PART VII

CAN MODELS COPE WITH THE CHANGE?

Introduction

Recently, Moorby (1987) reviewed the value of mathematical modelling in plant science, in a paper entitled "Can Models Hope to Guide Change?". In this paper Moorby was concerned primarily with the role of modelling in understanding the underlying mechanisms determining plant growth, and thereby providing guidance to manipulate and control growth. The value of a model is assessed more in terms of its potential for understanding the operation of a system, than the precision of its predictions. In attempting to construct models of crop growth in response to environment, areas of ignorance are identified and this should be used to guide future research effort. This is essentially the scientific purpose of mathematical modelling, seeking a greater depth of understanding of the physical world by studying simplified, mathematical abstractions of it, and drawing inferences about the behaviour of the physical system it represents. The process of abstraction requires assumptions to be made; for example the nature of interactions between variables and the functional form of the equations which describe them. The appropriateness of these assumptions imposes a limit on the validity of inferences made about the real world.

Models can be classified in different ways. Firstly, there is a distinction between empirical and mechanistic models. Empirical models use equations which fit the data well, they do not provide a causal explanation. Mechanistic models seek to explain the behaviour of a system in terms of physical, chemical and biological processes that may underly it. These processes will be at a lower level of empirical description than the behaviour one wishes to study: the increase in dry weight of a crop can be described in terms of the expansion and carbon exchange of the individual organs that it is comprised of. The level of detail used is dependent on the level of behaviour to be modelled. In modelling the stresses involved in a bridge structure design for example, only the bulk properties of the materials (Young's modulus, density etc.) used would be considered, whereas the atomic composition would be of interest if one was trying to improve the intrinsic strength or flexibility of a new material. A further distinction can be drawn between deterministic and stochastic models which concerns the treatment of random variation. Deterministic models produce a single value answer whereas stochastic models take account of the randomness in the system being modelled.

System models are used to describe complex systems and are usually composed of several sub-models, each of which relates to a separate part of the system and its validity should be testable, independently of the overall system model. The construction of such models can be carried out in either direction, although it is usually more efficient to adopt the 'Top-down' direction. This starts with the overall objective which is then broken down into a series of sub-goals or models and these in turn may be subdivided further into submodels at the next level down in the hierarchy. The submodels may be deterministic or stochastic in nature or a combination of both, and at the lowest levels of explanation are by necessity empirical.

The second and equally important role of modelling is as a management aid. Mathematical models are a quantitative representation of current understanding. Apart from the relatively simplest of decisions (e.g. whether irrigation is required or not) models designed to help decision making particularly at the farm and regional level, require complex systems models with the emphasis on cost-benefit analysis in monetary, socio-economic or environmental terms. This presents several problems. The propagation of errors can lead to serious discrepancies if ignored. The functional relations used in a model usually involve some degree of curve fitting to observed data, and the error or unexplained variation about the curve is ignored. In complex models functional relations are often drawn from several disparate sources and this may lead to incompatibility between equations. Another difficulty is the violation of predictor space. When a submodel is constructed and validated it is done so over a limited combination of values of its independent variables or predictor space. It is easy to overlook such unintentional violations when the model becomes very complex. Some thought needs to be given to developing suitable automatic monitoring techniques to identify such occurrences.

Knowledge so far has been restricted to that which can be represented in strict mathematical form. The scope of knowledge is much wider than this and Artificial Intelligence (AI) technology may provide a means of combining different types of information into a management tool. At the very least AI should provide a structured means by which an expert can rapidly construct or modify existing systems in order to address a new question within the scope of the knowledge base. Ultimately libraries of information in different forms could be set up from which appropriate rules, functions, submodels etc. are selected by an expert system in order to answer a particular question.

VII.1 A Modelling Perspective

Global warming presents research with new problems, both in the spatial and the temporal scales. The impact of global warming needs to be considered on several spatial scales, ranging from plant through crop, farm to regional and national levels. Time scale presents a different set of problems, especially with the uncertainties of long term forecasts of climate change. There are two aspects of climatic change to be considered, the transitional period and the new equilibrium (should one ever be achieved). The transitional period may present greater problems to the industry than a changed but relatively stable future climate. The rate of change and the uncertainty of future climatic conditions precludes detailed experimental investigations of crop growth in all but a limited number of climatic combinations that may cover future conditions. Simulation offers the means to cover a much greater range of climatic conditions at much reduced costs. However, there is the question of reliability, especially when one is moving into new combinations of climatic factors (e.g. daylength and mean temperature). It is essential that simulation work is supported by experimental observation which covers, at least in part, potential future climatic space.

With the change in climate, and in particular the rise in mean temperature, there will be the opportunity to introduce new crops which are currently grown in warmer latitudes. However, it is not simply a question of using previously observed crop performance data to evaluate a crop's suitability for introduction and likely productivity. Although the warmer temperatures in the future may be similar to those where the crop is currently grown, other climatic and edaphic factors may not. The combination of daylength and temperature will almost certainly be different. Pearl millet was thought by 'world experts' to be daylength insensitive. Controlled experiments revealed that pearl millet was in fact sensitive to daylength

(Ong and Everard, 1979). This mistake had been made by relying on field observations alone. Pearl millet is only grown in a limited range of latitudes around the equator and hence limited range of daylength. On closer examination, and knowing its sensitivity to daylength, the larger leaf area indices observed in crops grown in more northerly latitudes was attributable to differences in daylength (Carberry and Campbell, 1985). All climatic factors must be considered when extrapolating the results from one region to another, and predictions should be based on both physiological understanding as well as agronomic assessment.

VII.2 Scale of Simulation

Simulation is required at all levels from plant to national level and possibly international, particularly where decision making is involved. If the farmer is to introduce new crops and to adapt husbandry to new climates then he needs to know how the different crops are likely to perform over a run of several years. This requires long-term field evaluation studies or simulation based on the measured response of plant and crop processes as well as response of pests and diseases to the environment. Much of the latter information could be gathered under controlled environment conditions in a relatively short time, provided there is the finance. The ideal approach is to use simulation studies alongside biological research first. Initially, commercial evaluation would be on a limited scale only, allowing time for a proper risk assessment to be made based on sound understanding.

For commercial crops grown on a large area there is much information currently available and mathematical descriptions of varying complexity have been produced for many of them. Van Keulen and Seligman (1987) provide an excellent example of how an extensive search of current knowledge can lead to the development of a successful crop growth model, in this case for spring wheat, with commercial as well as scientific value. Many such models are often not in forms that are of immediate use in addressing the problems of global warming. The effects of increased carbon dioxide are rarely if ever included in a model of crop growth.

Unfortunately, knowledge of similar detail regarding smaller acreage crops will not be available. However, our understanding of the processes of crop development and growth gained from the major crops can be exploited in a limited way to good effect. Marshall and Thompson (1987a,b) applied the concepts of thermal time to the problem of predicting maturation dates of calabrese and produced a model that can be used in the design of sowing strategies which is tailored to the local climate. Methodology for objective decision making that can combine mathematical models of crop growth in relation to climate, pest and disease with rule-based knowledge and uncertainty (e.g. range of climate scenarios and their probabilities) needs to be developed further.

At the farm level planning involves several time scales, from immediate within-season decisions, through pre-season planning to longer term strategy. All levels require information on a range of crops but the amount of detail and the proportion of biological to non-biological information differs. Greatest biological detail is sought when within growth season decisions such as irrigation, nitrogen application, pest and disease control, are to be made. Information on crop performance for pre-season and mid- to long-term planning is required in a more summarised form. It is not usually specific to a particular field, rather it is based on average yield with some measure of the range of probable yields, pest and disease problems. Initially this information is derived from variety trials (see Section VI.1) and from the farmer's own experience. Since this is based on past experience, longer-term strategies will be prone to greater uncertainty, especially in light of a rapidly changing climate.

Decisions at regional and national level will need to consider supply in relation to the needs of the community. Mathematical models provide the means of estimating the supply of existing crops in relation to the changing climate, pests and diseases. It also has an important role to play in assessing the viability of introduction of new crops, deciding where research effort should be directed and the extent to which financial support to the industry may be required, at least in the introductory phase.

The major effect of climatic change on animal production (with the possible exception of wind on unhoused livestock) will be indirect via the effects on production of feedstuffs such as barley, oats, brassicas, grasses etc. and the possible introduction of new forage crops such as maize.

VII.3 Areas of Simulation

"Crop ecology requires close cooperation between agronomists, crop protectionists and workers in basic science such as physics, chemistry and biology" (Rabbinge, 1986). Simulation models provide valuable integrative tools that provide insight into the behaviour of systems and are an essential component in this interdisciplinary field.

The opportunities for mathematical modelling to enhance the benefits of research on the effects of global warming are too numerous to present here in detail. The opportunities are evident in all the sections presented in this report.

Within crop physiology, the first step to consider is the influence of weather on the development of the crop. The role of temperature on the rates of initiation of organs and their subsequent development is well understood (e.g. Ellis and Russell, 1984; Gallagher, 1979; Milford, Pocock and Riley, 1985 a,b; Ong, 1983a,b; Porter *et al.*, 1987). Models of the development of crops based on temperature, which also include photoperiodic and vernalisation effects have been developed mainly for cereals (e.g. van Keulen and Seligman, 1987; Weir *et al.*, 1984).

It is relatively simple to combine such models with the concepts of radiation interception and dry matter production (Monteith & Elston, 1971; Monteith, 1981) and construct models to predict potential crop yields i.e. those limited by temperature and solar radiation (e.g. MacKerron and Waister, 1985), and photoperiod where necessary. Such models are not able to simulate the effects of increased carbon dioxide concentration explicitly. More detailed models of canopy light interception and carbon dioxide exchange of the form used by e.g. Goudriaan and van Laar (1978) or Marshall and Biscoe (1981) are required to simulate effects of carbon dioxide. However, before this can be achieved research must be done on the adaptive effects of the photosynthetic and respiratory systems, and partitioning of carbon (e.g. Idso, Kimball and Mauney, 1988) and nutrients between roots and shoots to increased carbon dioxide concentration in a range of species. Effects on gas exchange as well as roots are essential components in estimating the effects on water use efficiency (see Section III.4).

As well as the effects on water supply, through enhanced partitioning to roots, there will also be effects on quantity and timing of nutrient availability. There are several models describing the cycling of nitrogen in the soil (Addiscot and Whitmore, 1987; Barraclough and Smith, 1987). Warmer winters will lead to earlier availability of soil mineral nitrogen through mineralisation and may occur at a different developmental stage than previously in winter sown crops. The risk of leaching may well be increased especially if the winters are wetter.

The influence of climate on disease distribution and intensity has been reviewed recently by Coakley (1988) and is discussed in Part V. Rouse (1988) has considered the role that simulation can play in linking disease models with those of crop growth to estimate the yield risk involved in different management practices. This role will become even more important due not only to consideration of the health of the environment but also with the changing weather introducing new diseases, pests and their associated host plants in the wild plant populations.

As well as the microclimatic effects on fungal activity and dispersion, there is the spread of viral diseases by insect vectors such as aphids (Section IV.1b) in potato leafroll (Marshall and Barker, 1988) and yellowing viruses in sugar beet (van der Werf, 1988). The dynamics of pest populations is another area that has received considerable interest in simulation. Ward, Rabbinge and den Ouden (1985) developed an explanatory model of potato-cyst nematode populations and attempted to link it to a crop growth model. The weakest link in this attempt was between the influence of nematode attack on root function and the reverse effects of root exudates on nematode activity. Spitters and Ward (1989) went on to evaluate a range of breeding and management strategies for the control of potato cyst nematodes using simulation techniques, although in this case they reverted from the earlier, more detailed population model using a daily time step to the simpler model of Jones and Perry (1978) with an annual time step.

These examples demonstrate some of the roles of mathematical modelling. At no time will knowledge be complete, yet decisions must be made. It is important that models continue to be developed, as they present a quantitative measure of our current understanding and ignorance. Only then can informed decisions be made, knowing their limitations.

VII.4 Conclusions

The rate of change of climate presents new problems. Decisions at the farm level and higher have frequently been based on past crop performances covering many years. Statistical regression analysis with simple climatic factors not directly related to biological processes may have been used to improve forecasts. Both these approaches rely on the assumption that neither the climate nor the response of crops to the environment are changing. Trend analysis does in fact attempt to account for some change e.g. the gradual increase in average cereal yields due to plant breeding and improved husbandry, but this is only of value at national level and there will be insufficient data to deal with climatic changes at the speed with which they are likely to occur (Section I.7). A similar problem presents itself to the plant breeder, there being no stationary climatic target to aim for. Mathematical modelling - combined with meteorological simulations and an understanding of the processes underlying development, crop growth, pest and disease dispersion, infection and crop damage - is the only means of dealing with climatic change during the transitional phase. It may take 50 years for the climate to reach a new equilibrium state even if atmospheric pollution rates are strongly curbed. If we continue to add CO_2 to the atmosphere at significant rates, it may take far longer.

Simulation can not replace experimentation. However, it ensures more efficient and faster exploitation of existing and new knowledge enabling more informed decision making at all levels in the agricultural industry and in matters relating to the environment. It is the most effective, quantitative means of combining information from the wide range of disciplines required to cover the questions posed by climatic change and to evaluate future scenarios. It is mathematical modelling that has used knowledge from the basic sciences to forecast global warming. Its role is even more essential in tackling the biological implications of climatic change.