The Effects of Climate Change on Agriculture

Article · March 2006

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Chapter 17: Effects of Climate Change on Agriculture

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17.1. Introduction

Climate is constantly changing, and the signal that indicates that the changes are occurring can be evaluated over a range of temporal and spatial scales. We can consider climate to be an integration of complex weather conditions averaged over a significant area of the earth (typically in the region of 100 km^2 or more), expressed in terms of both the *mean* of weather expressed by properties such as temperature, radiation, atmospheric pressure, wind, humidity, rainfall and cloudiness (amongst 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 change, such as rain storms, the mean and distribution that characterise a particular climate will start to change. Thus climate, as we define it, is influenced by events occurring over periods of hours, through to global processes taking centuries.

Changes in climate have over the millenia 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 (CO_2 fertilisation, lengthening of growing seasons, more rainfall) or negative way (more drought, faster growth thus shorter life cycles, salinization). In this chapter we will discus:

- Assessment of the available evidence about anthropogenically driven climate change and current thinking regarding global spatial distribution of changes that may occur;
- The internationally adopted protocols for evaluating climate change impacts as set out by the Intergovenrmental Panel on Climate Change and its parent/related international organisations;
- The sources of data for conducting impact assessment and the techniques for regionalising data to scales smaller than the resolution of global circulation models;

- Examples of quantitative models available for assessing climate change impact on bioresource industries[†], and protocols for their use;
- The types of impacts that should be considered when undertaking a climate change impact assessment; and
- The development of an approach to identifying how climate change can or should be managed by bioresource industries, and agriculture in particular.

Issues that relate to the occurance of extreme events and particular hazards have been considered in Chapter 7, and these are of most importance for *operational* and *tactical* planning, i.e. deciding how to do things over a period of 12 months or so and looking forward for a period of maybe 5 years. In this chapter we 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 perhaps 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 life-time, whether this is anthropogenically driven or not, it is necessary for informaiton to be aviable to end-users to permit suitable strategic plans to be made.

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 gereral, organisations that have the resources to employ personnel trained in the use of these tools, which only require moderate training to be used, will be able to conduct climate change impact assessments. The product 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 suitable for enterprise scale management.

[†] industries producing of fuel, feed, fibre and food using biological methods.

17.2 Summary of Evidence for Climate Change

Although instrumental observations commenced in some parts of Europe in the 17th 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 piped water infrastructure to be developed. Reservoirs needed managing, in turn requiring rainfall and temperature measurements to be undertaken. Approaches and equipment gradually became standardised and by the middle of the 19th century Europe and parts of North America had skeletal climate observing systems. The International Meteorological Organisation was established in 1873 largely to oversee standardisation of techniques in observing systems, a role also taken up by its successor the World Meteorological Organisation in 1953. By then much of the globe was integrated into a co-ordinated observational network incorporating oceanic and upper air components, supplemented in more recent times by radiosonde and satellite observations. Standardisation of observing procedures enabled global trends to be more confidently established and a number of global temperature time series were developed and carefully processed to provide confident estimates which generally showed good agreement that climate was indeed changing significantly (Figure 17.1).

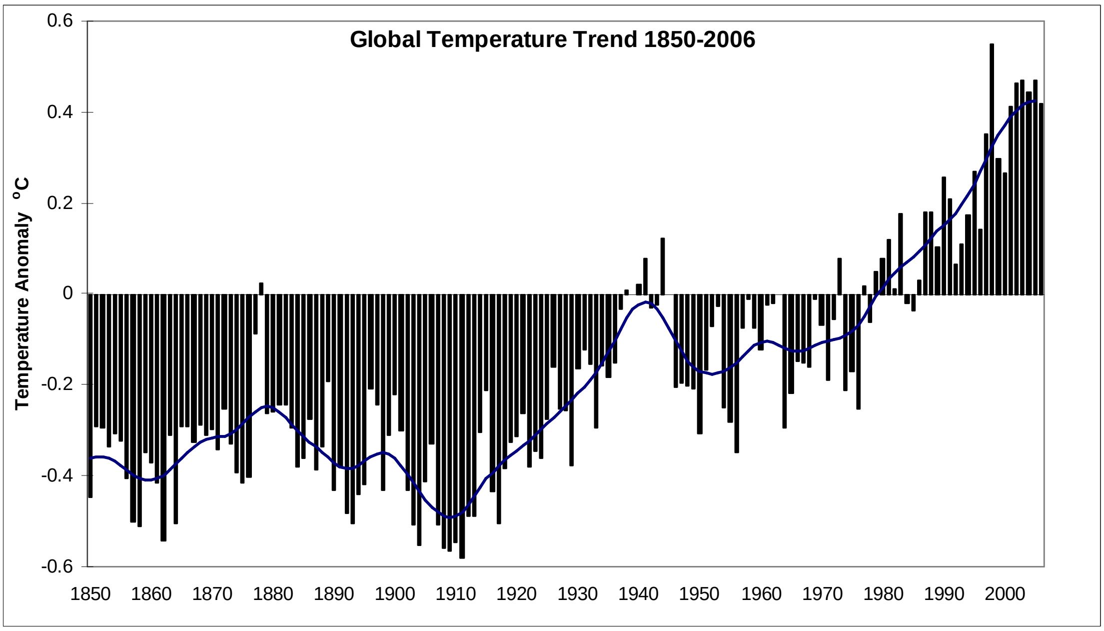

Figure 17.1. Annual Global Air Temperature Trend (difference from 1961-90 baseline).

(Source: Brohan *et al*, 2006)

The instrumental records show that global mean surface temperatures have increased by 0.6+/-0.2 C over the course of the 20th century and since 1976 a rate of increase of 0.15 C/decade has prevailed (IPCC, 2001). In recent decades warming has been most pronounced over the land masses and as far as the northern hemisphere is concerned the 1990s constituted the warmest decade of the warmest century of the last millennium. 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 Nino year (Kennedy et al, 2006). (El Niño is a large-scale ocean-atmosphere climate event which 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 whcih typically recurs every 2-7 years).) Indeed the consecutive years 2002-2006 all figure in the warmest eight years on record globally, indicating a period of accelerated warming is underway. The average global surface temperature in 2005 was 0.46 +/-0.1 C above the 1961-90 average (Kennedy et al, 2006), representing about 0.75 C above pre-industrial temperature levels. The warming has been greatest during the winter, spring and autumn seasons (Jones *et al*., 2001). Minimum 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 over the past century (Jones and Hulme, 1996). However, much more spatial variability in precipitation is occurring than with temperature. Over most mid and high latitude continental areas of the northern hemisphere precipitation increases are occurring, while in the sub-tropical Northern Hemisphere land areas, precipitation has decreased by 0.3% per decade (IPCC, 2001). Associated with these precipitation increases in the mid to high latitudes is a tendency towards an increase in the frequency of more intense precipitation events (IPCC, 2001).

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 only of the order of 0.05 C on global temperature averages over the course of the 20th century (Easterling et al, 1997; Peterson et al, 1999). Changes in solar irradiance of about 0.1% also occur over the course of the 11 year solar cycle which has also been implicated in recent global temperature changes, though it is now believed 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 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 exacerbating warming trends further.

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 realisation that human actions may re-activate some of these natural ocean-atmosphere mechanisms prematurely. On a shorter time scale, 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 Nino-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 impact on 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, 2001). The primary contribution has been made by CO_2 which has increased from pre-Industrial Revolution levels of 280 p.p.m.v. (parts per million volume) to current levels of over 380 p.p.m.v. 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, 2001). 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 its relatively short residence time in the atmosphere removing a tonne of methane 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 CO_2 (IPCC, 2001).

17.3 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 or 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 of what future greenhouse gas emissions projections are likely to occur and what future sulphate aerosol loading the atmosphere is likely to exhibit. In March 2000 the IPCC approved a new set of emissions scenarios based on assumptions regarding future demographic, economic and technological ‘storylines’. These were presented in a Special Report on Emission Scenarios (SRES) and the family of SRES projections are widely used to provide the input for GCM runs (Nakićenović et al, 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 elucidated by a ‘bottom-up’ approach. Climate adaptation policies may be developed from either or both approaches (Figure 17.2). Most adaptation policies show top-down emphases whereby emission models drive scenario models whcih in turn drive impact models. For agriculturalists a more individual, bottom-up, reponse is common, involving concepts of capacity, finacial 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 United Nations Development Programme (UNDP) Adaptation Policy Framework (Lim et al., 2005) is shown in Figure 17.3.

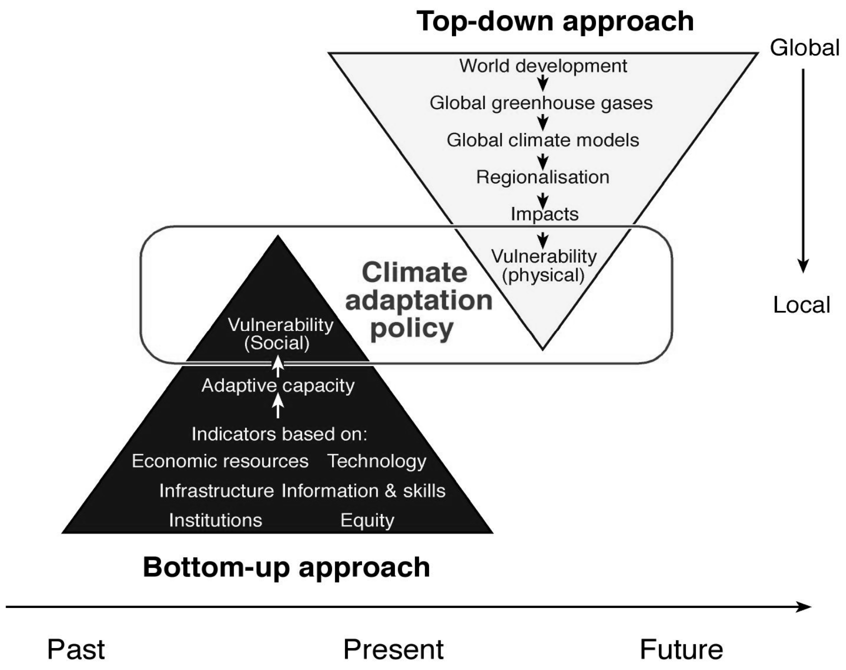

Figure 17.2. The top-down vs. bottom-up approach to climate adaptation policy.

(Source: Dessai and Hulme, 2004)

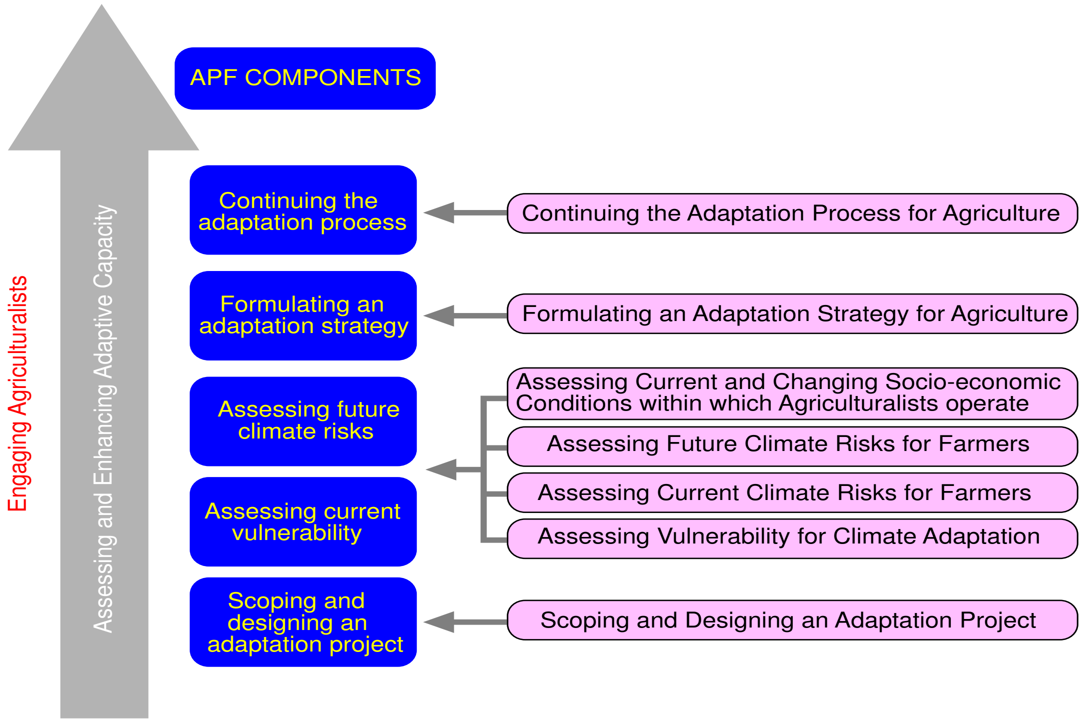

Figure 17.3. A climate change risk management approach based on the UNDP Adaptation Policy Framework (APF) (Source: Lim *et al*., 2005).

17.4 Sources of climate change data

17.4.1 Global Climate Model Outputs

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. Coupling of these components, and the incorporation of many more sub models, has been a major advance of the past three decades facilitated by exponential increases in computer power. In the past, runs of a model were often done on an equilibrium basis i.e. to compare a future climate mode, such as that after a doubling of 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. Presently, 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 2005 had a grid size of about 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 localised information.

GCMs provide an initial indication of key regional vulnerabilities for agriculture. In the developing world such vulnerabilities compound already existing problems such that adaptive potential is inevitably less than in the developed world. In sub Saharan Africa GCM rainfall change projections are inconsistent between the various models, with some projecting decreases and others slight increases. Generally though, reductions in cereal potential of up to 12% are expected by 2080 (Davidson et al, 2003). Egypt for example faces reductions of 11% in rice and 28% in soyabeans by 2050 (Eid and El-Marsafawy, 2002). Some areas, such as the uplands fare better from a lengthening of the growing season and in some regions livestock productivity may increase. However, for many areas, food producing potential seems set to decline, and Parry (1999) suggests that an additional 60-100 million people may be vulnerable to malnutrition by 2080. The complex interplay between socio-economic and climatic conditions renders African food security highly vulnerable to harvest failures over the coming decades.

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% 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% 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 migrate 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. Presently these include three locations in the United States, two in France, Japan and Australia and one in each of the UK, China, Canada and Germany. Among the best known are HadCM3 (UK), CCSM (US), CSIRO2 (Australia), ECHAM5 (Germany) and CGCM2 (Canada). GCM outputs are readily available through IPCC sources for most models (Intergovernmental Panel on Climate Change, 2006), and detailed instructions for downloading data can be found at the websites of Program for Climate Model Diagnosis and Inter-comparison (2006) and World Data Centre for Climate (2006).

17.4.2 Regional Climate Models for regional and local scale bioresource applications

The limitations imposed by computer processing capacity means that GCM grid sizes are inappropriate for policy makers 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 (RCM) 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 (GCM→RCM) is allowed. Multiple GCMs and ensemble-based approaches are increasingly used whereby weightings are attributed to individual GCMs depending on their ability to reproduce present climate (Wilby and Harris, 2006).

Due 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 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 for the UK and Ireland exists at the website of the UK Climate Impact Programme (2006).

17.4.3 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 involves pattern scaling whereby 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 which is also rather unsuitable for some climate parameters such as rainfall. A reduction in rainfall predicted by the GCM could by this method produce an output of negative rainfall in some instances as well as failing to capture changes, for example, in raindays or drought lengths for particular locations.

A family of approaches collectively described as Empirical Statistical Downscaling has become widely used where high spatial and temporal resolution climate scenarios 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 computational resources and produces results that are comparable to that of 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 are 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. However, due to the influence of ‘local’ factors on precipitation occurrence and amounts, the relationship between the large-scale predictors used when calibrating the statistical model and site specific variability is often obscured and hence, only reflect 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 involved the characterisation 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 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 e.g. that the rainfall yield on westerly winds at present will be the same as rainfall yield on westerly winds in the future. This may not always be a valid assumption. Weather generators output 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, desirable when examining extremes or sequences of particular weather types such as dry spells, heat waves and rain days.

17.4.4 Reliability of Extreme Event Prediction

Developing robust future climate scenarios from the techniques described above involves a pathway littered with uncertainties. Uncertainties in the emission scenarios, uncertainties in the internal functioning of the GCMs, inadequate or non existent parameterisation of various physical processes and neglected or badly handled feedback processes all constitute part of a cascade of uncertainty (Figure 17.4).

This means 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 was appraised 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 of an extreme event occurring, 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.

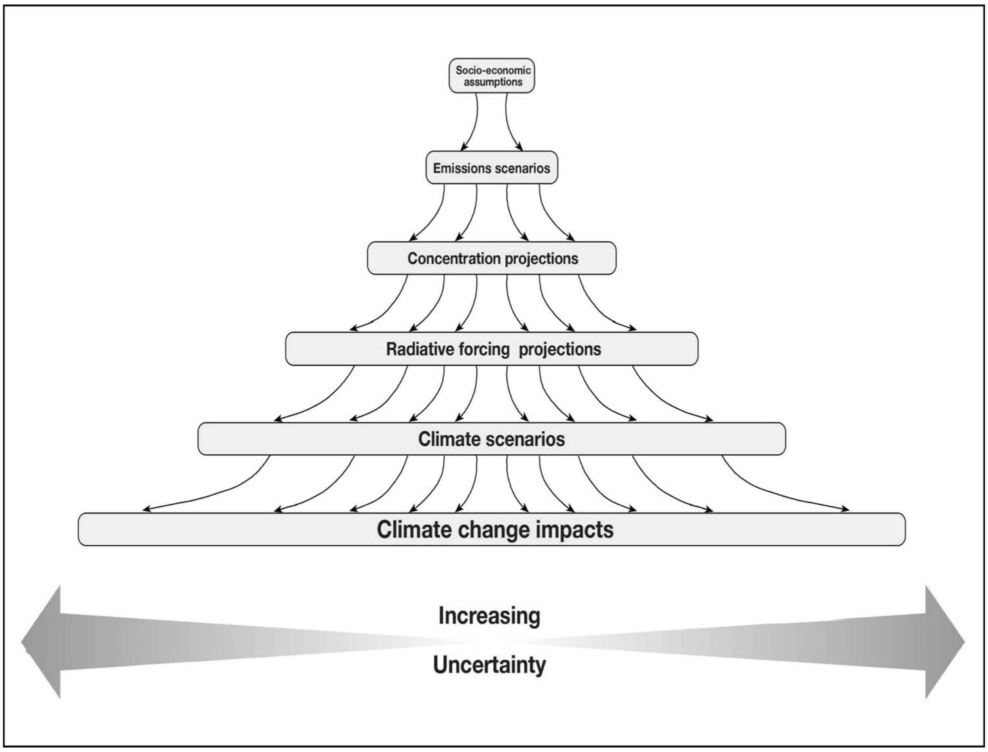

Figure 17.4. The cascade of uncertainty associated with evaluating impacts of climate change.

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 17.5). The PDFs may be further processed, multiple models may be added to the mix and ultimately expert judgement used to characterise the reliability of an estimate of an extreme climate event occurring over a fixed time period.

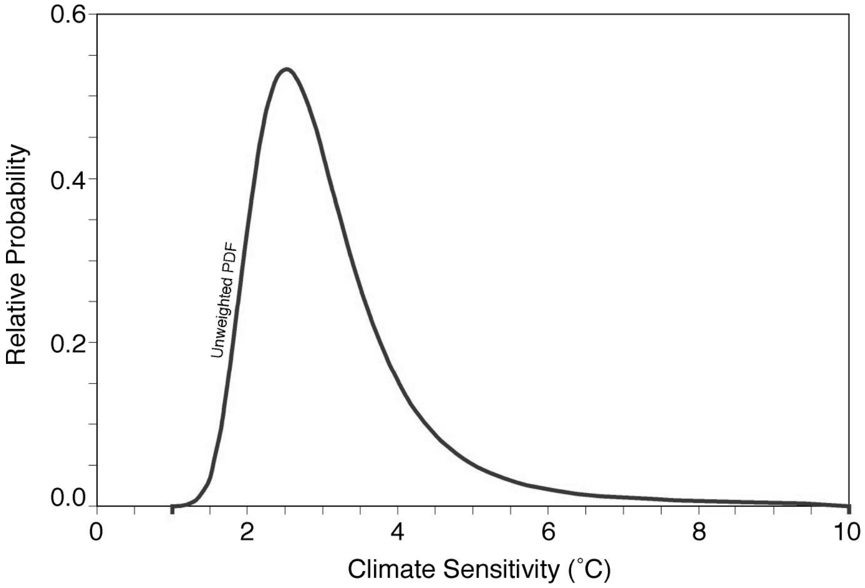

Figure 17.5. A hypothetical Probability Density Function indicating a range of possible global temperatures change for doubling of gobal greenhouse gas concentration (climate sensitivity) based on multiple or ensemble runs of a climate model.

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). Reliability of precipitation extremes is however much less than with temperature. 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 reliable extreme precipitation projections will be dependent on greatly improved grid size resolution by GCMs. This is currently occurring and will also further aid testing of climate change scenarios on crop, animal, forestry productivity and management.

17.5. Models for evaluating climate change impacts

Top-down evaluation of climate change impacts (Figure 17.2) can be undertaken by three main approaches:

(i) Using conceptual or theoretical concepts to *qualitatively* assess how climate change might influence agriculture. For example, if we know that a certain minimum amount of rainfall is required to fall in a particular time period for a crop to grow, we can use this concept 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 (a) an expert can integrate many concepts and form an overview impression of the situation; and (b) it requires very little hard-data to apply to a region. The disadvantages include (a) interacting effects are difficult to balance; (b) counter-intuitive concepts will not be considered; (c) the real magnitude of the impact is difficult to judge; and (d) 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.

(ii) Using small-scale *quantitative* simulation models, which can be either statistically based on mechanistic, to predict crop responses to climate change. In this case we might define a conceptual model of how a crop grows and how it interacts with weather and soil, and then build a series of mathematical/statistical equations that describe the conceptual processes. 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 (a) complex interactions can be more readily handled; (b) a formal sensitivity analysis can be undertaken; (c) the uncertainty associated with the model can be quantified; (d) a quantified result can be presented; and (e) a formal experimental design can be used to plan and undertake the exercise. The disadvantages are that (a) quite large volumes of data are required; (b) the models have to be tested and calibrated and doing this for future climates can be difficult; (c) it can be difficult to assess the tenability of model assumptions for future climate predictions; (d) the model might be amplifying uncertainty in the climate scenario data; and (e) 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 2nd order interactions which 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, i.e. 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.

(iii) 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 simples. 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 generalised manner (Parton et al., 1992).

A State-Pressure-Impact-Response-Adaptation (SPIRA) model (Figure 17.6), as suggested by McCarthy et al. (2001), which is effectively a top-down approach, can be used to direct a impact assessment using the three methods described (qualitative, small-scale mode, 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 Iglasias et al. (2000) to spatially evaluate changes in wheat production in Spain.

This woks 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 CO_2. The results are then used to derive predictor equations that can be used without recourse to daily weather datasets.

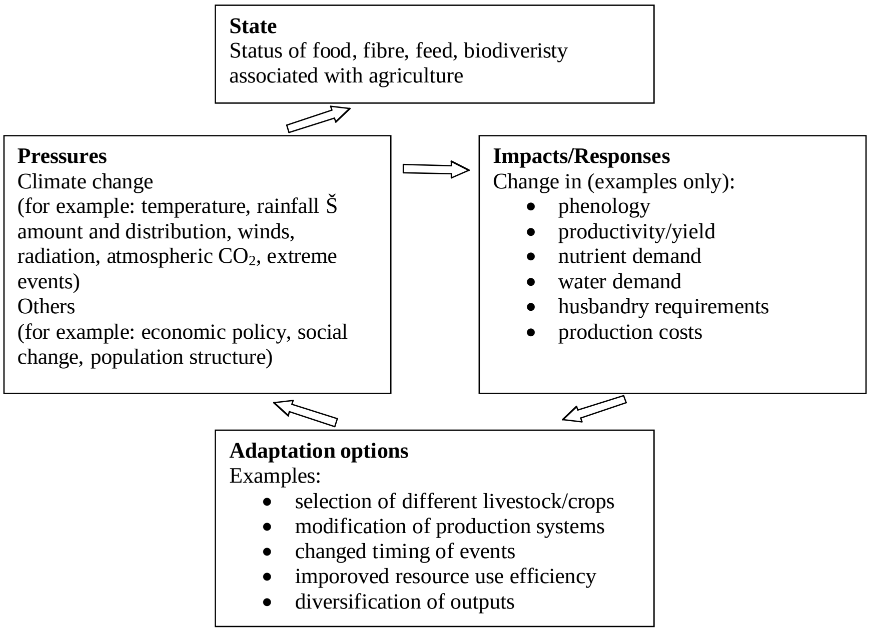

Figure 17.6. The SPIRA model (adapted from the example in McCarthy et al., 2001) is a framework for making climate change impact assessments.

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. In this chapter we will not consider economic and policy scenario testing but will focus on the models available for biophysical system simulation. Parry et al. (1999 and 2004) provide an example of a global approach to evaluating socioeconomic 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.

17.5.1. Crop models

We 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 consider some desirable characteristics for a crop model 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 (i) reliably predict yield as a function of weather variables; (ii) 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 parameterisation, calibration and testing; (iii) be available to users in a robust yet flexible package that readily facilitates implementation; (iv) have a CO_2 response equation in the simulation; and (v) operate at suitable spatial and temporal scales.

A review of literature for regional studies conducted using the CROPGRO (reviewed of the model: Hoogenboom et al., 1992), CERES (user manual: Goodwin et al, 1990) and SUBSTOR (described in: Singh et al., 1998) models reveals a predominance of work conducted for more developed countries (perhaps because the necessary data of suitable quality are available for these regions). Impacts assessed mainly focus on the effects of elevated CO_2, temperature, precipitation and radiation on yield, but some authors have examined how these factors influence crop suitability and changing spatial distributions of crops (e.g. Iglasias 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 like timing of water in Indian monsoon causing reduced yeild (Lal et al, 1998; 1999), the uncertainty of the yield forecasts (soybean and peanut yield increases, maize and wheat yield decrease) in the Southeastern USA (Alexandrov and Hoogenboom, 2004), the potential effect of the day-time vs. night-time rise in temperature (Dhakhwa et al., 1997) who suggested an asymmetrical change with greater change at night-time would have less impact on yield than a symmetrical change, and the potential significance of cultivar selection (Alexandrov et al., 2002, Kapetanaki and Rosenzweig, 1997). There have been studies for Africa and other developing regions (e.g. Jones and Thornton, 2003) but authors recognise that a model to predict yield changes is unlikely to capture the true impact of climate change on small-holders and non-mechanised 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; Hurley pasture model (Thornley and Cannell, 1997) for grass; GLYCIM (Haskett et al, 1997) for soybean; and CropSyst (Stockle 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 mechanisation and husbandry inputs are a significant part of the production systems used.

17.5.2. Animal models

A review of 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 impacts on animal production systems, with particular regard to the supply of nutrient to the animal (e.g. 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). Simulation of Production and Utilization of Rangelands 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 means 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). Published as a book reviewing the literature on beef cattle nutrient requirement, the accompanying computer models utilize current knowledge of factors which affect the nutritional needs of cattle and enables 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. The model was used by Frank et al. (1999) to evaluate climate change impacts on animals in the USA.

The testing of validity of assumptions, parameterisation 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 resist adaptation in these situations.

17.5.3. System models

Decision Support System for Agrotechnology Transfer (DSSAT) is a good example of a system modelling tool, currently available as version 4.0, which has been used for the last 15 years for modelling crop (type and phenotype), soil, weather and management or husbandry interactions (International Consortium for Agricultural Systems Applications, 2006), and has been used to assess climate change impacts (e.g. Holden et al., 2003; Holden and Brereton, 2003).

The minimum dataset required for DSSAT is: (i) *site weather data* (stochastic weather generators are provided to create daily data if only monthly mean data area available) describing maximum and minimum air temperature, rainfall and radiation; (ii) *site soil data* (basic soil descriptions can be used to parameterise a soil based on examples provided) describing horizonation, texture, bulk density, organic carbon, pH, aluminium saturation and root distribution and (iii) *management data* (planting dates, fertiliser 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:

- *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.
- *Management Module*□- deals with planting, crop husbandry, rotation management, fertilizer, irrigation and harvesting
- *Soil module* - a soil water balance sub-module 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.
- *Weather module* - reads daily weather data,□or generates suitable data from monthly mean values

- *Soil-Plant-Atmosphere module* - deals with competition for light and water among the soil, plants, and atmosphere
- *Crop growth simulation modules* – specific crop models, CROPGRO, CERES and SUBSTOR, 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, velvetbean, 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:

- *PaSim* (Riedo et al, 1998; Riedo et al., 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 sub-models 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.
- *Dairy_sim* (Fitzgerald et al, 2005; Holden et al., 2006). 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 similar climate.

- *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 sub-model, a water budget sub-model, grassland and forest plant production sub-models and functions for scheduling events. The model computes flows of carbon, nitrogen, phosphorus and sulphur. Initial data requirements are: monthly temperature (min, max, and average in degrees C), monthly total precipitation (cm), soil texture, plant nitrogen, phosphorus, and sulphur content lignin content of plant material, atmospheric and soil nitrogen inputs and initial concentrations of soil carbon, nitrogen, phosphorus and sulphur.
- *EPIC* (Williams et al, 1990). The Erosion Productivity Impact Calculator (also known as 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 time-step and can simulate up to 4000 years and 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 Rosenerg (1999).
- *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 considering (i) soil, climate, crop growth and decomposition sub-models for predicting soil temperature, moisture, pH, redox potential and substrate concentration profiles driven by ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity) and (ii) nitrification, denitrification and fermentation sub-models for predicting NO, N_2O, N_2, CH_4 and NH_3 fluxes based on modelled soil environmental factors.

17.5.4. Forest models

There are a large number of forest and related models that have been used to evaluate climate change impacts on natural and commercial forestry. Some examples will be used to illustrate the tools available.

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 parameterised 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 Burgman and Solomon (1995) and Lindner et al. (1997).

Forska/Forska 2 (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, CO_2 fertilization, and growing-season drought. All of the trees in a 0.1 ha patch interact by 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 was also used by Lindner et al. (1997)

It is necessary to recognise that forest models might not simulate meaningful changes over periods of 20-40 years from baseline due to the difficulty in capturing responses for complex ecosystems for relatively short time 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 changing atmospheric chemistry, drought and high winds may become detectable by simulation modelling for a shorter time period because the system is more readily modelled.

17.5.5. 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 is useful for examining the impact of climate change on the distribution of species and how this might change (e.g. Berry et al. 2002). 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., 2002).

17.6. Preparation for climate change impact assessment

17.6.1. The global context

Growth in world agricultural production during the last three decades of the 20th century averaged 2.2% per annum, a rate of growth expected to fall to approximately 0.8% per annum by 2040 (FAO, 2005). This slowdown reflects a decline in population growth rates and an attainment of medium to high per capita comsumption rates in many countires, which will reduce the rate of increase in demand for agricultural products; China has a particular influence. The deceleration of population growth is expected to be rapid, approaching 0.4% by mid century (UN, 2005), 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 less dependency on agriculture and other bioresources is less encouraging, with many sub-Saharan countries not being lifted by this ‘rising tide’ of food productivity. Climate change is likely to exacerbate food production difficulties primarily in the areas with unreliable rainfall in the tropics in the period up to 2040, 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.

17.6.2. Factors to consider for study design

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

1. *The vulnerability of the human community*. Is the area 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 there is money available to diversify production and still survive;
2. *The likely climate change that might occur*. This can be considered in two ways: are changes going to be 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 then 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;
3. *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;
4. *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; and
5. *The uncertainly associated with parameterising 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 (e.g. 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 then 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 to provide a framework for initial impact study design, but it must always be remembered that elevated CO_2 and other environmental properties will have interactions with these factors.

17.6.3. Specific weather related effects

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 (e.g. at night-time) the consequences for a crop may be very different to the same change being caused by an increase in day-time temperature. Rising night-time temperature can lead to decreases in yield (Kukla and Karl, 1993), whereas increasing day-time 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., 2004). Impact assessment relying on mean monthly temperature data for future scenarios (e.g. Holden *et al.*, 2004) 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 (e.g. winter wheat) or has a critical maximum temperature for survival (e.g. 32 ^{o}C for cotton fruit survival, 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 know effects of thermal accumulation (normally expressed as growing degree days, e.g. Keane and Sheridan, 2004). If growing degree days accumulate more rapidly then 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). It is important to try to capture the effects of temperature sequences during critical vernalization and growth periods when simulating climate change impact. Elevated temperature during early growth stages will often be beneficial, but during the time of maximum growth can be detrimental due to shortening this period. 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 CO_2 are major interactions that have to be considered in any impact assessment exercise.

Water availability. The availability of water is fundamental to agriculture. The impact of climate change can occur through three major routes: drought – a lack of water for a period of time causing severe physiological stress to plants and animals; flooding – an excess of water for a period of time causing physiological and direct physical stress to plants and animals; and timing of water availability – when severe lack or excess of water does not occur but its availability through 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 due to increased evapotranspiration and possibly related decreases in rainfall at critical times during the growing season.

Theoretically C_4 crops should require less water per gram of carbon assimilated than C_3 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 irreparable damage due to water stress compared to sorghum (Doggett, 1988) and is less suited to drought conditions due to its morphology and physiology. Interestingly, sorghum is also more tolerant of temporary water-logged conditions than maize. There is evidence that soybean yields suffer with both early and late water stress in the growing season (e.g. 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 mis-represent the impact of climate change in a region, however the cost of such detail in the model is usually a need for large amounts of data in order to parameterise 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 USA indicate that predicted decreases on yield are more extreme where 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 (e.g. Desta and Coppock, 2002) provide quantified evidence for the testing of models in these regions prior to future prediction of climate change impacts.

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 to long-term continuous wind. Short-term high wind speeds cause wind-throw while long-term continuous wind (of between 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 of >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 (e.g. hurricanes, tropical storms, tornadoes); and long-term changes in the wind climate (e.g. progressive but slight increase or decrease in mean wind speed or a change in wind direction distribution). For situations where wind will effect drying rates and soil water content, which in turn will influence crop production and demand for water, then wind climate must be considered, but might be captured in terms of a change in evapotranspiration rates. Where wind might have a devastating effect (e.g. 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.

Photosynthetically active radiation. Photosynthetically active radiation (PAR) is that proportion of solar radiation (about 50%) that 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 then a change in PAR will not have any effect, however if PAR decreases to the point that the plant photosynthesis becomes related to photon flux density 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 plant type (particularly C_3 vs. C_4) and cultivar specific. 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 CO_2, nutrient and water availability.

Elevated CO_2 effects. It is widely recognised that elevated atmospheric CO_2 will have an "fertilisation" effect increasing crop biomass, possibly crop yield, but not necessarily crop quality. Climate change impact modelling must take account of these effects, and preferably what is known of CO_2 interactions with other factors. The direct effects of increased atmospheric CO_2 concentrations on plant productivity are substantial. In ideal conditions photosynthesis can increase by 30-50% for C3 plants and 10-25% 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 CO_2 chambers suggest that doubled CO_2 concentrations enhance wheat and rice yields by 10-15% and potatoes by 30% (Derner et al, 2003). Grasslands show an increase of 15-20% in productivity (Nowak et al, 2004). Similarly, positive results are obtained for many forest crops, especially many commercial species, if fertilisers are used (Wittig et al, 2005). Interestingly, many potential biofuel crops such as miscanthus and willow also thrive under enhanced CO_2 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 reductions in mineral nutrients and protein content may occur (Wu et al, 2003).

By the period 2010-2030 it is estimated that yields will increase for many crops (CSCDGC, 2002): rice:15%; cotton: 19%; wheat: 15%; maize: 8%; beet: 8%; and tomato: 12%. On average a 17% increase in yield across all crops might be expected when atmospheric CO_2 reaches 550 ppm (Long et al., 2004) which is possible before 2050 (Houghton et al., 1992). Such a simplistic approach to impact modelling is however unacceptable for situations where the resources are not intensively managed, most specifically for open and rangeland grazing. In these situations the elevation of atmospheric CO_2 is likely to cause changes in the quality of food available to grazers (e.g. 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 CO_2 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 CO_2 and warmer temperatures will probably result in greater crop loss due to these factors (e.g. Stacey and Fellows, 2002).

Irrespective of the theoretical benefits of CO_2 on agriculture and bioresources, the secondary influences of climate change, namely temperature and precipitation change, will frequently be counterproductive. The extent to which these secondary influences will negate the positive direct influences of CO_2 fertilisation 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, signs of which are already apparent (Sweeney et al, 2002), and 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.

17.7. Assessing the effect of climate change on bioresource industries

The Intergovernmental Panel on Climate Change defined a standardised approach for climate change impact assessment (Parry and Carter, 1998; McCarthy et al., 2001). It is probably best for most impact assessments to be based on these types of defined formats, however other approaches have been used in the scientific literature. There are a number of issues that need to be considered when examining the impact of climate change. These can be grouped under the headings:

- 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 parameterisation 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: (1) not very sensitive to climate drivers and (2) there are only poor climate data available for the simulation site. Care must also be taken when crossing scale boundaries if generalising or becoming more specific in the interpretation of the results;

- 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? There is evidence that suggests predicted impacts are less severe when using coarser temporal resolution data (e.g. Carbone et al., 2003; Doherty et al., 2003) but if finer resolution data are not directly available then care must be taken to assess the uncertainty associated with data manipulation. If the expected responses are very time-dependent (e.g. changes in timing and rate of change of growth during crop development) then finer temporal resolution data (e.g. 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 form GCM, to RCM/statistically downscaled data to achieve the fine temporal resolution;
- Uncertainty – how certain can we be about the results of climate change impact studies? There is a cascade of uncertainty (Figure 17.4) associated with the process of assessing impact on agriculture which starts with the GCM, progresses through the regionalisation (RCM or statistical downscaling), feeds into the components of the yield or system model that is used (ie. soil, plant, water, 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 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.
- 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, then the predicted impacts of water supply may be biased. For climate change impact assessment it is important that the model is insensitive to less important parameters and variables, particularly those for which data are not readily available.

- 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 only be regionally important if (i) the region being assessed is very dependant on agriculture as a source of income and alternative crops cannot be found; (ii) if the region is food insecure and cannot import or grow substitutes and (iii) if the product does not grow in any other region.
- Adaptation options – having evaluated the impact of climate change on agriculture for a specific region or crop type the consequential 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 region, national, regional, local, farm) and in terms of strategic adjustments and tactical adjustments (example are presented in Table 17.1).

<table>
<tr><th colspan="5">Scale</th></tr>
<tr><th><i>Global</i></th><th><i>National</i></th><th><i>Region</i></th><th><i>Local</i></th><th><i>Farm</i></th></tr>
<tr><td rowspan="2">• Shifting centres of production</td><td colspan="2" rowspan="2">• Land allocation
• Labour supply/demand
• Balance of food and non-food crops
• Policy to support farm-level adaptations</td><td colspan="2">• Type of farming
• Rotations
• Crop “mixes”
• Balance of cash vs. food crops
• Water management</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">• Varity selection
• Animal breed
• Timing of activity
• Water conservation</td></tr>
<tr><td colspan="3">• Plant and animal breeding for heat and drought tolerance</td></tr>
</table>

Table 17.1. Examples of potential agricultural adaptations to climate change at various scales

17.7.1. A proposed action plan for climate change impact assessment

Having considered the necessary issues for the planning of a climate change impact study, a series of questions detailed in Table 17.2 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 can 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.

17.8. 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 (2006) publications and the academic literature is essential prior to commencing any impact assessment exercise to evaluate what is already known and to establish the state-of-the-art with regard to approach and methodology. Having done this, 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 parameterisation, calibration and testing prior to making impact forecasts. Provided a structured and planned approach is taken, and data are interpreted in light of stated assumptions and limitations, useful results should be produced.

<table>
<tr><td colspan="3">Do you have Global Climate Model data for your region and a means to use them?</td></tr>
<tr><th>NO</th><th colspan="2">YES</th></tr>
<tr><td rowspan="3">(a) Estimate climate change impacts from available global and regional map data considering: temperature, precipitation, PAR, wind and CO_2 elevation expected for the forecast time period
(b) Collate information on climate, policy, trade, social and economic factors
(c) Define a series of forecast scenarios and define a series of response envelopes within which current production systems can continue to function
(d) Make qualitative and semi-quantitative estimates of the types of impacts that might occur
(e) Do the future scenarios evaluated suggest that current production systems remain within the response envelope?
NO: What other options are there? Go back to step N1.3 and evaluate them
YES: Will production be sustainable?
NO: What other options are there? Go back to step N1.3 and evaluate them
YES: Continue. Publicise the results. Alert farmers and producers in the region if adaptation is necessary, provide information to policy makers to ensure a sustainable production environment is fostered for the future</td><td colspan="2">Can you downscale to a finer resolution using Regional Climate Models or Statistical Downscaling (do you have the tools and ground truth data available)?</td></tr>
<tr><th>NO</th><th>YES</th></tr>
<tr><td>You must be aware that quantitative predicted impacts can be less when using coarse-resolution climate data (e.g. Carbone et al., 2003; Doherty et al., 2003). A computer modelling experiment can be undertaken but should run in parallel with a qualitative/semi-quantitative analysis. Proceed using a suitable combination of steps from N1 and Y2.</td><td>(a) Consider whether to use output from a single GCM or a range of models; how many emission scenarios? Compile climate data and derive daily values as needed by the simulation models chosen (downscaled output or stochastically from monthly mean values)
(b) Collate information on climate, policy, trade, social and economic factors
(c) Define forecast scenarios and a series of response envelopes within which current production systems can function. Define optimisation rules for finding the best system (this will be necessary if considering more detail than a primary yield response). Define the scope of the study.
(d) Design a simulation experiment to evaluate the climate change impact. An iterative process may be a good idea. Consider factors such as: parameterisation, calibration, testing, availability of data, sensitivity analysis, cascading uncertainty (Figure 17.4). Try to capture the range on possibilities in the region, commence with a generalized approach and develop specificity. Evaluate what can be left out and omit as much as possible. Some factors are perhaps best dealt with qualitatively.
(e) Select a suitable model - use the simplest possible model that captures the system function. Test model sensitivity for properties lacking quantitative parameter values.
(f) Quantify the impacts as the difference between a standard baseline (1961-1990) and the forecast period. Evaluate whether the response is a significant signal with respect to the model sensitivity, any uncertainties that can be identified and natural variations
(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?
NO: What other options are there?
YES: Will production be sustainable?
NO: What other options are there?
YES: Continue. Publicise the results. Alert farmers and producers in the region if adaptation is necessary, provide information to policy makers to ensure a sustainable production environment is fostered for the future</td></tr>
<tr><td colspan="3">What adaptation will be required?</td></tr>
</table>

Table 17.2. Questions to ask as a route towards developing a climate change impact assessment project.

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