CHAPTER 8

EFFECTS OF CLIMATE CHANGE ON AGRICULTURE

8.1 INTRODUCTION

Climate is constantly changing, and the signals indicating that changes are occurring can be evaluated over a range of temporal and spatial scales. Climate can be viewed as an integration of complex weather conditions averaged over a significant area of the Earth (typically on the order of 100 km² or more), expressed in terms of both the mean of weather represented by properties such as temperature, radiation, atmospheric pressure, wind, humidity, rainfall and cloudiness (among others) and the distribution, or range of variation, of these properties, usually calculated over a period of 30 years. As the frequency and magnitude of seemingly unremarkable events, such as rainstorms, change, the mean and distribution that characterize a particular climate will start to change. Thus the factors influencing climate, as defined here, range from events occurring over periods measured in hours on up through global processes taking centuries.

Changes in climate have over the millenniums been driven by natural processes, and these mechanisms continue to cause change. “Climate change” as a term in common usage over much of the world is now taken to mean anthropogenically driven change in climate. Such climate change may influence agriculture in a positive way (CO₂ fertilization, lengthening of growing seasons, more rainfall) or in a negative way (more drought, faster growth resulting in shorter life cycles, salinization). This chapter will discuss:

(a) Assessment of the available evidence about anthropogenically driven climate change and current thinking regarding global spatial distribution of changes that may occur;
(b) The internationally adopted protocols for evaluating climate change impacts as set out by the Intergovernmental Panel on Climate Change (IPCC) and its parent/related international organizations;
(c) The sources of data for conducting impact assessment and the techniques for regionalizing data to scales smaller than the resolution of global circulation models;
(d) Examples of quantitative models available for assessing climate change impact on bioresource industries\(^1\) and protocols for their use;
(e) The types of impacts that should be considered when undertaking a climate change impact assessment;
(f) The development of an approach to identifying how climate change can or should be managed by bioresource industries, and by agriculture in particular.

Issues that relate to the occurrence of extreme events and particular hazards have been considered in Chapter 7, and these are of most importance for operational and tactical planning, namely, deciding how to do things over a period of 12 months or so and looking forward for a period of perhaps five years. This chapter will consider issues that relate to regional policy development, long-term agricultural planning and adaptation of production systems to changing climate, in other words, strategic planning for bioresource industries. Strategic planning has to be based on a time horizon of approximately 10 to 50 years, which corresponds to the time concept of climate and represents a period comparable to human life expectancy. If complex weather conditions are changing sufficiently rapidly that climate is changing noticeably in a lifetime, whether this is anthropogenically driven or not, it is necessary for information to be available to end-users to allow for suitable strategic planning.

The operational tools required for climate change impact assessment are output data from global climate models, statistical techniques and simulation models of biological systems. In general, organizations that have the resources to employ personnel trained in the application of these tools, the use of which requires only moderate training, will be able to conduct climate change impact assessments. The products of research and planning programmes run at national or regional scales then have to be made available to end-users in a suitably interpreted manner in order to be of value as warning or planning information in a form appropriate for enterprise-scale management.

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1 Industries producing fuel, feed, fibre and food using biological methods.
8.2 SUMMARY OF EVIDENCE FOR CLIMATE CHANGE

Although instrumental observations commenced in some parts of Europe in the seventeenth century, it was the Industrial Revolution that stimulated the initial growth of climate observing networks. In the crowded coalfield cities of northern Europe, public health considerations necessitated the development of piped water infrastructure. Reservoirs needed managing, which in turn required that rainfall and temperature measurements be undertaken. Approaches and equipment gradually became standardized and by the middle of the nineteenth century Europe and parts of North America had skeletal climate observing systems. The International Meteorological Organization was established in 1873 largely to oversee standardization of techniques in observing systems, a role also taken up by its successor, the World Meteorological Organization, in 1950. By then much of the globe was integrated into a coordinated observational network incorporating oceanic and upper-air components, supplemented in more recent times by radiosonde and satellite observations. Standardization of observing procedures enabled global trends to be established with greater confidence and a number of global temperature time series were developed and carefully processed to provide reliable estimates, which generally showed good agreement that climate was indeed changing significantly (Figure 8.1).

The instrumental records show that global mean surface temperatures have increased by 0.74°C over the period between 1906 and 2005, and since 1956 a rate of increase of 0.13°C/decade has prevailed (IPCC, 2007). Warming has been most pronounced over the land masses and high northern latitudes, though the average temperature of the global ocean has also increased to depths of at least 3 000 m (IPCC, 2007). Consistent with this unequivocal trend, the 1990s constituted the warmest complete decade of the warmest century of the last millennium, although the period 2001–2008 is already 0.19°C warmer (CRU, 2009). Different combinations of stations are used to calculate the global average by various scientific groups and most identify 1998 as the warmest year in the instrumental records, closely followed by 2005. Some groups, however, place 2005 as equal first or clear first in the series, which is somewhat unusual as 2005 was not a marked El Niño year (Kennedy et al., 2006). El Niño is a large-scale ocean–atmosphere climate event that results in a marked warming in sea surface temperatures across the equatorial Pacific Ocean. Global average temperatures tend to be higher in the few months after such an event, which typically recurs every 2–7 years. Thirteen of the 14 warmest years in the instrumental record of global surface temperature (since reliable observations commenced in 1950) have occurred in the past 14 years (CRU, 2009). The average global surface temperature in 2008 was 0.33°C +/-0.05°C above the 1961–1990 average (CRU, 2009). The warming has been greatest during the winter, spring and autumn seasons (Jones et al., 2001). Minimum

![Figure 8.1. Annual global air temperature trend (difference from 1961–90 baseline) (Brohan et al., 2006)](image)
temperatures have been increasing at approximately twice the rate of maximum temperatures, a phenomenon confirmed by many national-scale studies (Zhai and Ren, 1999; Sweeney et al., 2002; Vincent and Gullet, 1999).

Such decreases in the daily temperature range implicate cloud cover as a possible agent, and cloudiness has increased in most regions in recent decades. Associated with this, global land precipitation has increased by 2 per cent per over the past century (Jones and Hulme, 1996). Much more spatial variability is occurring with precipitation than with temperature, however. Over most mid- and high-latitude continental areas of the northern hemisphere, precipitation increases are occurring, while in the subtropics and tropics a downward trend is present, especially since the 1970s (IPCC, 2007). Associated with these precipitation increases in the land areas of the mid- to high latitudes is a tendency towards an increase in the frequency of more intense precipitation events (IPCC, 2007). Such events, more so than changes in the mean conditions, are likely to provide the most serious challenges for agriculture in the years ahead.

Since many observing stations have been located in urban areas, some concerns have periodically been voiced that global temperature changes might have been unduly biased by an urban heat island influence. This has been shown to be unfounded, with urban effects contributing only about 0.05°C to global temperature averages over the course of the twentieth century (Easterling et al., 1997; Peterson et al., 1999). Changes in solar irradiance of about 0.1 per cent also occur over the course of the 11-year solar cycle, which has been implicated in recent global temperature changes as well, though it is now believed that this contribution is not in itself capable of explaining the changes in global temperature of the past century (Tett et al., 1999). Uncertainties regarding the cooling influence of atmospheric aerosols have not yet been satisfactorily resolved, and these remain a major source of uncertainty for climate modellers. Of some significance for agriculturalists is the reduction in evapotranspiration and solar radiation receipt that anthropogenic aerosol loading on the atmosphere may have induced in recent decades in many areas, the so-called “global dimming” effect (Stanhill, 1998). As the application of air pollution controls becomes more widespread in the future, the aerosol load may decrease somewhat, thus further exacerbating warming trends.

Natural fluctuations within the climate system occur on a range of timescales from daily to multi-decadal to millennial, and over a large range of spatial scales. These variations have been revealed by a range of palaeoclimatic reconstruction techniques. Documentary sources, tree ring analysis, palynology, and ice and ocean core analysis have revealed windows into the past which show the longer-term temporal context into which present and future changes fit. Ice cores in particular have provided considerable insight into the climatic variations of the past 2 million years and have shown that astronomical forcing of climate is not in itself explanation enough. Climate sometimes changes in radical fashion within a few decades. Much more so than a decade ago, the capacity of the climate system to exhibit “abrupt” global-scale changes is now better appreciated. Regime shifts, often triggered by oceanic circulation changes, are now known to have occurred several times throughout the last glacial-interglacial cycle (Dansgaard et al., 1993) and there is a growing realization that human actions may prematurely reactivate some of these natural ocean–atmosphere mechanisms. On a shorter timescale, decadal modes of variability, including the Arctic Oscillation (an index of the pressure differences between the polar vortex and mid-latitudes), the North Atlantic Oscillation (an index of “westerliness” in Europe) and El Niño–Southern Oscillation (an index of atmosphere–ocean circulation changes in the eastern equatorial Pacific of which El Niño is the warm phase and La Niña the cold phase), are associated with significant changes in oceanic and atmospheric circulation, all of which may affect agricultural productivity over large regional scales.

The current scientific consensus attributes most of the recent warming to anthropogenic activities associated with increasing atmospheric concentrations of greenhouse gases (IPCC, 2007). The primary contribution has been made by CO$_2$ which has increased from pre-Industrial Revolution levels of 280 ppmv (parts per million by volume) to current levels of over 380 ppmv. This is a concentration that has not been exceeded during the past 420 000 years and most likely not during the past 20 million years (IPCC, 2007). A significant contribution to the atmosphere’s greenhouse gas loading also comes from methane. Methane concentrations have already doubled from their pre-industrial levels, with anthropogenic sources contributing over double the natural contribution. Over half the anthropogenic contribution comes from activities associated with bioresource exploitation. Due to methane’s relatively short residence time in the atmosphere, removing a tonne of this gas from the
atmosphere today would contribute 60 times as much benefit to reducing global warming over the next 20 years as removing the same amount of CO₂ (IPCC, 2001).

8.3 SUMMARY OF IPCC PROTOCOL FOR CLIMATE CHANGE IMPACT ASSESSMENT

Climate change impact assessments have traditionally been carried out by developing regionally specific scenarios and then using these to drive models in particular sectors of interest. Thus, for example, a global climate model (GCM) might be downscaled using a regional climate model (RCM) or statistical downscaling (SD) approach to generate high-resolution data for input to a hydrology model, a crop growth model, or a farm management model. To achieve this assessment, the assumptions made at the outset for the GCM are crucial. Central to this is the assumption about which future greenhouse gas emissions projections are likely to occur and what sort of future sulphate aerosol loading the atmosphere is likely to exhibit. In March 2000, IPCC approved a new set of emissions scenarios based on assumptions regarding future demographic, economic and technological “storylines”. These were presented in the Special Report on Emissions Scenarios (SRES) and the family of SRES projections are widely used to provide the input for GCM runs (IPCC, 2000). The scenario-driven impacts can then be examined and further questions of adaptation, vulnerability and risk management addressed.

This conventional “top-down” approach yielding adaptation and vulnerability estimates is increasingly seen as somewhat restrictive. It may be that a particular result is the starting point and the steps necessary to either attain or avoid it form the objective of the exercise. For example, an impact involving the melting of the Greenland ice sheet might be considered catastrophic for coastal flooding and the scenarios necessary to avoid this could be elucidated by a “bottom-up” approach. Climate adaptation policies may be developed from either or both approaches (Figure 8.2). Most adaptation policies show top-down emphases whereby emission models drive scenario models, which in turn drive impact models. For agriculturalists a more individual, bottom-up, response is common, involving concepts of capacity, financial considerations and risk assessment. Farmers are well aware of the basic tenets of risk management or avoidance, and frequently show great willingness to adapt to changing circumstances. A possible risk management approach for agriculturalists based on the United Nations Development Programme (UNDP) Adaptation Policy Framework (Lim et al., 2005) is shown in Figure 8.3.

![Figure 8.2. The top-down vs. bottom-up approach to climate adaptation policy (Dessai and Hulme, 2004)]
8.4 SOURCES OF CLIMATE CHANGE DATA

8.4.1 Global climate model results

Global climate models (GCMs) provide the major pillar for the provision of future scenarios with which to assess the likely impacts of climate change on agriculture. Initially these were relatively crude representations of climate with gross simplifications of key processes and limited incorporation of aspects of the climate system such as the oceans, cryosphere and biosphere. The coupling of these components, and the incorporation of many more submodels, has been a major advance of the past three decades that was facilitated by exponential increases in computer power. In the past, runs of a model were often done on an equilibrium basis, that is, to compare a future climate mode, such as that after a doubling of $\text{CO}_2$, with the present. The ongoing processes and changes involved in reaching this point, such as gradual increases in greenhouse gas loading, or deforestation trends, were not simulated in any detail. Sophistication of these models has also resulted from an improved understanding of the underlying climate processes involved, so that today transient models incorporating many complex components of the climate system are operational. Using combinations of models and multiple simulations from a single model further enhances the utility of GCMs. At present, GCMs are able to provide successful simulations of many aspects of current climate, an attribute that gives confidence in their ability to provide plausible future scenarios.

Typically, a GCM in 2009 had a grid size of 100–300 km, approximately 20 levels above the surface over land areas or below the surface over oceanic areas, and a time step of 10–30 minutes. There are four primary equations describing the movement of energy and momentum, together with the conservation of mass and water vapour, across the three-dimensional surface created. For many climatic processes, such as convective cloud formation, the resolution of several hundred kilometres is too coarse and simplifying representations are made. Inevitably, these limit the effectiveness of GCMs, particularly for users, such as agriculturalists, who need localized information.

GCMs provide an initial indication of key regional vulnerabilities for agriculture. In the developing world, such vulnerabilities compound already existing problems, which means that adaptive potential is inevitably less than in the developed world. In sub-Saharan Africa, GCM rainfall change projections are inconsistent among the various models, with some projecting decreases and others slight increases. Generally though, reductions in cereal potential of up to 12 per cent are expected by 2080 (Davidson et
Projected warming in Asia is most pronounced in the winter (Giorgi and Francisco, 2000). During winter, precipitation amounts are expected to decline significantly over many monsoon areas, although GCMs do not suggest that the summer monsoon rainfall will decrease in reliability significantly (Lal et al., 2000). Extreme events in Asia pose the greatest problem for farmers and there are some indications that extremes are already increasing in frequency (Lal, 2003). Rice yields are projected to decline by 5–12 per cent over India and China with a further 2°C rise in temperature (Lin et al., 2004), and overall rice production in Asia could fall by just under 4 per cent by the end of the present century (Murdiyarso, 2000). Wheat yields are also projected to fall in a similar manner and livestock farming will become difficult in some areas as pasture becomes less productive and migrates northwards (Christensen et al., 2004).

Global climate models are sophisticated and highly expensive to develop. As a result, they are maintained at only a relatively small number of research centres. At present these include three locations in the United States; two in France, Japan and Australia; and one each in Canada, China, Germany and the United Kingdom. Among the best known areCSIRO (Australia), CGCM2 (Canada), ECHAM5 (Germany), HadCM3 (United Kingdom) and CCSM (United States). GCM outputs are readily available through IPCC sources for most models (IPCC, 2006), and detailed instructions for downloading data can be found at the Websites of the Program for Climate Model Diagnosis and Intercomparison (PCMDI, 2006) and the World Data Center for Climate (WDC, 2008).

8.4.2 Regional climate models for regional and local-scale bioresource applications

The limitations imposed by computer processing capacity mean that GCM grid sizes are inappropriate for policymakers and are especially inappropriate for agriculturalists. Farmers are well aware of the importance of local factors, such as soil differences, slope, aspect and shelter, which can be key determinants of crop yield. Many hazards, such as hailstorms or intense convective rainfall, typically occur at sub-GCM grid scale. Downscaling of GCM output to a finer-mesh resolution has thus become a major research objective, and achievement, of climate scientists over the past decade. It is, of course, inevitable that downscaling introduces a further set of uncertainties in the climate scenarios produced (Giorgi, 2005; Wilby et al., 1999).

Regional climate models (RCMs) are produced by nesting a secondary model within one or more of the grid spaces of the GCM. Outputs from the parent GCM, such as pressure, wind, temperature and water vapour, at various altitudes for the area bounding a specified domain of interest, are used to drive the RCM. Within this domain, more spatially detailed output may be produced by the functioning of the RCM. Typically, RCMs offer resolution of approximately 20–50 km. Even this may be too coarse for agriculturalists. In addition, the RCM suffers from any inherent deficiencies in the parent GCM, since only a one-way influence is allowed (GCM → RCM). Multiple GCMs and ensemble-based approaches are increasingly used for which weightings are attributed to individual GCMs, depending on their ability to reproduce present climate (Wilby and Harris, 2006).

Owing to their increased spatial resolution, RCMs have many advantages over GCMs for assessing climate change impacts on agriculture. Land-use data, elevation, rainfall events and soil conditions may all be better represented by RCMs than by GCMs, and some processes, such as convective cloud behaviour, cannot currently be simulated satisfactorily on GCMs, but may be simulated more effectively on RCMs. Resolution is crucial. If it is too coarse, important fine-scale processes, such as cloud formation and local winds, may be lost. If it is too fine, mesoscale features, such as storms, may not be adequately handled by the model.

Regional climate models are much less expensive to run than GCMs and so have been developed for many countries. In some cases, numerical weather forecasting models have been adapted to provide an RCM product. Often RCMs have been developed for specific areas and output data can be difficult to obtain. One such source of regional climate model data exists at the Website of the ENSEMBLES Project of the European Union (ENSEMBLES, 2009).
8.4.3 **Statistical downscaling of GCM outputs for bioresource applications**

Even the improved spatial resolution of RCMs is not adequate to inform decisions in farming. A grid cell of 20 km would, after all, encompass a large city or a wide range of farming landscapes. Therefore, a number of alternative approaches to downscaling have been developed to address this problem. The most elementary approach involves pattern scaling, for which the projected changes of the GCM are simply translated equally to each data point within the domain of interest. For example, a projected warming of 2°C from the GCM would be added to each data location point within the domain. This, however, freezes any geographical variation within the domain, meaning that the present climate spatial pattern remains immutable. It is an approach that is also rather unsuitable for some climate parameters, such as rainfall. A reduction in rainfall predicted by the GCM could, following this method, produce an output of negative rainfall in some instances. It may also fail to capture changes, for example, in rain days or drought lengths for particular locations.

A family of approaches collectively described as empirical statistical downscaling has become widely used where climate scenarios with high spatial and temporal resolution are required. The principles of statistical downscaling are based on the development of mathematical transfer functions or relationships between observed large-scale atmospheric variables, such as upper-air observations, and the surface environmental variable of interest. The relationship is initially established using present-day observational data, and then “forced” using GCM output in order to derive climate scenarios for future time slices. Statistical downscaling is done to a point location and may be achieved for a range of variables, such as wind speed, sunshine hours, precipitation and temperature, depending on the choice of predictor variables. This form of downscaling requires substantially less in the way of computational resources and produces results that are comparable with those based on output from RCMs. As a consequence, the use of statistical downscaling methodologies to produce climate scenarios from GCMs is now the favoured technique for many researchers.

The use of statistical downscaling requires that a number of assumptions be made, the most fundamental of which assumes that the derived relationships between the observed predictor and predictand will remain constant under conditions of climate change and that the relationships are time-invariant (Yarnal, 2001). It also assumes that the large-scale predictor variables are adequately modelled by the GCM for the resultant scenarios to be valid. Busuioc et al. (1998), in their verification of the validity of statistical downscaling techniques, found that in the case considered, GCMs were reliable at the regional scale with respect to precipitation in their study area and that the assumptions of validity of predictor–predictand relationship held up under changed climate conditions. Von Storch et al. (1993) suggested that if statistical downscaling is to be useful, the relationship between predictor and predictand should explain a large part of the observed variability, as is the case with temperature, and that the expected changes in the mean climate should lie within the range of its natural variability. Due to the influence of “local” factors on precipitation occurrence and amounts, however, the relationship between the large-scale predictors used when calibrating the statistical model and site-specific variability is often obscured and hence reflects only a small part of the actual observed variability. This situation is further complicated in areas with significant relief effects on precipitation.

In addition to the regression-based method, a number of other downscaling techniques are included in the family of statistical downscaling. These include approaches based on weather pattern classification and weather generators. Weather pattern methods involve the characterization of atmospheric circulation according to a typology, such as the Lamb weather type (Lamb, 1972). The weather variable in question would then be matched to each type or category and changes in the future occurrence of these would be used to rebuild the climatology for the variable for that future time (Sweeney, 1997). An important assumption of this approach is that the present relationship between the variable concerned and the circulation typology is robust for the future: that the rainfall yield on westerly winds at present will be the same as rainfall yield on westerly winds in the future, for instance. This may not always be a valid assumption. Weather generators produce realistic time series of a climatic variable according to some predetermined statistical constraints. Again, these can be tailored to present conditions initially and then used to simulate future conditions constrained by GCM output. Such an approach is useful for producing large volumes of output data, which is desirable when examining extremes or sequences of particular weather types, such as dry spells, heat-waves and rain days.
8.4.4 Reliability of extreme event prediction

Developing robust future climate scenarios from the techniques described above involves a pathway littered with uncertainties. Uncertainties in the emissions scenarios, uncertainties in the internal functioning of the GCMs, inadequate or non-existent parameterization of various physical processes and neglected or badly handled feedback processes all constitute part of a cascade of uncertainty (Figure 8.4).

This means that great caution is needed in interpreting the reliability of scenarios for policy formulation purposes. This is especially relevant with reference to changes in the frequency of extreme events. Such changes often are dramatic and a very wide range in estimates may occur with even slightly different model runs. Despite this, it is important that likely changes in extreme event frequencies be quantified as far as possible to enable protective measures or alternative actions to be addressed. For example, if a farmer could be apprised of a change in the precipitation regime, such that the once-in-a-decade drought might change to a two-year return period, economic appraisals might suggest alternative crops or management practices. Once a farmer has an idea of the risk that an extreme event may occur, the potential severity can then be considered. For climate change considerations, an objective method of risk analysis can therefore provide a way of placing potential climate hazards in the context of other hazards and enabling decision-makers to choose when and where to react to potential problems.

One way of extracting probability estimates of extreme events from GCMs is to undertake multiple runs with slightly different initial conditions. Each run will produce the same trend, but a slightly different pathway due to internal model variability and slightly different end points. These ensemble runs provide a basis for constructing probability distribution functions (PDFs), which provide a “best guess” as well as a confidence estimate for extremes (Figure 8.5). The PDFs may be further processed, multiple models may be added to the mix, and ultimately expert judgement may be used to characterize the reliability of an estimate of whether an extreme climate event will occur over a fixed period.

The reliability of extreme temperature prediction from GCMs is considered good and a number of studies show that the models perform satisfactorily in predicting current maximum/minimum temperature climatologies, as well as warm/cold spells (Kharin and Zwiers, 2000; McGuffie et al., 1999). The reliability of the prediction of precipitation extremes is much lower than that of temperature, however. This is to be expected, given the great spatial variability precipitation exhibits and the typical grid size of GCMs and even RCMs. Where projected daily precipitation amounts were correlated with grid-box average observations, more success was apparent (Hennessy et al., 1997). It would appear, though, that in the future reliable

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Figure 8.4. The cascade of uncertainty associated with evaluating impacts of climate change
extreme precipitation projections will be dependent on greatly improved grid-size resolution by GCMs. This is already occurring and will also further aid testing of climate change scenarios on crop, animal and forestry productivity and management.

8.5 MODELS FOR EVALUATING CLIMATE CHANGE IMPACTS

Top-down evaluation of climate change impacts (Figure 8.2) can be undertaken by means of three main approaches:

(a) Using conceptual or theoretical concepts to qualitatively assess how climate change might influence agriculture. For example, if one knows that a certain minimum amount of rainfall is required to fall in a particular period for a crop to grow, this concept can be used to evaluate whether, based on global circulation model predictions, the crop will still be viable in the medium term. This approach has the advantages that an expert can integrate many concepts and form an overview impression of the situation, and very little hard data are required in order to apply it to a region. Some of the disadvantages are that interacting effects are difficult to balance, counter-intuitive concepts will not be considered, the real magnitude of the impact is difficult to judge, and for complex systems it is almost impossible for a single person to juggle all the concepts involved. The complexity of agriculture and most other bioresource industries, all of which have significant spatial and temporal interactions, means that using a qualitative approach to evaluating climate change is not all that valuable for end-users.

(b) Using small-scale quantitative simulation models, which can either be statistically based or mechanistic, to predict crop responses to climate change. In this case a conceptual model of how a crop grows and how it interacts with weather and soil might be defined, and then a series of mathematical/statistical equations that describe the conceptual processes could be built. This approach works well for considering primary interactions with climate, which are concerned largely with biophysical issues such as crop yield. The main advantages of this approach are that complex interactions can be more readily handled, a formal sensitivity analysis can be undertaken, the uncertainty associated with the model can be quantified, a quantified result can be presented, and a formal experimental design can be used to plan and undertake the exercise. The disadvantages are that quite large volumes of data are required; the models have to be tested and calibrated and doing this for future climates can be difficult; it can be difficult to assess the tenability of model assumptions for future climate predictions; the model might be amplifying uncertainty in the climate scenario data; and it is difficult for untrained end-users to treat precise quantitative output data as having associated uncertainty. The output of this approach to climate change impact assessment can be very useful to end-users, but can perhaps be misleading unless placed within an interpretive framework or considered in terms of second-order interactions that encompass whole systems, rather than just the primary yield component. It is possible that the impact of climate change on a complex mixed-farming system may be relatively small, namely, that the system has the flexibility to adapt to the change, but it may be quite significant in terms of individual crop yields. Rosenzweig and Iglesias (1998) provide a review of the use of crop models for climate change impact assessment.

(c) Using system-scale quantitative modelling, which can be mechanistic, empirical, statistical or, more likely, a combination of all three. Such an approach to climate change impact assessment has the advantage that it should fully consider enterprise-scale interactions, but the amounts of data required and the tenability of assumptions can be limiting. In general, when using system models some parts of the system will be modelled in detail,
often mechanistically, and others will be kept very simple. For example, the CERES family of crop models (Jones and Kiniry, 1986) consider crop phenology in great detail, but treat the soil as a simple bucket. In contrast, the CENTURY model considers soil carbon and nitrogen dynamics in detail but treats the crop in a more generalized manner (Parton et al., 1992).

A state–pressure–impact–response–adaptation (SPIRA) model (Figure 8.6), as suggested by IPCC (2001), which is effectively a top-down approach, can be used to direct an impact assessment based on the three methods described (qualitative, small-scale model, system model).

For global-scale evaluation, Parry et al. (1999, 2004) used a technique of developing statistical transfer functions to predict yields in terms of predictors such as temperature and available water. This was achieved by using calibrated simulation models to evaluate yield response to climate parameters. The resulting transfer functions can be used to undertake spatial analysis of yield when spatial climate datasets (monthly data) are available. The crop yield results were interpreted by Parry et al. (2004) using a global economic model. The statistical transfer function approach was also used at the national scale by Iglesias et al. (2000) to spatially evaluate changes in wheat production in Spain. This works on the basis that once a model has been calibrated and tested using current climate data, it can be used to run “experiments” to predict yield with changes in temperature, available water and atmospheric CO2. The results are then applied to derive predictor equations that can be used without recourse to daily weather datasets.

It is beyond the scope of this chapter to consider the full social and economic impacts of climate change on bioresource industries, particularly agriculture, where families are intimately linked to land management in a way that is not found with enterprises such as forestry. There are two main views regarding the presentation of results from a climate change impact assessment programme. On the one hand, results can be expressed in biophysical terms – changes in yield, predicted requirements for system adaptation – and on the other hand, results can be expressed in economic terms – the crop/system’s ability to yield more or less profit. This chapter will not consider economic and policy scenario testing, but will focus on the models available for biophysical system simulation. Parry et al. (1999, 2004) provide an example of a global approach to evaluating socio-economic impacts.

A further consideration is the issue raised by Hulme et al. (1999), who advocate that in order to avoid drawing erroneous conclusions from climate change impact assessment with models, an attempt should be made to identify the nature of “natural climate variability”, derived by using global circulation models without climate forcing, and “climate change”, derived using the same model but with climate forcing. They contend that in some circumstances natural climate variability will be more important to end-users than climate change impacts. From an operational and management point of view, it is perhaps irrelevant to worry about whether the conditions predicted to be encountered in the future will be driven by anthropogenically induced climate change or natural climate variability – all that is required are clear pictures of what is most likely to happen and an estimate of the uncertainty associated with the prediction.

8.5.1 Crop models

This section will not discuss all crop models that are available for simulating crop growth, but will consider some examples that have been used by scientists throughout the world and will review some desirable characteristics for a crop model that is to be used for climate change impact assessment.

For a crop model to be useful as a climate change impact assessment tool, it has to reliably predict yield as a function of weather variables and have a relatively limited number of essential variables and parameters – models developed to express understanding derived directly from research are not particularly suited to practical application where limited data might be available for parameterization, calibration and testing. It must also be available
to users in a robust yet flexible package that readily facilitates implementation, have a CO₂ response equation in the simulation, and operate at suitable spatial and temporal scales.

A review of literature for regional studies using the CROPGRO model (for a review of the model, see Hoogenboom et al., 1992), the CERES model (a user manual is provided by Goodwin et al., 1990) and the SUBSTOR model (described by Singh et al., 1998, 1999), has revealed a predominance of work conducted for more developed countries (perhaps because the necessary data of suitable quality are available for these regions). The impact assessments focus mainly on the effects of elevated CO₂, temperature, precipitation and radiation on yield, but some authors have examined how these factors influence crop suitability and changing spatial distributions of crops (for instance, Iglesias et al., 2000; Rosenzweig et al., 2002; Jones and Thornton, 2003). While workers tend to conclude that increases in yield are likely, they discuss issues of importance such as timing of water in Indian monsoon, which can cause reduced yield (Lal et al., 1998, 1999), and the uncertainty of the yield forecasts (soybean and peanut yield increases, maize and wheat yield decreases) in the southeastern United States (Alexandrov and Hoogenboom, 2004). The potential effect of the daytime vs. night-time rise in temperature is discussed by Dhakhwa et al. (1997), who suggest that an asymmetrical change, with greater change at night-time, would have less impact on yield than a symmetrical change. Another important issue is the potential significance of cultivar selection (Alexandrov et al., 2002; Kapetanaki and Rosenzweig, 1997). There have been studies for Africa and other developing regions (for example, Jones and Thornton, 2003), but authors recognize that a model to predict yield changes is unlikely to capture the true impact of climate change on smallholders and non-mechanized farmers in these regions.

Other crop models have been used for climate change impact assessment: EuroWheat (Harrison and Butterfield, 1996; Hulme et al., 1999) for wheat crops; the Hurley pasture model (Thornley and Cannell, 1997) for grass; GLYCIM (Haskell et al., 1997) for soybean; and CropSyst (Stöckle et al., 1994; Tubiello et al., 2000) for various C₃ and C₄ crops, mainly cereals. A characteristic of the work published in scientific literature is that most models are not well adapted to subsistence and low-input production systems, and therefore example studies tend to focus on agricultural production in more developed countries, where mechanization and husbandry inputs are a significant part of the production systems used.

### 8.5.2 Animal models

A review of the literature reveals that there are many crop models available for climate change impact assessment, but there are few animal models that have been used to evaluate the impact of climate change on the animal. Most work focuses on how climate change affects animal production systems, with a particular emphasis on the supply of nutrients to the animal (for instance, the production of grass) and related environmental impacts (soil–water models). Two examples that can be found in the literature are:

- **SPUR** (Wight and Skiles, 1987), which stands for Simulation of Production and Utilization of Rangelands. It is an ecologically based model designed to help optimize rangeland management systems. By considering hydrology, plant growth, animal physiology and harvesting, the model can forecast the effects of environmental conditions on range ecosystems, in addition to the animal simulation based on the Colorado beef cattle production model. The detail and complexity of the animal model mean that it may be excessively detailed for climate change impact work (Mader et al., 2002). The inputs for the animal component include breeding season, calving season, castration date and day of weaning. Animal parameters include birth weight, yearling weight, mature weight, milk production, age at puberty and gestation length. The climate data required are precipitation, maximum and minimum temperature, solar radiation, and wind run. The SPUR model can also be regarded as a system model, as it simulates soil, plant and animal interactions. It is placed under the category of animal model because it has been used for climate change impact assessment for animals (Hanson et al., 1993; Eckert et al., 1995).

- **National Research Council Nutrient Requirements of Beef Cattle** (NRC, 1996). It was published as a book reviewing the literature on beef cattle nutrient requirements, and the accompanying computer models utilize current knowledge of factors that affect the nutritional needs of cattle and enable the user to define these factors to customize the situation for a specific feeding program. The model uses information on diet type, animal status, management, environment and the feeds in the diet. The effect of temperature on voluntary feed intake (VFI) is at the centre of the model. The model uses climate variables,
primarily average daily temperature, to generate an estimate of daily VFI. Based on daily VFI, estimates of production output (daily body weight gain) can then be produced. Frank et al. (1999) used the model to evaluate climate change impacts on animals in the United States.

Testing the validity of assumptions, parameterization and calibration of animal models for less-developed countries is of particular importance given the forecast of drought and heat stress on animals in tropical, semi-arid and Mediterranean regions, and the potential constraints that might hinder adaptation in these situations.

8.5.3 System models

The Decision Support System for Agrotechnology Transfer (DSSAT), which is currently available in version 4.0, is a good example of a system modelling tool. It has been used for the last 15 years for modelling crop (type and phenotype), soil, weather, and management or husbandry interactions (ICASA, 2006), and it has also been employed to assess climate change impacts (for instance, in Holden et al., 2003; Holden and Brereton, 2003).

The minimum dataset required for DSSAT consists of site weather data describing maximum and minimum air temperature, rainfall and radiation (stochastic weather generators are provided to create daily data if only monthly mean data are available); site soil data describing horizonation, texture, bulk density, organic carbon, pH, aluminium saturation and root distribution (basic soil descriptions can be used to parameterize a soil based on examples provided); and management data (planting dates, fertilizer strategies, harvesting, irrigation and crop rotations). Additional detail can be used as required by the research programme. The system then allows the user to define a crop/management scenario using a series of modules:

(a) Land module – defines the types of soils and fields when the system is being used for site-specific work. Can be generalized for climate change impact assessment.
(b) Management module – deals with planting, crop husbandry, rotation management, fertilizer, irrigation and harvesting.
(c) Soil module – a soil water balance submodule and two soil nitrogen/organic matter modules including integration of the CENTURY model. For climate change impact assessment much of the detail can be ignored if suitable data do not exist.
(d) Weather module – reads daily weather data or generates suitable data from monthly mean values.
(e) Soil–plant–atmosphere module – deals with competition for light and water among the soil, plants and atmosphere.
(f) Crop growth simulation modules – specific crop models (CROPGRO, CERES and SUBS-TOR), each of which is well established in the scientific literature, are used to simulate the growth of 19 important crops (soybean, peanut, drybean, chickpea, cowpea, velvet bean, faba bean, pepper, cabbage, tomato, bahia grass, brachiaria grass, rice, maize, millet, sorghum, wheat, barley and potato).

The DSSAT systems can be regarded as a flexible system model, but there have been a number of other specific system models developed, many with a view to understanding more about climate change impacts. Typically, these models focus on a combination of agricultural production and biogeochemical cycling. Examples include:

(a) PaSim (Riedo et al., 1998, 2000). The pasture simulation model is a mechanistic ecosystem model that simulates dry matter production and fluxes of carbon (C), nitrogen (N), water, and energy in permanent grasslands with a high temporal resolution. PaSim consists of submodels for plant growth, microclimate, soil biology and soil physics. It is driven by hourly or daily weather data. Site-specific model parameters include the N-input from mineral and/or organic fertilizers and atmospheric deposition, the fractional clover content of the grass/clover mixture, the depth of the main rooting zone, and soil physical parameters. Different cutting and fertilization patterns as well as different grazing regimes can be specified as management options.
(b) Dairy_sim (Fitzgerald et al., 2005; Holden et al., 2008). Dairy_sim was designed to assess the interactions between climate and management in spring-calving milk production systems based on the grazing of grass pastures. The simulator comprises three main components: a grass herbage growth model, an intake and grazing behaviour model, and a nutrient demand model. The model has been improved to better account for soil water balance and field trafficability, but does not explicitly consider biogeochemical cycles. The level of detail was specified as appropriate for climate change impact studies, but is probably regionally constrained to the Atlantic Arc of Europe and areas with a similar climate.
(c) CENTURY (Parton et al., 1987, 1995). The CENTURY model simulates carbon, nutrient and water dynamics for grassland and forest ecosystems. It includes a soil organic matter/decomposition submodel, a water budget submodel, grassland and forest plant production submodels, and functions for scheduling events. The model computes flows of carbon, nitrogen, phosphorus and sulphur. Initial data requirements are: monthly temperature (minimum, maximum and average in degrees C), monthly total precipitation (cm), soil texture, plant nitrogen, phosphorus, sulphur content and lignin content of plant material, atmospheric and soil nitrogen inputs, and initial concentrations of soil carbon, nitrogen, phosphorus and sulphur.

(d) EPIC (Williams et al., 1990). The Erosion Productivity Impact Calculator (also known as the Environmental Policy Integrated Climate) model was designed to assess the effect of soil erosion on productivity by considering the effects of management decisions on soil, water, nutrient and pesticide movements and their combined impact on soil loss, water quality, and crop yields for areas with homogeneous soils and management. The model has a daily timestep and can simulate up to 4000 years; it has been used for drought assessment, soil loss tolerance assessment, growth simulation, climate change analysis, farm-level planning and water quality analysis. Examples of its application include Mearns et al. (2001) and Brown and Rosenberg (1999).

(e) DNDC (Zhang et al., 2002). The denitrification-decomposition model is a process-oriented model of soil carbon and nitrogen biogeochemistry. It consists of two parts, the first of which considers soil, climate, crop growth and decomposition submodels for predicting soil temperature, moisture, pH, redox potential and substrate concentration profiles driven by ecological drivers (such as climate, soil, vegetation and anthropogenic activity). The second considers nitrification, denitrification and fermentation submodels for predicting NO, N₂O, N₂, CH₄ and NH₃ fluxes based on modelled soil environmental factors.

ForClim is a simplified forest model based on the gap dynamics hypothesis (so-called “gap” models) that was designed to use a limited number of robust assumptions and to be readily parameterized so that it could be used for climate change impact assessment (Bugmann, 1996). It has a modular structure that considers environment, soil and plants separately but interactively, and was tested by evaluating whether it could simulate forest structures related to climate gradients. Examples of its use include Bugmann and Solomon (1995) and Lindner et al. (1997).

The FORSKA/FORSKA 2 models (Prentice et al., 1993) simulate the dynamics of forest landscapes with phenomenological equations for tree growth and environmental feedbacks. Establishment and growth are modified by species-specific functions that consider winter and summer temperature, net assimilation, and sapwood respiration as functions of temperature, CO₂ fertilization, and growing-season drought. All of the trees in a 0.1 ha patch interact through competition for light and nutrients. The landscape is simulated as an array of such patches. The probability of disturbance on a patch is a power function of time since disturbance. This model does not explicitly consider soil fertility but assumes uniform patch conditions and simulates the effect of nutrient limitation using maximum biomass curves. It is also used by Lindner et al. (1997).

It is necessary to recognize that forest models might not simulate meaningful changes from baseline over periods of 20–40 years due to the difficulty of capturing responses in complex ecosystems over relatively short periods. The impact of climate change is more likely to be visible over periods of 75–150 years. For commercial, monoculture forestry, the impact of changes in atmospheric chemistry, drought and high winds may become detectable by simulation modelling for a shorter period because the system is more readily modelled.

8.5.5 Other bioresource models

While most models used by the agricultural community (in its broadest sense) to assess impacts of climate change can be directly related to production aspects, there are models available that look at wider environmental issues that overlap with agricultural activity. A good example of such a model is SPECIES: spatial evaluation of climate impacts on the envelope of species (Pearson et al., 2002). This is a scale-independent model that uses an artificial neural network model coupled to a climate–hydrology model to simulate the
relationship between biota and environment and it is useful for examining the impact of climate change on the distribution of species and how this might change (Berry et al., 2002a). The approach requires quite intensive observations in the region being examined and thus is most useful where there is a well-established and dense meteorological observation network. The SPECIES model has also been used to evaluate forest responses to climate change (Berry et al., 2002b).

8.6 PREPARATION FOR CLIMATE CHANGE IMPACT ASSESSMENT

8.6.1 The global context

Growth in world agricultural production during the last three decades of the twentieth century averaged 2.2 per cent per annum, a rate of growth expected to fall to approximately 0.8 per cent per annum by 2040 (FAO, 2005). This slowdown reflects a decline in population growth rates and an attainment of medium to high per capita consumption rates in many countries, which will reduce the rate of increase in demand for agricultural products. China has a particularly influential role. The deceleration of population growth is expected to be rapid, approaching 0.34 per cent by mid-century (United Nations, 2009), resulting in greater food security globally and a fall in the numbers currently experiencing malnutrition (projected to decrease from current levels of 800 million people to less than half this value by mid-century (FAO, 2005)). When viewed spatially, the picture of decreased dependency on agriculture and other bioresources is less encouraging, with many sub-Saharan countries not being lifted by this “rising tide” of food productivity. In the period up to 2040, climate change is likely to exacerbate food production difficulties, primarily in tropical areas with unreliable rainfall; and as with most natural hazards, it is the poor who are most vulnerable and also the most constrained in terms of their options for adaptation.

8.6.2 Factors to consider for study design

When undertaking analysis to evaluate the potential impact of climate change and to prepare for climate change effects, a number of factors should be considered when designing a study:

(a) The vulnerability of the human community. Is the area’s food secure? Furthermore, is the community dependent on locally produced food, does it require significant food imports, or is it a net exporter of some products and importer of others? An evaluation of post-production food miles might reveal something of the nature of the community, as might an economic analysis to evaluate whether money is available to diversify production and still enable the community to survive;

(b) The likely climate change that might occur. This can be considered in two ways: are changes going to be a gradual shifting of mean values with little change in extremes and ranges, or will there be more extreme events? And how much uncertainty is there regarding the nature of the change? In areas where the only data available are the outputs from GCMs, the resolution at which evaluations can be made is quite coarse. RCMs and statistical downscaling (provided suitable field observations exist) permit the spatial resolution of the evaluation to be finer;

(c) The likely socio-political situation of the area. If there are a range of possible economic and policy scenarios, can suitable modelling frameworks be developed to account for them, or can a theoretical framework for analysing the results be established? Economic uncertainty is probably as important as climate change uncertainty when interpreting the data collected for a climate change impact study;

(d) The availability of suitable models to simulate primary and secondary impacts on agricultural systems. Models for subsistence and tropical garden crops tend to be lacking, and reliable simulation of CO$_2$ effects and complex interactions can also be troublesome;

(e) The uncertainty associated with parameterizing and calibrating models to evaluate impacts. There is a trade-off with this issue in that it is desirable to model interactions that occur within a production system (for instance, elevated temperature and CO$_2$ impacts on yield and the interaction with pests and diseases), but as more detail is included in the model it becomes more difficult to be sure that the output of the study has captured a climate change impact rather than a result associated with uncertainty related to input parameter values. There is perhaps a case for keeping the quantitative modelling quite simple and developing a comprehensive yet qualitative interpretive framework, rather than trying to capture all interactions in a simulation system. A study design that provides a “response envelope” is perhaps the best way forward in areas where data are scarce or associated with great uncertainty.
The impact predicted as a result of the study will depend on the combination and interaction of vulnerability, physical environment, social environment and the hazard, which in this case will be climate change. When vulnerability and hazard coincide in an environment that resists adaptation, an adverse impact can be expected. The major climate hazards that might be expected and the general nature of their impact are considered in the following sections in order to provide a framework for initial impact study design; it must always be remembered, however, that elevated CO₂ and other environmental properties will have interactions with these factors.

**8.6.3 Specific weather-related effects**

**8.6.3.1 Temperature effects**

The effect of changing temperature as a result of climate change can be interpreted in terms of a number of interactions with crops and animals. Care should be taken when preparing scenario data for use with a model and when planning a modelling experiment to work out how temperature changes are likely to occur. If mean monthly temperatures increase due to increases in minimum temperature (for example, at night-time), the consequences for a crop may be quite different compared to situations in which the same change is caused by an increase in daytime temperature. Rising night-time temperature can lead to decreases in yield (Kukla and Karl, 1993), whereas increasing daytime temperature might increase yields in northern latitudes (by increasing growing-season length) but decrease yields in middle latitudes (due to earlier ripening) (Droogers et al., 2003). Impact assessment relying on mean monthly temperature data for future scenarios (for example, Holden et al., 2003) must be used carefully when stochastically deriving daily temperature data from monthly means. It is important to understand the consequences of using mean monthly data as opposed to mean monthly minimum and maximum data.

When choosing a model and designing an experimental approach, it is necessary to consider the nature of the likely temperature impact on a given crop. If a crop is sensitive to temperature thresholds, such as a requirement for a low-temperature vernalization period (for example, winter wheat), or has a critical maximum temperature for survival (such as 32°C for cotton fruit survival, as reported by Reddy et al., 2000), the modelling scenario has to be sensitive to these issues. It is perhaps easier to capture effects like overall elevated growing season temperature, but the simulation model used should be sensitive to the known effects of thermal accumulation (normally expressed as growing degree-days, for example, in Keane and Sheridan, 2004). If growing degree-days accumulate more rapidly, the crop will normally progress through its growth cycle faster and the growing season will be shorter. For most crops, elevated temperature causes a reduction in yield as there is less time for the capture of light, water and nutrients by the plant (Lawlor and Mitchell, 2000). When simulating climate change impact, it is important to try to capture the effects of temperature sequences during critical vernalization and growth periods. Elevated temperature during early growth stages will often be beneficial, but during the time of maximum growth it can be detrimental because this period is shortened. An understanding of the development of the plant is crucial to developing a meaningful simulation experiment to capture climate change impacts.

Temperature increases will also have some direct consequences for animal productivity. Increased thermal stress will reduce animal eating and grazing activity (Mader and Davis, 2004) and can cause reductions in yield and fertility. These consequences are likely to be most severe in tropical, semi-arid and Mediterranean regions, rather than temperate areas where neutral or positive effects might be seen. Where cold limitations are removed in temperate areas, productivity might even increase. In order to capture the potential impact of climate change, it is necessary to model the plant and animal part of animal production systems where it is envisaged that temperature changes might cause stress to the animal. In general, higher temperatures during the growing season will be associated with higher radiation and a demand for more water, which along with elevated CO₂ are major interactions that have to be considered in any impact assessment exercise.

**8.6.3.2 Water availability**

The availability of water is fundamental to agriculture. The impact of climate change can occur through three major routes: drought, which is a lack of water for a period of time causing severe physiological stress to plants and animals; flooding, which is an excess of water for a period of time causing physiological and direct physical stress to plants and animals; and timing of water availability, that is, when a severe lack or excess of water does not occur, but its availability throughout the year changes so as to no longer be suitable for current agricultural practices, crops or animals. When evaluating climate change impacts in areas
typically using irrigation, the analysis of water availability must consider how the supply is buffered/stored for irrigation use. Irrigation demand is likely to rise in most regions with temperature increases, as a result of increased evapotranspiration and possibly related decreases in rainfall at critical times during the growing season.

Theoretically, C₄ crops should require less water per gram of carbon assimilated than C₃ crops (Young and Long, 2000) and this means that crops like sorghum and maize should be more tolerant of water stress than other cereal crops. In reality, maize suffers more irreparable damage due to water stress than does sorghum (Doggett, 1988) and is less suited to drought conditions due to its morphology and physiology. It is interesting to note that sorghum is also more tolerant of temporary waterlogged conditions than maize. There is evidence that soybean yields suffer with both early and late water stress in the growing season (for instance, Jones et al., 1985) and therefore timing of water availability might be important. These brief examples illustrate the importance of choosing the best possible model for the intended impact assessment. A model that cannot account for species or plant breeding effects may misrepresent the impact of climate change in a region; the cost of such detail in a model, however, is usually associated with a need for large amounts of data in order to parameterize and test the model. The temporal resolution of a model is also important because it should be sufficient to capture transient extreme events. Studies in the United States indicate that predicted decreases in yield are more extreme when short-term weather events are simulated than when predictions rely on mean data (Rosenzweig et al., 2002). Recent examples of extreme temperature and associated drought could be used to test the suitability of a model for climate change impact assessment. The 2003 drought in Europe (Ciais et al., 2005) and droughts since the mid-1980s in Africa (for example, Desta and Coppock, 2002) provide quantified evidence for the testing of models in these regions prior to future prediction of climate change impacts.

8.6.3.3 Wind effects

Wind can affect crops, forests, animals and the soil, in each case having a direct impact on the productivity and perhaps sustainability of a system of production. For most field crops, wind is important as a regulator of evapotranspiration and as a modifier of canopy structure. While agricultural crop models will tend to capture evapotranspiration effects, morphological influences are usually regarded as being unimportant and are not explicitly modelled. The occurrence of a relatively continuous moderate wind is advantageous for the control of virus diseases in crops such as potato (Mercer et al., 2004), but such issues are very difficult to capture in a meaningful way by most modelling exercises. Wind can have both positive and negative influences on production livestock. In areas with cold stress, wind amplifies the problem, particularly for young animals. When heat stress is a problem, wind can effectively raise the temperature at which production declines by increasing heat loss from the animal. It has been stated that wind is the most important weather variable influencing forestry in western Europe (Ní Dhubháin and Gardiner, 2004), causing physiological, morphological and anatomical impacts. The impact of infrequent and quite short-term storm events will be quite different from that of long-term continuous wind. Short-term high wind speeds cause windthrow, while long-term continuous wind (in the range of 7–15 m s⁻¹) can cause deformation and stunted growth. In areas where soil is poorly structured and dominated by silt or fine sand, continuous wind above 10 m s⁻¹ can cause erosion to occur. Consideration should be given to whether such environmental consequences are likely to be important in a given region when designing a modelling experiment for impact assessment.

The most important question to ask when assessing climate change impacts is whether it is necessary to capture wind effects and if it is, whether this can be done reliably. The question relates to the two types of impacts: short-term high winds (such as hurricanes, tropical storms, tornadoes), and long-term changes in the wind climate (such as a progressive but slight increase or decrease in mean wind speed or a change in wind direction distribution). For situations where wind will affect drying rates and soil water content, which in turn will influence crop production and demand for water, wind climate must be considered, but might be captured in terms of a change in evapotranspiration rates. Where wind might have a devastating effect (for instance, in monsoon regions and the Caribbean) it is necessary to at least interpret the results of crop models in terms of the likelihood of a complete loss of crop output.

8.6.3.4 Photosynthetically active radiation

Photosynthetically active radiation (PAR) is that proportion of solar radiation (about 50 per cent) which actively drives photosynthesis (wavelengths between 0.4 and 0.7 μm). Monteith (1977) established that biomass growth could be expressed as
a function of PAR, the fraction of PAR intercepted by foliage (FPAR), the radiation use efficiency of the plant (RUE) and time. Most models driven by weather data require an estimate of either incident solar radiation (usually expressed in terms of energy per unit area per unit time) or sunshine hours (for conversion using a suitable empirical formula) in place of a PAR value. In terms of photosynthesis it is actually the number of photons per unit area per unit time that is important because all photons in PAR have a similar ability to drive light reactions in photosynthesis (Finkle et al., 2004). The main issue to consider when simulating climate change effects causing changes in PAR is whether the plant is growing in conditions of saturated irradiance. If the plant remains in saturated conditions, a change in PAR will not have any effect; if PAR decreases to the point that the plant photosynthesis becomes related to photon flux density, however, it will be necessary to capture this in the simulation model. The nature of the relationship between photon flux density and photosynthesis and the amount of energy required for photosynthesis is specific to plant type (particularly C3 vs. C4) and cultivar. For intensively managed monoculture crops and forages, there is little need to consider plant competition for light with climate change, but for agriculture that is currently sustained by (semi-)natural ecosystems, changing plant competition for PAR may be very important, as might interactions with CO2 and nutrient and water availability.

8.6.3.5 Elevated CO2 effects

It is widely recognized that elevated atmospheric CO2 will have a “fertilization” effect, increasing crop biomass and possibly crop yield, but not necessarily crop quality. Climate change impact modelling must take account of these effects and preferably what is known of CO2 interactions with other factors. The direct effects of increased atmospheric CO2 concentrations on plant productivity are substantial. In ideal conditions, photosynthesis can increase by 30–50 per cent for C3 plants and by 10–25 per cent for C4 plants (Ainsworth and Long, 2005). Such increases are not readily translated into crop productivity, however. In the real world, soil conditions, nutrient availability, pests and diseases, and competition from weeds and other crops render yields much reduced from these figures. Experiments with food crops growing in enriched CO2 chambers suggest that doubled CO2 concentrations boost wheat and rice yields by 10–15 per cent and potato yields by 30 per cent (Derner et al., 2003). Grasslands show an increase of 15–20 per cent in productivity (Nowak et al., 2004). Similarly, positive results are obtained for many forest crops, especially many commercial species, if fertilizers are used (Wittig et al., 2005). It is interesting to note that many potential biofuel crops, such as miscanthus and willow, also thrive under enhanced CO2 concentrations (Veteli et al., 2002). Less confidence exists that any increases in crop yields will automatically be translated into increases in nutrient quality, and some experiments suggest that reductions in mineral nutrients and protein content may occur (Wu et al., 2004).

It is estimated that yields for many crops will increase by the period 2010–2030 (CSCDGC, 2002), with a projected boost in rice yields of 15 per cent, and figures of 19 per cent for cotton, 15 per cent for wheat, 8 per cent for maize, 8 per cent for beet, and 12 per cent for tomato. On average a 17 per cent increase in yield across all crops might be expected when atmospheric CO2 reaches 550 ppm (Long et al., 2004), which is possible before 2050 (IPCC, 1992). Such a simplistic approach to impact modelling is, however, unacceptable for situations in which the resources are not intensively managed, most specifically for open and rangeland grazing. In these situations the elevation of atmospheric CO2 is likely to cause changes in the quality of food available to grazers (for example, in protein content) and the types of food (changes in plant communities) (Ehleringer et al., 2002). While major impacts such as thermal stress and drought are likely to overshadow a CO2 influence on plant communities in tropical, semi-arid and Mediterranean climates, a change in plant communities and food quality may need to be captured when modelling extensively managed grazing systems in temperate situations. Changing plant community interactions will probably extend to pests and diseases and the interaction of elevated CO2 and warmer temperatures will probably result in greater crop loss due to these factors (for example, in Stacey and Fellows, 2002).

Irrespective of the theoretical benefits of CO2 for agriculture and bioresources, the secondary influences of climate change, namely temperature and precipitation change, will frequently be counter-productive. The extent to which these secondary influences will negate the positive direct influences of CO2 fertilization is not at all clear, however, and further research is necessary to establish which influence dominates yield outcomes. The result is also likely to vary spatially, as well as for specific crops and management practices. Certainly, higher temperatures will extend the growing season in mid-latitudes, and signs of this are already apparent (Sweeney et al., 2002). Higher
temperatures will also increase substantially the potential crop yields in high mid-latitude locations and permit the agricultural margin to move to higher altitudes. Frost damage will be substantially reduced at some locations (Howden, 2003). Greater warmth in summer may also induce greater heat stress.

8.7 ASSESSING THE EFFECT OF CLIMATE CHANGE ON BIORESOURCE INDUSTRIES

A standardized approach for climate change impact assessment has been defined by IPCC (Parry and Carter, 1998; IPCC, 2001). It is probably best for most impact assessments to be based on these types of defined formats. Other approaches have been used in the scientific literature, however. There are a number of issues that need to be considered when examining the impact of climate change. These can be grouped under the following headings:

(a) Spatial resolution – do you want to address issues on a regional, national, catchment or farm scale? At larger scales there is little point in choosing an approach that requires detailed model parameterization and vast amounts of data for testing and running the models. At smaller scales there is little point in using very detailed system simulations if they are not very sensitive to climate drivers and there are only poor climate data available for the simulation site. Care must also be taken when crossing scale boundaries if generalizing or becoming more specific in the interpretation of the results.

(b) Temporal resolution – do you have suitable data to work at daily, weekly or monthly time steps? Is the time step appropriate for the types of impact envisaged for the system and to drive suitable models? Evidence suggests that predicted impacts are less severe when coarser temporal resolution data are used (for instance, in Carbone et al., 2003; Doherty et al., 2003), but if finer resolution data are not directly available, care must be taken to assess the uncertainty associated with data manipulation. If the expected responses are very time-dependent (for example, changes in timing and rate of change of growth during crop development), then finer temporal resolution data (for example, daily) will be needed. A simulation model that requires sub-daily time-step weather data will probably not be suitable for climate change impact assessment due to the uncertainty associated with moving from GCM to RCM/statistically downscaled data to achieve the fine temporal resolution.

(c) Uncertainty – how certain can one be about the results of climate change impact studies? There is a cascade of uncertainty (Figure 8.4) associated with the process of assessing impact on agriculture; it starts with the GCM, progresses through the regionalization (RCM or statistical downscaling), feeds into the components of the yield or system model that is used (soil, plant, water and nutrient modules may interact and have different sensitivity to the main climate drivers), and finally influences the interpretation in light of the regional policy, social, political, infrastructure and economic framework. As the impact assessment becomes more quantitative and the models used become more complex, the uncertainty becomes less clear. It is necessary to choose tools for impact assessment that capture the essence of the systems of production in the region but do not require undue levels of detail in order to run the models.

(d) Sensitivity – how sensitive is the model to the climate drivers? Most modellers will assess overall model sensitivity to input variables as part of the process of undertaking a modelling exercise. For complex system models, it is desirable to evaluate the sensitivity of each major competent or module in order to understand how the model sensitivity may influence the interpretation of the results. For example, if a model is used that has a plant development component that is very sensitive to weather data, but a soil component that is not, the predicted impacts of water supply may be biased. For climate change impact assessment, it is important that the model be insensitive to less important parameters and variables, particularly those for which data are not readily available.

(e) Socio-economic environment/trade buffers – consideration must be given to the framework in which the results are to be assessed. An increase/decrease in yield will be regionally important only if the region being assessed is very dependent on agriculture as a source of income and alternative crops cannot be found, if the region lacks food security and cannot import or grow substitutes, and if the product does not grow in any other region.

(f) Adaptation options – after the impact of climate change on agriculture for a specific region or crop type is evaluated, the logical follow-up is to consider the adaptations that
are possible. There are a number of ways of doing this, ranging from using simulation models to expert knowledge. Adaptations can be viewed at a range of scales (global, national, regional, local, farm) and in terms of strategic adjustments and tactical adjustments (examples are presented in Table 8.1).

8.7.1 A proposed action plan for climate change impact assessment

Following this review of the necessary issues for the planning of a climate change impact study, the series of questions detailed in Table 8.2 provide a route towards a suitable plan of action. These questions require detailed consideration in light of local knowledge and data availability. Initially, the most important question is whether a study has the capacity to access and manipulate global climate model data in a manner meaningful for the intended impact assessment. Even if global climate model data can be accessed, this does not mean that the data are automatically going to be useful for impact assessment if the region has a number of distinct agroclimatic zones that need to be considered. If qualitative or semi-quantitative approaches have to be used, then significant work may still be undertaken that can be of value to end-users. It is very important that the results of the assessments undertaken are interpreted and presented in a manner useful for the end-user.

8.8 CLOSING OBSERVATIONS

This chapter should provide a good starting point for undertaking a climate change impact assessment. It provides information on concepts that have to be considered during the planning stage, sources of information and data, modelling tools and other concepts for estimating impacts, and a structured framework for developing the process. These ideas are, of course, somewhat transitory in that current thinking in this area is rapidly evolving. Consultation with the latest Intergovernmental Panel on Climate Change (2007) publications and the academic literature is essential prior to commencing any impact assessment exercise in order to evaluate what is already known and to establish the state of the art with regard to approach and methodology. Once this has been done, the type of study undertaken will be dictated by the quality and resolution of climate forecast data and the availability of field data in the region for model parameterization, calibration and testing prior to making impact forecasts. Provided that a structured and planned approach is taken and data are interpreted in light of stated assumptions and limitations, useful results should be produced.

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<td>Balance of food and non-food crops</td>
<td>Crop “mixes”</td>
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<td>Policy to support farm-level adaptations</td>
<td>Balance of cash vs. food crops</td>
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<td>Water management</td>
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<td>Variety selection</td>
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<td>Animal breed</td>
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<td>Timing of activity</td>
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<td>Water conservation</td>
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<td>Plant and animal breeding for heat and drought tolerance</td>
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</table>
Table 8.2. Questions to ask as a route towards developing a climate change impact assessment project

<table>
<thead>
<tr>
<th>Do you have global climate model data for your region and a means to use them?</th>
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</thead>
<tbody>
<tr>
<td><strong>NO (1)</strong></td>
</tr>
<tr>
<td>(a) Estimate climate change impacts from available global and regional map data, considering: temperature, precipitation, PAR, wind and CO₂ elevation expected for the forecast time period.</td>
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<tr>
<td>(b) Collate information on climate, policy, trade, social and economic factors.</td>
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<td>(c) Define a series of forecast scenarios and define a series of response envelopes within which current production systems can continue to function.</td>
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<tr>
<td>(d) Make qualitative and semi-quantitative estimates of the types of impacts that might occur.</td>
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<tr>
<td>(e) Do the future scenarios evaluated suggest that current production systems remain within the response envelope?</td>
</tr>
<tr>
<td><strong>NO: What other options are there? Go back to step N1(c) and evaluate them.</strong></td>
</tr>
<tr>
<td><strong>YES: Will production be sustainable?</strong></td>
</tr>
<tr>
<td><strong>NO: What other options are there? Go back to step N1(c) and evaluate them.</strong></td>
</tr>
<tr>
<td><strong>YES: Continue. Publicize the results. Alert farmers and producers in the region if adaptation is necessary, provide information to policymakers to ensure a sustainable production environment is fostered for the future.</strong></td>
</tr>
<tr>
<td>(g) Evaluate the impacts with respect to the defined forecast scenarios and envelopes of response. Do the future scenarios evaluated suggest that current production systems remain within the response envelope?</td>
</tr>
</tbody>
</table>

What adaptation will be required?
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CHAPTER 8. EFFECTS OF CLIMATE CHANGE ON AGRICULTURE


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