1930-1960 and 1970-2000. Then study the statistical properties of each one of those two datasets (means, but also frequency dry spells, of storms, probability of subsequent days with rainfall, etc.). 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). This method has the advantage that it is based in observed changes. Of course the projections may be as bad (or worse) than the traditional method of GCMs.

Finally, an interesting approach is to use a scenario that occurs within the natural climate variability of the region, such as a drought scenario. It is essential that the agricultural evaluations include and test more than one possible scenario and analyse the sensitivity of the response in the context of the current trends of climate. The use of more than one scenario and approach results in a span of outcomes which gives a pertinent notion of uncertainty.

4. Limitations and sources of uncertainty

4.1. Climate change scenarios

Climate change scenarios are derived from global climate models (GCMs) driven by changes in the atmospheric composition that in turn is derived from socio-economic scenarios (SRES, see below). A main challenge is to interpret the results derived from climate scenarios that are used as inputs. In all regions, uncertainties with respect to the magnitude of the expected changes result in uncertainties of the agricultural evaluations. For example, in some regions projections of rainfall, a key variable for crop production, may be positive or negative depending on the climate scenario used. The uncertainty derived from the climate model related to the limitation of current models to represent all atmospheric processes and interactions of the climate system. The limitation of projecting the socio-economic development pathways is an additional source of uncertainty.

4.2. Climate variability

Regional climates naturally fluctuate about the long-term mean. For example, rainfall variability occurs with regard to the timing and quantity, affecting agriculture each year. It is clear that changes have occurred in the past and will continue to occur, and climate change modifies these variability patterns, for example resulting in more droughts and floods. Nevertheless, there are a lot of uncertainties, especially about rainfall scenarios for the future.

4.3. Stakeholders adaptation

The limitations for representing adequately the range of stakeholder choices for adaptation limit the potential results in the V&A assessment. For example, uncertainty on the future choice of strategies when population, social conditions, and competition for natural resources (i.e., water).

4.4. Agricultural models

The 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; there are no problem soil conditions such as high salinity or acidity; and there are no catastrophic weather events such as heavy storms. The agricultural models simulate the current range of agricultural technologies available around the world; they do not include potential improvements in such technology, but may be used to test the effects of some potential improvements, such as improved varieties and irrigation schedules. Provided that the limitations are carefully evaluated, 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 (i.e., drought years, changes in policy for application of agro-chemicals, changes in water input, among others).

4.5. Effects of CO2 on crops

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 result, in theory, plants growing in increased CO_2 conditions will produce more biomass and will consume less water. Experiments in greenhouses confirm such plant behavior, nevertheless due to the multiple interactions of physiological processes, result only in changes smaller than the theoretical ones. In field conditions, the changes are even smaller. Most of the crop models used for climate change evaluations include and option to simulate the effects of CO_2 increase on crop yield and water use (see Rosenzweig and Iglesias, 1998). It is difficult to validate the crop model results since there are only a very limited number of these experiments worldwide, raising uncertainty of the simulated results.

4.6. Issues of scale

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

4.7. Socio-economic projections

The limitations for projecting socio-economic changes not only affect the SRES scenarios but also the potential adaptive capacity of the system. For example, uncertainty of the population (density, distribution, migration), gross domestic product, technology, determine and limit the potential adaptation strategies.

5. Integrated Assessments

One common feature of the different approaches to climate impact assessment is that they all have a geographical dimension. Climate and its impacts vary over space, and this pattern of variation is likely to change as the climate changes. These aspects are of crucial importance for policy makers operating at regional, national, or international scale, because changes in resource patterns may affect regional equity, with consequent implications for planning. Thus the geographical analysis of climatic changes and their impacts, where results are presented as maps, has received growing attention in recent years. This trend has been paralleled by the rapid development of computer-based GIS, which can be used to store, analyze, merge, and depict spatial information. As computer power improves, the feasibility of conducting detailed modeling studies at a regional scale has been enhanced. The main constraint is on the availability of detailed data over large areas, but sophisticated statistical interpolation techniques and the application of stochastic weather generators to provide artificial climatological data at a high time resolution may offer partial solutions. An example of a GIS integrated assessment tool for agricultural vulnerability and assessment is the FAO AEZ model (FAO, 1996; 2002).

6. Information on Datasets

Which data are available or not will frequently affect the type of climate impact assessment that is made, particularly if time and funds are limited. Studies of the impacts of climate change on agriculture require a quantitative description of the exposure unit and the current (baseline) agricultural conditions in the study area. Data are also needed for projecting future (reference case) conditions in the absence of climate change (e.g., projected increases in agricultural technology or fertilizer use). Although specific data requirements will vary with the scope of the study and the method selected (this is discussed in more detail later), the groups of data generally be required and an orientation of the possible data sources is outlined in Table 8.

Table 8. Summary of the datasets required and possible sources

Dataset	Possible sources	Comments
Experimental crop phenology and yield	At the local level, experimental agricultural and extension services of most agricultural Universities and /or Ministries of Agriculture	Necessary to calibrate the agricultural models; two years of data is acceptable; associated data on crop management is required
Yields for the crops to be studied	At the local level, extension services of most Ministries of Agriculture	Time series to evaluate natural yield variability
Climate data	Meteorological institutes; International Organizations (e.g., FAO; NOAA)	Time series to evaluate natural climate variability and to develop scenarios
Soil characteristics	Ministry of Agriculture; International Organizations (e.g., FAO)	Include soil depth and 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 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, labor, fertilizer and irrigation inputs
Land use	Maps or digital from the Ministries of Agriculture or the Environment; Satellite data from International Organizations	Geographically explicit data necessary to enable spatial extrapolation from sample sites across the study area
General socioeconomic data	Ministry of Agriculture; International Organizations; stakeholder consultation	Include the contribution of sample sites' agricultural production to total output of the study area, percentage of working labor in the agricultural sector
Other	Stakeholder consultation	Additional data may be needed for specific studies (for example, water irrigation requirements, rates of soil degradation and erosion

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