Introduction

The challenges that climate change presents to humanity require an unprecedented ability to predict the responses of crops to environment and management. Geographic information systems (GIS) and crop simulation models are two powerful and highly complementary tools that are increasingly used for such predictive analyses. The role of both technologies in predicting future situations centres around extrapolation. For GIS, extrapolation from the past based on correlation in a very loose sense plays an important role. For crop models, extrapolation based on how known processes respond to factors of interest (i.e. simulation) is a key factor. GIS and crop models can be integrated, providing predictions that combine the spatial perspective of GIS with the stronger representation of temporal processes of simulation models. This chapter reviews the use of these two tools for predicting impacts of climate change and examining options for adaptation. Increasingly, downscaled outputs from a range of global general circulation models under differing future scenarios are used as key inputs for both tools. Examples are given for major food crops and key agricultural zones, with a bias towards tropical and subtropical regions. Consideration is also given to factors limiting efficient application of the tools to climate change research. Both technologies will see increasing use in climate change research and in applications of research in decision making. Credible studies of crop responses to climate involve dealing with large sets of data and potentially millions of simulations, especially if adaptation is considered. While the computational challenges are daunting, the greater challenge is how to devise efficient protocols for selecting the most meaningful scenarios, interpreting the results and summarizing outputs for decision makers.
a rapid and efficient manner is another important factor. The suite of advanced global general circulation models (GCMs) that inform major assessments such as those of the IPCC (e.g., Solomon et al., 2007), and the accompanying emission scenarios developed for the IPCC assessments (IPCC, 2000) form the basis of many climate change assessments (e.g., Parry et al., 2004; Lobell et al., 2008). Increasingly, the outputs of the GCMs under differing emissions scenarios are available in data formats suitable for direct use in GIS-based systems (e.g., the WorldClim data set (2009) see http://www.worldclim.org/futdown.htm). The availability of multiple GCM outputs, coupled to GIS-based systems, has permitted increasing opportunities for analysis of spatial convergence or divergence of GCM outputs at global or regional scales (Neelin et al., 2006; Lobell et al., 2008).

Crop models integrate available information on plant ecophysiology, soil chemistry, agroclimatology and related fields, and simulate key processes thought to determine crop performance in a given environment. For climate change assessments, yield responses for major crops are derived mainly from applications of crop growth simulation models coupled to global or regional climate change models and run under a range of emission scenarios. Coupling mainstream crop simulation models such as CERES and APSIM to a suite of five to ten widely accepted advanced GCMs, for example the Hadley Centre’s HadCM3 or CSIRO’s MK3, and evaluation under the standard range of IPCC emission scenarios has been a common approach (e.g., Defra, 2004, 2005).

Meta-analysis of several such global simulation studies as reported by the IPCC Third Assessment Report (TAR) (IPCC, 2001) and supported by the IPCC FAR (2007) is, not surprisingly, revealing differences between crops and regions, but several global trends are apparent. With global warming, many studies are now indicating an increasing polarization between the high-latitude developed countries and the low-latitude developing regions (e.g., Parry et al., 2004). Taking a major cereal crop like wheat as example, slight increases in yields at mid- to high latitudes are predicted if moderate mean temperature increases (1–3°C) occur. However, further warming, even in temperate regions, causes yields to decrease. In subtropical and tropical regions, wheat is often already near its limit of maximum temperature tolerance, so small temperature increases (1–2°C) reduce yield. Outputs from such simulation studies are providing useful information to inform future decision-making processes, although several uncertainties still remain, for example the extent and role of CO₂ fertilization effects (Long et al., 2006; Tubiello et al., 2007).

Crop simulation models and GIS are vital tools in predicting the impacts of climate change in agricultural systems. The two tools are complementary and the role of both technologies in predicting future situations centres around extrapolation. For GIS, extrapolation from the past based on correlation in a very loose sense plays an important role. For crop models, extrapolation based on how known processes respond to factors of interest (i.e., simulation) is a key factor, with the models often supported by GIS.

This chapter reviews the use of these two tools for predicting impacts of climate change and examining options for adaptation. GIS and crop models can be integrated, providing predictions that combine the spatial perspective of GIS with the stronger representation of temporal processes of simulation models.

Examples are given for major food crops and key agricultural zones, with a bias towards tropical and subtropical regions. Consideration is also given to factors limiting efficient application of the tools to climate change research. The focus is exclusively on climate change and increased CO₂, but principles are similar for O₃, N deposition and other factors, which are often included within global change.

Role and Applications of GIS

A GIS represents a computer-based system for the management of geographically referenced data – that is, data that can be
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GIS is a computer technology that uses a geographic information system as an analytic framework for managing and integrating data; solving a problem; or understanding a past, present, or future situation. GIS is, therefore, about modelling and mapping the world for better decision making.

Common tasks within a GIS include the input, storage, manipulation, analysis and display (often in the form of maps or graphs) of georeferenced data. Mapping is a key output of any GIS, but it is certainly not the only functionality. Common data inputs include data in either vector or raster (gridded) formats. The latter are particularly useful for the representation of continuous data (e.g. climatic variables) and cell-by-cell modelling.

Globally, GIS is applied to disciplines ranging from managing utility networks to health, archaeology and ecology. Increasingly, it is a common component of climate change assessments. The geographic aspect of GIS makes it an interesting option for application to agricultural problems and priority setting because so many of the environmental and socio-economic factors that impact agriculture or agricultural research vary greatly over regions (e.g. Benson, 1996). Typical examples would include rainfall patterns, soil variability, disease and pest distribution, market locations, crop distributions, land-use patterns and human demographics (Table 13.1).

Historically, GIS has seen widespread use for delineation of suitability zones and agroecological zonation (e.g. Hartkamp et al., 2001; Setimela et al., 2005). The ability to combine multi-thematic data based on common geography has been an extremely powerful tool. Common approaches to general

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crop suitability mapping have included the geographical overlay and intersection of key factors such as optimal temperature and moisture ranges, soil types and topographic features. GIS is perfectly suited for undertaking such analysis.

Similar approaches have been undertaken to determine environmental niches in which wild relatives of crops are most likely to occur. The example of the FLORAMAP™ and HOMOLOGUE™ tools developed at Centro Internacional de Agricultura Tropical (CIAT) (Jones and Gladkov, 2001; Jones et al., 2005) typifies this approach. Climatic and environmental conditions existing at known collection sites are used to derive a probabilistic determination of extrapolated similarity zones. This extrapolation, often based on relatively sparse input data, has been used to determine priority zones for future collection efforts of valuable genetic resources or in situ conservation (Jarvis et al., 2003). Both FLORAMAP™ and HOMOLOGUE™ output climate similarity probability maps in GIS data formats.

Location-based climatic factors have also formed the basis of zonations for targeting germplasm of major food crops. Mega-environment classifications have been defined by the International Maize and Wheat Improvement Center (CIMMYT) for both maize and wheat to delimit broadly homogenous global production zones (Braun et al., Chapter 7, this volume). They have been used to assist with priority setting and targeting of germplasm (Setimela et al., 2005; Hodson and White, 2007). For wheat, the extensive network of international wheat trials was the foundation for mapping mega-environments. GIS tools permitted the extraction of climatic and edaphic data from the trial sites and subsequent cluster analysis determined quantitative limits for separation of the major global environments (Hodson and White, 2007). For maize, a similar approach was taken, with the climatic and edaphic data extracted from trial site locations being fundamental to the analysis. In the case of maize, germplasm performance data from the trials was combined with the environmental data and entered into a genotype-by-environment (G × E) analysis.

The resulting mega-environment criteria reflected the major drivers of G × E (Setimela et al., 2005). For both maize and wheat, the final mega-environments had clearly defined quantitative climatic parameters as their foundation, hence mapping of the spatial distributions was a simple task.

Climate-based mapping of potential pest and disease probability occurrence zones is also relevant to the scope of this review. This has been undertaken using very similar approaches to those described for wild relatives and crops. The CLIMEX model developed by Sutherst and Maywald (1991) combines climatic suitability (a growth index) with stress indices to produce an overall index of suitability for a given species at a specific location. Conditions under which known distributions are found are used to infer potential distributions in new areas. The model has been successfully applied to a range of pest and disease species (e.g. Sutherst et al., 1996; Sutherst and Maywald, 2005). As in the case of FLORAMAP™, model outputs are displayed in map form and exported in GIS data formats.

Abiotic stresses, such as drought, have also been assessed using GIS-based analytical approaches. Again climate is a key driver and GIS captures the spatial variation that is essential to interpretation in an agricultural context. One example of an approach to drought modelling was the ‘failed season’ approach described by Jones (see Thornton et al., 2006) and applied to Africa. A water balance model was used, coupled to derived daily climate data for 30 years obtained from the MARKSIM™ weather generator (Jones and Thornton, 2000). A season was determined to fail if an insufficient water balance was maintained throughout the growing season of a typical crop. The final outputs were mapped as a probability of failed seasons at a 30 arc sec (approximately 1 km² grid) for the entire African continent.

These examples illustrate how GIS has been the key technology applied to a range of differing agroecological themes. Spatial integration of multi-thematic data sets was a common element, but so too was use of climate data. This pivotal role of GIS in
agroclimatic analysis is relevant whether the analysis is based on current or historical climate data or predicted future climate data. The increasing availability of outputs from a range of GCMs under varying emission scenarios is permitting a range of GIS-based assessments of the potential characteristics of future crop production zones, and associated abiotic and biotic stresses. Several illustrative case studies will be described in succeeding sections that build upon the examples and themes already outlined.

Role and Applications of Crop Simulation Models

Crop simulation models use quantitative descriptions of ecophysiological processes to predict plant growth and development as influenced by environmental conditions and crop management that are specified for the model as input data (Table 13.2). Many models developed by a single researcher or laboratory are used for a single purpose and have a short life. Others evolve over time and are similar to modern software packages. Among the longer lived models that have seen widespread use in climate change research are APSIM (Keating et al., 2003), the Cropping Systems Model (CSM) series (Jones et al., 2003; Hoogenboom et al., 2004), CROPSET (Stockle et al., 2003) and EPIC (Meinardus et al., 1998).

The simplest models estimate daily growth through conversion factors for intercepted solar radiation to biomass, whereas complex models may simulate growth at a timescale of minutes and include routines to simulate key biochemical pathways of photosynthesis. Hay and Porter (2006) provide a general review of the physiological processes described in models, and Tsuji et al. (1998) describe multiple aspects of models, including soil and weather processes and example applications.

A typical model simulates assimilate production by estimating gross photosynthesis and then reducing the assimilate pool through respiration and senescence. The resulting net pool is then allocated to

| Table 13.2. Examples of data inputs required for a typical crop model that runs with daily time steps. |
|-----------------|--------------------------------------------------------------------------------------------------|
| **Variable**    | **Comments**                                                                                     |
| **Daily weather** |                                                                                                 |
| Maximum and minimum air temperatures | Affect almost all plant and atmospheric processes and are also used to estimate soil temperatures |
| Solar radiation  | Key for establishing potentials for photosynthesis and evapotranspiration. Data are often either unavailable or inaccurate |
| Precipitation   | Affects moisture levels in the soil profile and runoff                                          |
| Dewpoint or vapour pressure deficit | Affects potential evapotranspiration. Average relative humidity is often reported but is a poor indicator of evaporative demand because of confounding with temperature |
| Wind speed       | Affects potential evapotranspiration                                                              |
| **Soil properties** |                                                                                                 |
| Albedo           | Reflectivity of soil to solar radiation. Affects soil temperature and evaporation                  |
| Runoff characteristics | Used to estimate what fraction of precipitation is lost to runoff                              |
| Infiltration characteristics | Used to estimate how moisture enters the profile, is distributed through soil layers, or drains out of the profile |
| Initial water and nutrient levels | Establishes soil conditions for germination and subsequent growth. Preferably determined by soil horizons to the maximum depth of root development |
| **Crop management** |                                                                                                 |
| Sowing rate      | Used to estimate initial stand of plants                                                          |
| Row spacing      | Used to estimate light interception by crop canopy                                               |
| Fertilization    | Type, amount and date of application for any fertilizers                                          |
different plant organs through partitioning rules. The rules assign priority to rapidly growing tissues such as leaves, with onset of reproductive growth representing a key developmental switch. Priorities also shift in order to satisfy the crop demand for water and nutrients. If supplies are limiting, more assimilate is allocated to root growth in order to increase extraction from the soil. Thus, under water or nutrient deficits, root growth may be favoured over leaf, stem or reproductive growth. Furthermore, nutrients may be mobilized from inactive tissues (e.g. older leaves) to organs with high demand.

The timing of key developmental stages such as seedling emergence, end of main stem leaf appearance, anthesis and physiological maturity are simulated using procedures that are analogous to the accumulation of growing degree days (heat units). As required for a given crop, however, the procedures may consider vernalization and photoperiod responses. Models for simulating root and tuber, forage and bioenergy crops are similar to those for seed and grain crops, but allocate assimilates to vegetative storage organs (Singh et al., 1998).

Water and nutrient budgets are usually modelled both for the plants and for the soil, requiring descriptions of root growth through the soil as well as the soil and atmospheric processes that affect water and nutrient dynamics.

Temperature responses

The main effects of temperature are modelled on assimilate production, phenology, soil processes and evapotranspiration. Relatively few models explicitly consider high temperature stresses causing abortion of reproductive structures or irreversible damage to vegetative organs. For models that estimate daily growth through a radiation use efficiency (RUE) approach, the potential RUE is adjusted by a simple temperature function. In the version of the CERES models implemented in the CSM series, these temperature functions weight the daily maximum three times more than the minimum, on the assumption that daytime temperatures influence growth more than night-time temperatures. More complex models such as those using the Farquhar model may involve multiple temperature responses that are evaluated at scales of minutes, and the parameters are determined by measuring component physiological processes.

The occurrence of stages such as flowering and maturity is hastened by temperature, but interactions with vernalization (a requirement for cold temperatures prior to flowering) and day length can override the basic effect of temperature on development.

Physical and chemical processes affecting water and nutrient availability also respond to temperature. The net result is that the basic temperature responses described by models are more complex than one might expect.

Response to CO₂

In RUE-based models, the main effect of CO₂ is through a factor that scales RUE downwards or upwards, a key distinction being whether the crop has a C₃ or C₄ photosynthetic pathway. More complex models combine descriptions of diffusion of CO₂ into the leaves and of the biochemical processes of photosynthesis.

Plants also respond to elevated CO₂ by reducing stomatal conductance, so most models also include an effect adjusting leaf or canopy conductance or transpiration per se (e.g. Tubiello and Ewert, 2002). In models that simulate a complete energy balance, reducing transpiration increases canopy temperature. Thus, an indirect effect of elevated CO₂ is to warm the plants, which should further affect photosynthesis, respiration and development.

Differences among species and cultivars

Qualitatively, the most important physiological processes have proven to be similar across crop species. Furthermore, soil and atmosphere processes are largely species independent. Thus, differences among species are simulated mainly through changes in parameters rather than through
fundamental differences in physiology. Exceptions include differences between C₃ and C₄ photosynthetic mechanisms, the nature of vernalization or photoperiod responses and how these affect phenology, and the ability of legumes to fix atmospheric N. Morphological constraints are also important, especially with regard to growth of seeds, storage roots or other economically important organs. Key parameters that distinguish among species include response curves for temperature and CO₂, critical and maximal levels of nutrients, factors for sensitivity to water or nutrient deficits, and parameters for potential growth of leaves, stems, roots and seeds or fruits.

Parameters for differences among cultivars can involve phenology, partitioning coefficients and reference organ sizes (e.g. maximal area of an individual leaf or mass of a seed). Phenology requires consideration of the relative duration of different phases, and responses to vernalization (if present) and photoperiod. Values of the parameters are usually determined through iterative parameter adjustment and comparison with observed data from field trials (e.g. Piper et al., 1996). This calibration process is problematic because it requires that detailed sets of accurate observations be available. The error inherent in data from field studies makes it difficult to discern whether differences between observed and simulated data are due to incorrect parameter values or to errors in the model per se. Various groups are exploring how to use information from genetics or genomics to parameterize cultivars more reliably (e.g. White and Hoogenboom, 1996; Yin et al., 2000; Messina et al., 2006).

**Crop management**

To simulate the growth of a crop, the model must know how the crop is to be grown, whether for a real world or hypothetical situation. Management information includes the date and manner of planting, the cultivar used, fertilization and irrigation practices, and for some crops, harvest practices (Table 13.2). Tillage and residue management may also be considered. The information either establishes the initial conditions for the simulation or modifies aspects of the environment, such as through addition of N or water to the soil profile.

Basic application of crop models in climate change research

Assuming an appropriate model is at hand and a reference crop production scenario exists, simulating the effects of climate change mainly involves running the model for the weather and CO₂ scenarios of interest. For a single site or region, the scenarios may be specified as fixed (e.g. an increase in daily mean temperature of 2°C) or relative (a 20% decrease in daily precipitation). These adjustments may be held constant over the crop cycle or varied. The choice depends on the objectives and the source of the climate change scenario. Because a season might be unrepresentative of long-term trends, simulations are usually run for 20 or more years. The requisite weather data may come from historical records or from weather generator software that reproduces the statistical properties of historic conditions (e.g. Mavromatis and Jones, 1998; Jones and Thornton, 2003).

A single set of runs can be compared to equivalent runs using unadjusted weather, thus providing one estimate of the potential impact of climate change on economic yield or a diverse range of other traits. None the less, such a comparison ignores the potential that producers will adapt their practices to the changing environment. We examine two hypothetical cases, one for soybean and planting dates and one for maize and N fertilizer response, to illustrate a few of the issues that may be relevant. Both studies assume an increase in CO₂ from 380 ppm (the approximate level in 2005) to 580 ppm.

**Soybean planting date**

Crop response to planting date is readily modelled to examine how warming might affect the potential growing season. For temperate climates, logical expectations are that warming would allow earlier or later
plantings, while elevated CO$_2$ should increase growth and yield. However, warming accelerates development and causes earlier flowering and maturity, which would reduce growth, and at the higher temperatures in summer months, growth might decline further due to a decrease in photosynthesis and increase in respiration.

For Gainesville, Florida (latitude 29°38´N; elevation 10 m), the CSM-CROPGRO-SOYBEAN model predicts that very early plantings result in delayed flowering due to low temperatures, and, as expected, warming reduces the delay (Fig. 13.1a). By April, however, longer day lengths begin to slow development for both treatments. With an early May planting, the warming regime is predicted to slow flowering slightly due to supra-optimal temperatures. Note that the model assumes no effect of CO$_2$ on phenology.

The yield responses suggest that the beneficial effects of elevated CO$_2$ roughly balance the detrimental effects of temperature up to early May, but subsequently,
elevated CO$_2$ provides a small but consistent benefit equivalent to 5–10% of the yield expected for historical conditions (Fig. 13.1b). For plantings around 1 April, additional yield benefit might be obtained by substituting a later-flowering cultivar.

Maize response to warming, elevated CO$_2$ and N

Maize crop growth was simulated for 25-year periods at Palmira, Colombia, an equatorial location (latitude 3°29’N; elevation 965 m) with a mean annual temperature of 25°C. A September planting date was used, corresponding to the onset of the rainy season. The crop was assumed to be rainfed, fertilized at 50, 100 or 200 kg N/ha, and otherwise well managed.

Seed yield declines with increasing temperature for the 200 kg/ha N at ambient (380 ppm) CO$_2$ (Fig. 13.2a) and elevated CO$_2$ (Fig. 13.2b), but not at the other two N levels. Warmer temperatures promote early flowering (Fig. 13.2c), so a portion of the temperature effect on yield relates to the shorter growth duration (Fig. 13.2d). One interpretation of the response to N is that at lower N levels, yield is limited by N and not assimilate production. Alternatively, assumptions about how to model interacting temperature and N stresses in the CSM-CERES-MAIZE model may merit review.

Coupling GIS to crop models

GIS and simulation models complement each other for data management, analysis and presentation. Simulation models have traditionally been used on a site-specific basis, but the coupling to GIS is appealing because it permits the possibility for simultaneous investigation of spatial and temporal variables.
phenomena. Visualization of model summary outputs, for example yield response, via a GIS also adds an extra dimension. As a result, there has been a rapid growth in the number of applications interfacing GIS and simulation models since the late 1980s (Hartkamp et al., 1999). Multiple examples now exist of crop models, typified by the Decision Support System for Agrotechnology Transfer (DSSAT) family, and linked to GIS at a range of spatial scales from field to region (see summary table in Hartkamp et al., 1999). Simulations run over large geographical regions extend the model outputs to areas that have not been validated, so serve more as a sensitivity analysis for the model rather than a precise calculation. However, such assessments do permit the possibility for the evaluation of multiple scenarios in relative terms within a spatial framework. The HarvestChoice project (HarvestChoice, 2009a) is taking such an approach, attempting to simulate yield potential of major crops on a continent-wide basis under a range of differing technological scenarios (see HarvestChoice, 2009b). Availability of highly disaggregated data sets, both spatial and temporal, is fundamental to this approach, and although progress is being made, several challenges still remain.

**Case Studies of Applications of GIS and Modelling to Climate Change**

The application of GIS-based systems to agro-climatic analysis under current climate conditions has already been outlined. The availability of a range of GCM outputs run under a suite of emission scenarios is now permitting similar approaches for potential future climates. With any such approaches it should always be borne in mind that outputs from the GCMs are not precise and variation occurs between different models and scenarios. In addition, for agricultural assessments downscaled GCM results are usually required and this introduces another set of uncertainty. Despite these caveats, the results of such studies can provide useful indications of the potential magnitude of change and the spatial variation that may occur. Selected examples are given below in order to illustrate the range of approaches being undertaken.

**Climate change and crop wild relatives (genetic diversity)**

Tools such as FLORAMAP™ and HOMOLOGUE™ have provided a useful means by which environmental niches and priority areas for wild relative diversity can be identified. Incorporation of future climate data into such tools is providing indications on how the environments supporting wild relatives might change. Using FLORAMAP™ with HadCM3 model data, Jones and Beebe (2001) looked at predicted wild bean environments in Central America in 2055. Their conclusion was striking: in five out of the seven countries studied, the results indicated the virtual disappearance of suitable wild bean habitat by 2055. Jarvis et al. (2001) used a similar approach for wild Arachis species (the closest relatives to cultivated groundnut) in South America. Again the predicted scenarios for 2055 were striking: 12 out of 17 species were predicted to go extinct and four of the remaining five likely to be dangerously threatened. A comparative study of wild relatives of groundnut (Arachis), potato (Solanum) and cowpea (Vigna) under future 2055 climate scenarios reported similar results: high extinction rates, decreased range sizes and increased fragmentation of environments (Jarvis et al., 2008). Such analyses have raised awareness of the potential threat posed to wild relatives and the subsequent loss of important genetic diversity. Use of GIS has allowed graphic visualization of the decline in suitable environments, highlighting where the major effects might occur and providing a quantitative assessment of fragmentation patterns.

**Shifting abiotic and biotic stress distribution**

The previously described mega-environment concept used by CIMMYT captures crop-stress related information. Heat stress is an important yield-limiting factor for wheat and this is captured in one of the mega-environment definitions (ME5).
Redefinition of the mega-environments based on future climate data derived from the CCM3 model (Govindasamy et al., 2003), indicated substantial potential expansion of these lower potential heat-stressed environments in South Asia by 2050 (Hodson and White, 2007 – see Fig. 13.3). Subsequent incorporation of additional GCM data for 2020 (from HadCM3, CSIRO and CCCMA, the Canadian Centre for Climate Modelling and Analysis) also indicated a similar considerable expansion of heat-stressed wheat production environments.

Drought stress is another major concern under climate change. The failed season model previously described provides a framework for looking at future scenarios. Using the HadCM3 A1 scenario for 2050, Thornton et al. (2006) illustrated the potential shifts in frequencies of failed seasons within sub-Saharan Africa. Results obtained indicated a quite dramatic increase in the probability of failed seasons across the agricultural regions of Africa. Embedding the model within a GIS environment permitted clear visualization of the shifting spatial distributions.

Changes in the distributions, species composition and timing of occurrence of agricultural pests and diseases are other factors that will undoubtedly respond to global change, but as a result of complex dynamics between hosts and pests and large variation in pest response to climatic conditions and CO₂ levels, trends are difficult to predict. In broad terms, warmer more humid conditions usually favour insect pests and diseases. Models such as CLIMEX provide opportunities to determine suitability indices for particular species under future climate scenarios (e.g. Sutherst et al., 2000).

Maize in Africa and Latin America

Jones and Thornton (2003) used CSM-CERES-MAIZE to examine impacts of climate change on maize production in Africa and Latin America to 2055. Using GIS, they excluded non-maize regions and assigned soil data to each pixel associated with weather data. The simulations considered four maize cultivars varying in growth duration, and planting dates were assigned based on mean onset of the growing season. Only 50 kg N/ha was applied so that results would correspond to low-input, smallholder farming. The results suggested that climate change would reduce yields by an average of 10%, but with important regional variation, especially in mountainous areas.

Rice in Asia

A common concern in climate change studies is how sensitive projected impacts are to projections for increased greenhouse gases and to the GCM used. Masutomi et al. (2009) compared projections based on differing Special Report on Emissions Scenarios (SRES) as used in 14–18 GCMs, using rice production in Asia as a test case. In the 2020s, all scenarios agreed that the yield-reducing effects of climate would be large enough to offset possible benefits from elevated CO₂. Yield variability also increased with rising CO₂. Overall, the results confirmed that while estimated impacts varied depending on the SRES and GCM, trends were consistent in showing that production will be likely to decrease while yield uncertainty increases.

Low-cost adaptation strategies for rainfed and irrigated production in the Midwestern USA

Easterling et al. (1992) examined adaptation options with notable detail, considering planting dates, N levels, and the possibility of introducing a fallow. Their paper also stands out because potential adaptations were selected based on input from experts. Of 21 potential changes, however, only ten could be simulated with the EPIC model. Earlier planting, longer-season cultivars and furrow dyking would reduce the impacts of warming. Beyond adaptations for single crop species, of course, one can compare how different crops or crop sequences respond to climate change (O’Neal et al., 2005; Thomson et al., 2006).
Fig. 13.3. Comparison of relative distribution of irrigated spring wheat mega-environments (MEs) in South Asia. ME1 is for favourable climatic conditions, and ME5 is for regions where heat stress is expected. (a) MEs under current climatic conditions. (b) MEs for a 2050 scenario (2 × CO$_2$, ccm3 model; Govindasamy et al., 2003). From Hodson and White (2007) reprinted with permission from Cambridge University Press.
Yield loss due to rice blast and warming in Asia

Most simulation studies focus on crop response to abiotic factors. The study of Luo et al. (1998) is one of the few cases where a disease model, for rice blast, was coupled to a crop model, CERES-Rice, to assess potential impact of global warming. Tests were run for 30 years of generated weather data from 53 locations in five countries. Yield impacts varied with region. Blast is favoured by moist conditions with moderate temperatures, so impacts were greater in cooler rice producing regions.

Knowledge, Data, Technology and Intellectual Constraints

The accuracy of crop models is constrained by uncertainty over physiological processes related to climate change. This includes effects of CO₂ and temperature on photosynthesis (Crafts-Brandner and Salvucci, 2004) and net crop responses (Long et al., 2006; Tubiello et al., 2007). There also is evidence that CO₂ affects crop growth and development through mechanisms besides carbon fixation and transpiration. Elevated CO₂ can either accelerate or slow development, depending on the plant species (Reekie et al., 1994; Ellis et al., 1995) and affect plant morphology (Pritchard et al., 1999).

Ignoring whether data for CO₂ and climate change scenarios are accurate (see Jarvis, Chapter 2, this volume), basic availability and accuracy of data required for GIS and modelling still pose major constraints. Data limitations exist in several key areas. Soils, crop distributions, land cover and pest/disease distributions would all be good examples. Crop distribution data sets are inaccurate and incomplete even for major crops at the global to regional scale. The combination of crop survey and census data with remote sensing data, to produce grid cell maps with crops allocated into the most suitable areas, is a promising approach (Leff et al., 2004; You and Wood, 2006; You et al., 2009). However, poor quality inputs often limit the utility of outputs in certain areas.

These and other data constraints imply that future change scenarios may often be based on imperfect current base scenarios. For simulation models, the list of model inputs in Table 13.2 indicates the dimensions of the task. To accurately describe any production situation, one needs information on management. Ideally, the information should be specified as decision rules, such as for how a producer decides when to plant rather than an average planting date.

Standardized formats exist to describe field experiments (Hunt et al., 2001), and integrated crop information systems offer the potential of linking management information with crop genetics (e.g. McLaren et al., 2005). Remote sensing may provide data for crop distributions, yields and production cycles (e.g. Lobell et al., 2003) as well as facilitate high-resolution characterization of soil and weather conditions (e.g. Minasny et al., 2008; NASA, 2009).

Development of models and associated software tools remains a largely individualistic process. Hundreds of models have been programmed, but few have survived past their initial publication. Modularization of model components, discussed since at least 1985 (Reynolds and Acock, 1985), should allow researchers to interchange components and focus on science rather than programming. However, there has been minimal progress in establishing modelling frameworks for modules where scientists can readily test hypotheses about specific processes. More recently, computer scientists have argued for use of the Unified Modelling Language (UML) as a way of separating specific scientific hypotheses from actual coding of software (Papajorgji, 2005).

Credible studies of crop responses to climate involve dealing with large sets of data and potentially millions of simulations, especially if adaptation is considered. While the computational challenges are daunting, the greater challenge is how to devise efficient protocols for selecting the most meaningful scenarios, interpreting the results, and summarizing outputs for non-specialists. GIS-based mapping has special value for communicating complex data, and use in climate change might be enhanced.
through animation or dynamic user navigation interfaces.

Conclusions

GIS and crop simulation modelling will see increasing use in climate change research and in applications of research in decision making. Maps are especially valuable for allowing people to understand how climate change impacts, as well as possible adaptations vary, across the landscape.

Examples highlighted in this review illustrate how the combination of GIS and crop models may assist with policy and breeding decisions in relation to climate change. Knowledge surrounding the potential shifts of abiotic and biotic stresses can help guide prioritization and targeting of key traits within crop breeding programmes. Increasingly, options exist to undertake analysis under a range of future climate scenarios that incorporate data from a range of sophisticated GCMs. Such an approach can lead to probabilistic outputs that can be used to guide decisions regarding the likely importance of specific traits in different geographic regions in the future. In combination with secondary data sets (e.g. crop distributions and demographic data) this can provide useful indicators regarding likely focus areas for important traits (e.g. drought and heat stress). Valuable information, particularly from crop models, may also be obtained on the potential value of specific adaptation mechanisms – either in terms of phenology or crop management.

Similarly, for decisions relating to the conservation of plant genetic diversity and plant genetic resources, outputs from a GIS/modeling-based approach can provide useful insights. The case studies highlighted here illustrate how priority regions, either for *in situ* conservation of important wild relatives or for prioritized collection efforts for *ex situ* conservation, can be identified. In both the conservation of plant genetic resources and the priority setting of breeding traits the lead time to obtain the desired results (e.g. a new variety or adequate protection of a priority region) can be considerable. The application of GIS/modeling technology within a future climate framework as outlined in this review is one way that can guide decision making on an appropriate time frame.

Limitations of the two technologies per se relate to our incomplete knowledge of physiological processes, the availability and accuracy of data, and implementation of the tools through software systems. Both technologies may provide useful insights for future decision making, but it is unlikely that they will capture in totality the full complexity and unpredictability of a rapidly changing climate.

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