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"THE DEVELOPMENT OF MODELS FOR PRACTICAL USE IN CROP PROTECTION"

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USE OF MODELS IN INTEGRATED CROP PROTECTION

THE DEVELOPMENT OF MODELS FOR PRACTICAL USE IN CROP PROTECTION

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INTRODUCTORY COMMENTS

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This IOBC Bulletin is the first prepared by the working group 'Use of models in integrated crop protection' formed at the EPPO Conference at Paris in 1976. The group aims at the co-ordination, initiation and development of models, systems analyses and data bases for use in integrated pest and disease control. In furtherance of this aim, individuals from the group have been involved with symposia, courses and services to other crop or subject-orientated groups within the IOBC. Formal meetings of the group have been held in Giessen, West Germany (1977), Wageningen, the Netherlands (1978), Wye, United Kingdom (1979), Versailles, France (1980) and Stuttgart, West Germany (1982); the main activities have been the formation of a Septoria sub-group involved in the development of forecasting models for winter wheat, the compilation of an 'Inventory of Models', and the preparation of this bulletin.

The aims of this bulletin are to provide a comprehensive introduction to the range of models and techniques of modelling likely to be found in crop protection, to appraise critically the reasons and justifications for modelling (the 'why' and 'when'), to consider some of the wider implications of modelling, to provide a guide to the terminological differences that abound in the literature, and to encourage participation in the group by crop scientists and other interested parties. The bulletin is complementary to the 'Inventory of Models' which is also to be published as an IOBC Bulletin.

The contributions to the bulletin fall into three main areas, although these overlap to some extent. In the first, an overview of mathematical modelling in relation to the various objectives and activities of crop protection is given (Jeger). The second consists of three approaches to modelling that stem from the view points of population dynamics (Rabbinge & Carter), crop physiology (Rabbinge) and decision theory (Norton). The third is concerned with the status of models in crop protection; the extent to which they are, or are likely to be, used for practical purposes (Jeger & Tamsett), and the provision of this information as part of a data base system. Reports on the biometeorological inputs and support required to operationalise models have already been presented to the working group by Müller at Versailles in 1980. The bulletin concludes with recommendations of the sub-group responsible for the preparation of this report but responsibility for the views expressed in the individual chapters lies with the authors, and these views do not represent any concensus on the part of the sub-group.

MATHEMATICAL MODELS: THEIR NATURE AND DEVELOPMENT TO PRACTICAL ENDS IN CROP PROTECTION

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1. Introduction

Mathematical models are simplified and approximate representations, in mathematical or symbolic form, of natural phenomena perceived directly through the senses or indirectly through instruments. The concern of this bulletin is with the development of models suited for a specific task in crop protection, namely the management of a pest or pathogen population to a defined target that in some way represents optimal control. The intent of this chapter is to provide a personal commentary on modelling objectives, approaches and techniques rather than a comprehensive review or classification of models. The main emphasis is on plant pathological, rather than pest (animal) problems but exemplars are drawn as appropriate from other areas which have particular affinities, notably population ecology.

The main point made is that this development takes us from activities, for convenience termed 'scientific', to activities termed 'technological', and that both activities fall into the compass of crop protection. The activities are not considered as qualitatively different (certainly not in methods or equipment), nor is an appeal made to 'pure' as opposed to 'applied' activity; they are considered as convenient ends of a spectrum defined in terms of the objectives and perspectives of the practitioners. Although the distinction can be overstated, it is not entirely arbitrary and is crucial to the argument of this chapter. Science is concerned with the explanation of natural phenomena and is unique in striving for and insisting on a concensus of rational opinion (Ziman, 1968). Technology, by contrast, must provide the means to accomplish a specific task within the framework of available knowledge. Consensus is rarely a prime concern, the role is to innovate and to change natural phenomena.

The lack of recognition of a spectrum of objectives and perspectives has led to disagreement, misunderstanding, even hostility, amongst modellers. According to Bakker (1964) disagreement between adherents of different scientific theories arises because of limited knowledge of the processes involved, differences in scientific methods and ideals of knowledge, and differences in terminology. These differences can be emphasised by the spectrum noted above. In particular, the terminology used in crop protection varies greatly and examples of this will be given throughout this chapter. The standardisation of terminology is an attractive idea and has been attempted on occasion (e.g. Anon., 1968). Such attempts can have negative effects, however, and the case for explaining rather than defining terms has been made. Scientific terms must be open (Nalimov, 1981) if they are to serve, not only for existing concepts, but also for those emerging and to come in the future. The way to overcome terminological barriers is by mutual understanding rather than by codified agreement (Whittaker, 1970). A different view must hold for terms involving dimensioned quantities, but these are relatively few in plant pathology (Butt & Royle, 1980).

2. Modelling as part of 'scientific' activity

The function of science is 'to establish general laws covering the behaviour of the empirical events or objects with which the science in question is concerned, to connect together our knowledge of separately known events, and to make reliable predictions of events as yet unknown' (Braithwaite, 1968). The essential feature of science is the hypothetico-deductive method applied to empirical material, as outlined by Medawar (1969). It is not the intention here to dispute or qualify that view. The position taken is that all science is empirical, i.e. data-based, and must make contact with the observable, however complex the edifice of theory (a scientific theory is taken as a hierarchical system of hypotheses which provides an explanation of natural phenomena); that science provides a provisional explanation, not merely a description of observable data, and by so doing enables predictions to be made; that verification, or proof, of any part of a theory is not possible, whereas refutation, or disproof, of some parts is; and that the status of scientific theories is determined by peer acceptability, the explanatory (or predictive) power of the theory and the availability of alternative theories.

This position holds in the biological as well as in the physical sciences, although problems may arise in the nature of explanation (e.g. causal or teleological). The main difference from the physical sciences seems to lie in the number of levels of integration in biology, and from this stems the debate on holism vs reductionism. According to McIntosh (1980) ecology is one of the few academic disciplines devoted to holism and yet some, e.g. Harper (1982) dispute the holist view and argue for reductionist studies for explaining ecological phenomena. To a certain extent such opposing views are the results of terminological differences. According to Harper, holism is the view that the whole is more than the sum of its parts and their interactions, but it is not clear who actually holds this view. Smith (1970), for example, certainly asserts that whole ecosystems must be studied, but also individual processes and their interactions. A compromise in terminology would be to recognise holism as seeking an explanation at any one level of integration, whereas reductionism seeks an explanation at a lower level. The hierarchical structure of biological sciences raises important questions concerning the nature of explanation; for example, the suggestion that an explanation at one level requires only description at a lower level, (Loomis et al., 1979; Thornley, 1980), a view that has obvious implications for the modeller.

A comprehensive review of developments in ecological sciences has recently appeared (McIntosh, 1980) and considers the extent to which ecology has achieved the hypothetico-deductive ideal, and the maturity of its terminology. Substantial differences in ideals of knowledge between different groups of theoretical ecologists are noted; broadly speaking, the reductionist, analytic-centred views of population ecology and the holist, synthetic-centred views of systems ecology. The former are in the tradition of hypothetico-deductive science, the latter deriving their concepts largely from engineering. These divergent views are certainly apparent in plant pathology (Robinson, 1976) but again differences in terminology abound, and holism is not always equated with the systems viewpoint (Shrum, 1978; Kranz & Hau, 1980).

What then is the role of mathematical modelling in science? In some areas of the physical sciences, theory is almost entirely mathematical in content (Kuhn, 1976) and the view is held that scientific knowledge ought to be reducible to mathematical form. Although the types of model used in the physical sciences do not carry over in all cases to the biological (Bharucha-Reid, 1960), they have certainly proliferated and, according to Wickwire (1977), mark the transition from a descriptive to a predictive science. If mathematical models are to be seen as theories which explain natural phenomena (see Levin (1981) for a critique of this view), then such models can be used for prediction. This is using the word prediction in the scientific sense, an explanatory model necessarily predicts. This corresponds to the usage of Mankin et al., (1975) but unfortunately other uses abound and the term predictive is often used as an antonym to explanatory.

Explanatory models, then, should be subject to the same criteria for acceptance as scientific theories and ultimately to the criterion of rejectability. The verification of such models, according to the view of science taken, is a meaningless concept and misleading. How have explanatory models fared in ecology and crop protection? Pielou (1981) considers that explanation is the task ecological models perform least well and considers other more suited and equally important tasks. Passioura (1973) makes a trenchant commentary on the use and abuse of explanatory models in crop physiology (see Loomis et al., 1979). It should be noted that both approaches noted by

McIntosh (1980) have been claimed to lead to explanation. The theoretical population ecologist studies the behaviour of fluctuating populations in terms of classical Volterra-Lotka equations, for example, in order to identify general rules and principles, whereas the systems ecologist studies a whole system, suitably identified, in terms of subsystems, state and driving variables. The trend in plant pathology is certainly in the latter direction (Kranz & Hau, 1980; Rabbinge & Carter, this bulletin), but it seems too early to comment on the explanatory success of such models. Exceptions to this trend can be found in theoretical epidemic models (Fleming & Holling, 1982; Jeger, 1982; Barrett, 1983) and 'physical' spore dispersal models (Legg & Powell, 1979; Aylor, 1982).

Although science is ultimately concerned with explanation, much of the short term activity is concerned with the exploration of experimental systems rather than the testing of key hypotheses, and so too with modelling. Suppositions are made, expressed mathematically, and the consequences or range of possible solutions explored (Wangersky, 1979). The value of such modelling is that it can be linked to experimentation as an interactive activity throughout the gestation and development of a research programme, especially where no a priori expectations exist (Jeger et al., 1981a,b). Other very different, modelling techniques may also be valuable in these exploratory areas. It has been argued that only models which explain as opposed to describe natural phenomena can be used to predict. Accordingly the most common descriptive model in crop protection, the linear or multiple regression model, cannot by these criteria be used for prediction. The most valuable area for these, and for other multivariate techniques, is in preliminary investigation, in exploration, where the avoidance of modelling preconceptions is at a premium (Pielou, 1981). The danger with such descriptive models is that parameters can acquire a physical meaning not originally intended rather than being accepted as curve fitting constants.

The quite valid distinction between explanation and description, in science and in modelling, has been made. Unfortunately the term empirical has also been used in a sense equivalent to descriptive and opposite to explanatory. Yet all science is empirical, as argued above, and hence to derogate a descriptive model as 'empirical' gives the explanatory model a status beyond that of a scientific theory.

3. Modelling as part of 'technological' activity

By contrast with science there have been few treatises on the nature of technology, an exception being that of Simon (1966). The technologist must accomplish a specific task, must modify or control natural phenomena within the confines of available knowledge. The prime responsibility is to employer, customer or patient. Technology uses the same techniques and procedures as science and, indeed, interacts strongly in terms of what is possible in each activity. The technologist, however, is concerned with research that increases our power over nature and not so much our understanding of it. The question arises: is it necessary to have understanding in order to have power? The practice of crop protection, as part of agriculture, is an eminently technological subject. An extension of the above question is to ask whether the knowledge required for the improvement of agricultural systems is scientific or not and if so, whether such knowledge can be applied within a practical context (Spedding, 1979)?

There seem to be no major differences in objectives between technologists working with physical systems and those working with biological ones except those provided by ethical considerations. The objectives are to optimise, design, control or forecast, and usually to do so within some economic framework. What is the role of modelling in achieving these objectives? In many cases it is claimed that comprehensive explanatory models developed to meet scientific objectives are necessary, and may be used directly or simplified for practical use (Rabbinge & Carter, this bulletin). Alternatively, models have been proposed to meet immediate technological objectives and these will be considered further.

As stated in the previous section a scientific theory is by definition an explanation of natural phenomena that is open to falsification and as such can be used for prediction. A term used synonymously by many authors is forecasting. It has been argued above that the term prediction is best used in its scientific sense only; it is now argued that forecasting is best used only where there is no preconception as to the explanatory basis of the forecast. Poole (1978) uses the term 'statistical prediction' for what here is termed forecast. In a comprehensive review, the view is stated that understanding of dynamics is not essential for day to day forecasting. Forecasting can be based on the recognition of regularity as well as on an explanation of it. If forecasting is the purpose of a model then reliability is the most important feature, interpretation of the model is immaterial. Most models used for this purpose in crop protection have been linear or multiple regression models (Butt & Royle, 1973; Krause & Massie, 1975; Young, Prescott & Saari, 1978; Shrum, 1980); techniques that have been found useful in other areas such as moving averages or ARIMA (Poole, 1978; Pielou, 1981), have rarely been used by plant pathologists.

Forecasting is not the only objective of the technologist. Optimisation, design and control are tasks often required, each involving mathematical techniques that may be unfamiliar to those involved in 'scientific' activity. These objectives have often been set in the related area of agricultural economics (Dent & Anderson, 1971; Anderson, 1972) and models with these objectives are increasingly making an impact on pest and pathogen management, both with regard to strategy (designing and optimising control strategies) and tactics (decision-making). Various examples of this impact can be found in Norton (1977), Norton & Conway (1977), Walker (1977), Conway & Comins (1979), Thompson & White (1979), Betters & Schaeffer (1981), Heaton *et al.*, (1981), Menz & Webster (1981) and Shoemaker (1981).

This section ends with a conclusion of the joint EPPO/WMO Symposium on Meteorology for Plant Protection held at Geneva in 1982 and to be published in 1983. The following measures were considered essential: 'establishment of pest risk forecasting models which are simple and accessible to the user; stimulation of growers' awareness of these systems, and instructions in their use; establishment of the cost benefits to be obtained from the application of pest risk forecasting systems, with particular reference to the cost of chemical control, the optimisation of yield, and possible effects on the environment'. This conclusion specifies objectives that are undoubtedly technological and the role of 'scientific' activity in support of them, whether major or minor, has not been established with any certainty. It is important that appropriate procedures for evaluating models used in meeting these objectives are used, and this is considered in the penultimate section.

4. Mathematical modelling techniques

Modelling, to this point, has been considered in terms of the objectives and perspectives of the activities to which it relates, i.e. 'scientific' or 'technological'. There is a diversity of ways in which models may be formulated, and an equal diversity in the techniques used to obtain solutions. Some of these techniques have been used throughout the spectrum of activities described, some in parts only. This section does not discuss what is done with some models (e.g. simulation - see Rabbinge & Carter, this bulletin) nor is it an exhaustive compilation of mathematical techniques, but rather identifies some that have been little used in crop protection, especially plant pathology, and may therefore be unfamiliar. This will be done with reference to the classification proposed by Anderson (1972), who gives comprehensive citations, largely with regard to models in agricultural economics.

Time dependence:- Solutions to the model may be trajectories in time or time-dependent. This covers the continuous-time differential equation models used by both theoretical population and systems ecologists. Virtually all dynamic models in plant pathology have been of this type, as have those most concerned with pest or competition problems. The equations which specify the model, even if autonomous (i.e. parameters not dependent upon time or other external variables) are usually non-linear, global solutions are not possible, and numerical methods are required to obtain solutions. The danger, especially with higher order systems of equations, is that numerical methods cannot always be relied on to reveal all qualitative aspects of dynamic behaviour, and this applies even more strongly to the complex systems models. The advantage of the simpler theoretical population models is that techniques such as phase plane analysis can be used to establish local equilibria, stability properties and much of the qualitative behaviour of the population, and hence be invaluable in exploratory work, obtaining insight and suggesting strategy. Such techniques (May & Anderson, 1979) have been used with regard to predator-prey systems, human and animal epidemiology, and competition studies, but with only a few examples in plant pathology (e.g. Jeger et al., 1982).

Continuous time models are but one way of formulating dynamic models (Pielou, 1981). Discrete models using difference equations have occasionally been used in plant pathology (Leonard, 1969; Barrett, 1978; Jeger et al., (1981a), but alternative methods involving transition matrices, signal-flow graphs or networks have not been used. In many ways discrete models may be more appropriate for most pathogens whose infection 'behaviour' is discontinuous and dependent upon well-defined periods of wetness.

Stochastic elements:- Solutions to the model may not be fixed for a given input set. Again terminological ambiguities abound. Stochastic has been used to describe any model in which the output is in the form of a probability distribution (even if fixed for a given input set), also for any model which relies on historical weather data (such data, it is argued are probabilistic - being only a sample from a much wider set). It was originally supposed that stochastic techniques were necessary to account for the inherent natural variation, rather than that caused by sampling error, in biological material. It has been found, however, that apparently simple deterministic models can lead to such chaotic behaviour for small changes in input parameters that the output is indistinguishable from that of stochastic models (May & Oster, 1976; Bunow & Weiss, 1979), and this must call into question the view that improvements in measurement and sampling techniques will suffice to test most models. Stochastic models have rarely been used or deemed necessary in plant pathology, largely because the host population is static and is comprised of a large number of individuals, unlike the counterpart in any human epidemiology. Stochastic models, of necessity, can be extremely complex (Rabbinge & Carter, this bulletin) and seem contrary to the spirit of a simple model subject to an experimental test.

Optimisation procedures:- Solutions may be obtained by optimisation, given alternative courses of action. Optimisation is a clear technological objective and models that use such procedures are becoming more prevalent in the theory, if not the practice of pest control (Wickwire, 1977; Shoemaker, 1981), and should extend to plant pathological problems. Mathematical techniques for optimisation vary from the sophisticated (say linear programming) to the relatively simple (decision theory - Norton, this bulletin).

5. Evaluation of models

The spectrum of activities introduced is critical for the evaluation of models. At the 'scientific' end, if the purpose of the model is to explain natural phenomena, then the criteria for evaluation of the model can only be that of rejectability. In so far as this is not achieved, the model is provisionally accepted. Unfortunately the ability to formulate and solve comprehensive models far exceeds the present ability to test them (Rao & Jessup, 1982). Where the purpose of the model is to assist in exploration, in the sense described, then the criteria for evaluation can only be a subjective view of the model's role or value in a research programme. At the 'technological' end, where the purpose is to control or modify natural phenomena, then the criteria for evaluation can only be whether the model achieves the purpose for which it was intended (it is probably known to be false!). Unfortunately the evaluation of models is often discussed independently of what the model is intended to do. There is now an accumulating literature concerned with evaluation of models, mainly of the systems type (Smith, 1970; Dent & Anderson, 1971; Anderson, 1974; Miller, 1974; Mankin *et al.*, 1975; Caswell, 1976; Van Keulen, 1976; Kranz & Royle, 1978; Loomis *et al.*, 1979; Leggett & Williams, 1981; Reynolds *et al.*, 1981; Teng, 1981; McKinion & Baker, 1982; Rabbinge & Carter, this bulletin), and even a cursory appraisal will convince of the ambiguities in terminology. If terms are omitted, for the present, then several procedures can be identified.

1. Ensuring that the model operates as intended. For example, if implemented on a computer, does the programme correspond to the model formulation?

2. Calibrating or estimating unknown parameter values by repeated runs of the model with a range of values. Output is compared with actual data and the reasonableness of the estimates assessed.

3. Analysing the sensitivity of model output to changes in input or parameter values.

4. Analysing the robustness of the model by making changes in modelling suppositions.

5. Testing the accuracy or reliability of the model by comparing the gross output, or predictions of the model, with actual data.

6. Testing the internal behaviour or consistency of the model (e.g. sub-model output) for counterbalancing errors.

7. Determining the range of independent variables over which the model is valid.

8. Determining the utility of the model. Does it achieve the purpose for which it was intended?

It is not proposed to codify these procedures into terminological slots. Two terms, however, 'verification' and 'validation', occur so regularly that they will be discussed with regard to these procedures. Verification usually corresponds to procedure 1 and is clearly of importance for any model, whatever its purpose (Rabbinge, this bulletin). The procedure can rarely be considered complete, however; models are still being debugged years after their construction. Further, it seems impossible to verify the internal consistency of any mathematical structure (Nalimov, 1981). Unfortunately the term verification has also been used to describe procedure 5, thus perpetuating the myth that models can somehow be proved true and the use of the term in this context should cease. Validation is the other term used to describe procedure 5. At the 'scientific' end of the spectrum, however, the term that is more appropriate is invalidation, i.e. corresponding to falsification. Claiming that a model is validated because its output agrees with actual data within an acceptable margin of error is giving the model a status to which no scientific theory can aspire, and is naïve if not dangerous. Explanatory models can only be accepted in so far as they have not been invalidated. If a modeller is not prepared to accept the test of falsification or invalidation, then the model should not be termed explanatory.

At the 'technological' end the truth or validity of a model is irrelevant. The only criterion is whether the model is useful for its intended purpose (procedure 8). If, for example, the purpose of the model is to forecast then what is important is the accuracy of the forecast, the range of conditions over which the degree of accuracy is acceptable, and the feasibility of responding to the forecast. Inevitably there will be a subjective element in this evaluation. Although statistical procedures exist for determining 'goodness of fit', there are none for determining model utility in the sense described. For this reason it is doubtful whether the model designer can ever decide if the model serves as intended. Consider the analogy of a new design of orthopaedic bed. It is the sufferer who must decide whether the new design alleviates back-ache, not the designer of the bed. In crop protection, it is the farmer who must provide the final judgement (Rhoades & Booth, 1982). The important needs for crop protection are criteria for evaluating model utility, and the willingness and logistical means both to submit models for independent evaluation and to undertake them on the behalf of others.

6. Development of models to practical ends in crop protection

To repeat, the main concern of crop protection is the management of a pest or pathogen population to a target that in some sense represents optimal control. This is, undoubtedly, a 'technological' objective and models which are developed to facilitate this should, as argued above, be evaluated in a 'technological' perspective. There seem to be two routes by which such models may be developed;

by taking comprehensive models designed to meet 'scientific' objectives, and presumably based on sound biological principles, and directing or adapting them to the practical task at hand, or by the construction _de novo_ of 'technological' models. Ironically the former may entail the simplification of comprehensive system models, the latter more sophisticated techniques for forecasting, optimisation and control. The suggestion that both routes are necessary (Jameson, 1976) seems unduly pessimistic.

Consider the former route. Two alternative approaches can be identified. The model remains reasonably complex but requires expertise in implementation, interpretation and dissemination down to the individual user; alternatively, the model is simplified to provide decision rules for use directly by the user (Loomis _et al._, 1979; Rabbinge & Carter, this bulletin). There are few published examples of this simplification being achieved in practice. Davis & Thiele (1981) used regression analysis on model output in order to identify key variables but this was still for the applied research rather than implementation level. The model system EPIPRE (Rabbinge & Carter, this bulletin) falls between the two viewpoints. Comprehensive 'scientific' models have been simplified, but the model still requires expertise in implementation; it is not used directly by the individual grower. It remains a moot point whether the decision rules could have been developed directly.

The latter technological route has been more commonly taken, although some models (e.g. Strizyk, 1980) cannot so readily be categorised. In plant pathology, models of the regression or infection period type, based on weather, are relatively simple and some have now been programmed into microprocessor-based warning devices (e.g. Jones & Fisher, 1980). Such devices can be very flexible indeed, cover a wide range of disease or pest models, and have been evaluated to some extent, but their role in practical crop protection has not yet been demonstrated. Models for forecasting, optimisation and control are more sophisticated than most models used to date, have proved useful in other technological areas, and require evaluation as they begin to make an impact in crop protection.

This chapter has raised several important questions concerning the objectives, identification, development and evaluation of models. It is important that these questions are addressed if models are to find practical uses in crop protection, and will be done in the remaining chapters of this bulletin.

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APPLICATION OF SIMULATION MODELS IN THE EPIDEMIOLOGY OF PESTS AND DISEASES; AN INTRODUCTORY REVIEW

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1. Introduction

Watt (1961a, b, 1963, 1964) was one of the first people to realise the full potential of agricultural pest modelling. Watt's main interest was to use models to evaluate different control strategies, and he was able to show theoretically that pest populations could reach higher levels after the application of a pesticide than in its absence (Watt, 1961a). Watt (1961b) was also concerned with modelling field populations and later extended his ideas to resource management (Watt, 1968).

Conway (1973, 1977) criticised many of the existing mathematical pest models for being too general (producing only obvious or trivial results), for ignoring the economic aspects of control, for failing to initiate the interaction between modelling and experimentation and for their irrelevance to pest management systems. The first criticism is now less important as systems teams start to tackle specific problems with specific objectives. The analytical approach however is still interested in general models e.g. to account for the searching strategies of predators and parasitoids. The second point is a reflection of two considerations; most modellers are trained in one subject, in this case biology, and know little of economics and the economic aspects of crop protection have not often been calculated. These considerations are changing as entomologists and phytopathologists realise the importance of damage levels, economic thresholds and action levels. The third criticism is possibly unjustified. Model builders quickly realise what experimental work needs to be done to provide the missing data for their models. Very often however with an analytical approach the importance of directly unmeasurable variables and parameters are stressed, e.g. the mutual interference constant of predators. These values are usually calculated from graphs and are very often an incorporation of many biological processes into one variable or parameter. Thus they are purely descriptive with little explanatory value. Analytical models are, because of their abstract character, usually difficult to validate in the real world. Very often the author gives examples where his model fits observations in the field but this does not answer the question as to whether his theoretical considerations are valid. This makes the value of these analytical models for interpretation of a specific field situation limited, and conclusions on the mode of action of a system speculative and dangerous. Finally, models are now being employed in pest management systems.

2. Types of models

Mathematical models can be classified into three partially overlapping types; analytical, statistical and simulation. The analytical models mentioned in the introduction are of interest in theoretical considerations of ecological concepts but quickly become too complex if applied to field populations. In many cases knowledge and insight of the ecological processes are lacking or are of a rudimentary nature. Statistical models, usually regression type, are purely empirical not relying on causal relationships and hence describe rather than explain processes. They are rarely consistent in the long term and when they do fail, the model itself cannot be used for explanation. They are therefore of limited use in plant protection. Simulation models are dynamic and can either be deterministic (based on mean values) or stochastic (based on probability distributions). The majority of pest simulation models are deterministic, as the use of stochastic models is very expensive in computing time and often unnecessary. Fransz (1974) discusses stochastic processes in relation to his work on the pr[illegible]y behaviour of mites. He gives a number of ways that stochastic variables can be simulated either with single or population processes. He concludes that when some characters of the animals with stochastic variation have curvilinear relations with other variables (i.e. rate variables) the outcome of a deterministic model in which averages are used may deviate from the expectation value of a stochastic model. Thus, generally there are two reasons to use stochastic models: 1) when a reliable estimate of the expectation value is desired and curvilinear relationships between a stochastic characteristic and one of the state variables are present, 2) when interest lies in the variance of model output. Unfortunately many biological properties show curvilinear relationships and the high variation in these characteristics often necessitates the use of stochastic models. Since these models are very time consuming and therefore expensive to run, several techniques have been developed to prevent the use of expensive, and often inappropriate, Monte Carlo methods. Fransz (1974) developed 'compound simulation', which is the application of deterministic simulation models to classes of individuals. Within each class the relation is assumed to be linear. The number of classes depends on the required balance between accuracy and computer time. The calculation of each class of individuals is made at each time step of integration, after which the contents of the classes are updated and another computation starts. In this way only one simulation needs to be carried out for each set of conditions, instead of 1000 times in Monte Carlo methods. Sabelis (1981) describes the application of Fransz's methods, Monte Carlo techniques and queuing techniques, to the predation process of mites. The latter method is an especially powerful approach that requires only a limited amount of computer time. Basically, this method may be compared with calculating the waiting time of a client in the waiting room of a dentist. The client may enter the waiting-room (gut) at a certain rate in expectance of the service (digestion). An evaluation of the mentioned models, i.e. deterministic, stochastic compound or queuing, is done in an acarine system by Sabelis (1981). He shows that the deterministic model gives erroneous results and that the outcomes of the three other models fall within the confidence intervals of the measurements, the latter with the least computing time.

3. Strategy in model building

Ruesink (1976) has listed some of the agricultural pest models. He proposes that the frontiers of model building lie not with the production of more models, these can be turned out by anyone familiar with the techniques, but with the production of improved submodels for important processes. This is a view shared by some phytopathologists (Rijsdijk & Zadoks, pers. comm.). Ruesink (1976) has produced a methodology for developing models which needs further refinement and extension. The first step should be to define the objective of the system analysis before the objects within the system, and hence the boundary of the system, are defined. The modeller usually then produces flow- or relational diagrams prior to formulating equations. This latter procedure is usually carried out section by section, i.e. submodels, so that each part can be checked for accuracy (validated) independent of all other parts. There is also at this time a two-way interaction between model building and experimentation. Output from the submodels indicates the importance of each process so that experimental effort can be concentrated on relations that primarily determine the behaviour of the system. Once all the submodels have been coupled to produce a first generation model it has to be verified. Verification means testing to see that the computer program in fact operates on input data in the intended way (Loomis *et al.*, 1979). Thus the production of negative numbers of animals indicates that the model is not working correctly but unfortunately not all errors are so easy to spot! Verification is a step which is often left out (see Jeger, this volume). Next the model has to be validated as it has to be accurate and reliable if prediction is the aim. Teng *et al.* (1980) describe some of the procedures they have used in validating their model, BARSIM-I, a simulator of barley leaf rust epidemics. The most simple test is a subjective comparison of model output with field results; preferably from a number of different sites over a number of years so that environmental circumstances may vary considerably. Not only should the model predict accurately the timing and size of the peak population density but the growth curve should be of the same type as observed in the field. By plotting a scatter diagram of field observations against model predictions a further impression of the accuracy of the model can be made. Regression analysis on these data should yield a regression coefficient (b) not significantly different from 1, an intercept (a) close to 0, and a correlation coefficient which approaches 1 so that a high percentage of the observations is being 'explained' in statistical terms. Sensitivity analysis can be carried out once the reliability of the model has been proven. This is the process of changing the values of rates, variables, parameters and initial conditions in the model to determine their importance. This again leads to feedback with experimentation so that model building is an ongoing process. There is some danger in this approach as differences between model calculations and experimental outcomes at the system level may lead to adaptation of the input relations which are not in agreement with the results of experiments at the process level. In this way, the process of model building is loosing its meaning as simulation has degenerated into a sophisticated way of curve fitting. Deviations between model results and experiments at the system level should lead to a reorientation of the conceptualisation and implicit hypotheses in the model.

A good, validated and reliable model may be used in sensitivity analysis to test the relative importance of different input relations and to pin-point the deficiencies in our knowledge. After this process of sensitivity analysis, simplification is usually possible and may lead to summary models which are used in decision making to predict the population dynamics of pests and diseases in a crop protection management system.

A very fundamental question in all types of simulation models which use numerical integration methods concerns the choice of the time interval of integration. An appropriate time interval is necessary as too small time intervals will lead to an overuse of computing time, and too big time intervals will lead to erroneous results and in extreme cases to oscillations. The time interval is dictated by the time coefficient (De Wit & Goudriaan, 1978). It characterises the rate of change of the system and is best defined as the inverse of the relative rates (De Wit & Goudriaan, 1978). The smallest time coefficient is found by writing all rate equations explicitly. If an appropriate time interval of integration is used, errors due to the method of integration are negligible. However, modellers do not always realise the danger of using inappropriate time intervals of integration, and their time step is dictated by observation frequencies of the driving variables. This may lead to considerable calculation errors and even induce oscillations with increasing amplitude when the time step of integration exceeds twice the time coefficient (Ferrari, 1978).

4. Examples of models

4.1 Insect models

Most insect pests have more than one generation in a season and very often the generations overlap, thus preventing the use of key factor analyses (Morris, 1959; Varley, Gradwell & Hassell, 1973). These, basically graphical, methods are intended to indicate the major regulating factor of an insect population. Hughes (1962, 1963) proposed an analytical approach, based on the time-specific life table method, to study aphid populations. The basic assumption of this method is that the population has developed a stable age distribution. Carter *et al.* (1978) were able to show, with the aid of a computer model, that this did not occur in the field. The simulation approach appears to be a better way to investigate the population dynamics of aphids and many other pests.

Although Watt proposed the use of the models in 1961, it was not until 1968 that Hughes and Gilbert published a paper concerned with modelling a specific species the cabbage aphid Brevicoryne brassicae L., its predators, parasitoids and hyperparasitoids. One important concept that Hughes & Gilbert (1968) introduced into modelling was the use of a physiological time scale. This allows the modeller to neglect the daily vagaries of temperature. Instead 'time' is measured in day degrees; the cumulative total of temperature (above a certain threshold temperature) x time (in days). Four assumptions are made when dealing with this time scale; i) aphid development is primarily dependent on temperature, this is probably reasonable although Hughes (1963) did remark on the effect of different host plants and different physiological conditions of the same host plant on aphid development. These effects could be introduced in the model explicitly when their effects are known. ii) Development rate is linear with regard to temperature over the normal range of temperatures which is true for most aphid species studied (Hughes, 1963), iii) there is a constant threshold temperature below which development is zero, this temperature is only theoretical as development is non-linear at lower temperatures and it probably varies for different strains of the same species (Carter et al., 1980), and iv) fluctuating temperatures have the same effect as a constant temperature. This last assumption means that the aphid response to changing temperature is instantaneous. There is little information available on this but the evidence collected so far indicates that this assumption is justifiable (Rabbinge et al., 1979). In mites this hypothesis has been verified experimentally (Rabbinge, 1976; Sabelis, 1981, 1983) and is valid. However in other development processes, e.g. germination of seeds, it is not the case (Jansen, 1974). Gutierrez et al. (1976) emphasise the importance of the non-linear relationship between development and temperature at the extremes of the temperature range. Sharpe & DeMichele (1976) have produced a stochastic model which explains development processes on an enzyme kinetics basis. How important this will turn out to be for pest modelling remains to be seen.

Hughes and Gilbert's model is deterministic and employs no direct interaction between the different mortality factors. The model uses discrete time steps to simulate continuous processes and Hughes and Gilbert ran the model with different time steps to discover an accurate but efficient one. The result was a time step one quarter of an instar period (the physiological time for any of the first three instars). Thus the time interval of integration was determined by trial and error. This is the most appropriate way in large simulation models as direct determination of the time coefficient is only possible in small models.

Gutierrez et al. (1976) have attempted a truly systems approach to pest management on cotton. They started with analytical models to clarify what information would be required for ecosystem models. Next the team built a model for plant growth (Wang et al., 1977) which can be coupled to a number of pest models. These pests are either defoliators or they attack the fruits. This represents one of the first attempts to explain the effects of pests on their host plant and hence the final yield. Attempts have been made to add a further level to insect models, where the insects are vectors of disease (Gutierrez et al., 1974). Obviously this further complication increases the problems involved; the results and conclusions have not been very important, so far, in controlling diseases transmitted by insects.

The increasing economic importance of cereal aphids in Western Europe during the last decade has stimulated the development of models on the population dynamics of these insects. Carter (1978) and Rabbinge et al. (1979) developed such models; a detailed description of these models being given elsewhere (Carter, Dixon & Rabbinge, 1982). With these models, the population development of cereal aphids during a season may be simulated. An explanation for the population dynamics of cereal aphids can be given on the basis of insight gained by this modelling effort. It has been demonstrated that wing formation induced by a shift in assimilate composition during the medium milky ripe crop development stage is important in determining peak density. The decline in aphid population density induced by emigrating alatae is amplified by natural enemies; parasites, predators and Entomophthora spp. The simulation studies shows also that immigration is relatively unimportant after flowering, and that the potential of biological control of cereal aphids with presently available natural enemies is lim[illegible].

4.2 Non-insect invertebrate models

Most of these models are concerned with the population dynamics of mites, which are probably the most important invertebrate pests after insects. However, the first model discussed concerns nematodes which have special features making them, perhaps, easier for study.

Jones & Perry (1978) have produced a model to describe the population build-up of cyst-nematodes within and between years. Cyst nematodes are relatively immobile, which makes experimentation and modelling easier than with insects and fungi. In northern Europe these species only pass through one or possibly two generations per year and the observed maximum annual multiplication rate is less than 100-fold. Problems are encountered in sampling the nematode populations as they are aggregated around the roots and are difficult to extract and count. Also, eggs may remain unhatched for several years, thus complicating predications of population increase from year to year. However, this carry over proportion is density-independent and remains virtually constant from year to year.

Jones & Perry (1978) fitted a logistic-type equation for population growth within a year. The major density-dependent factor in these species is intra-specific competition (delays in growth rate due to their struggle for limited resources) and also, possibly, more males than females being produced as the density increases. They then constructed a model to predict yearly population changes under different rotation systems. The input of the model consisted of information about the population processes of the nematode and the crop rotation policies.

Thus the model can be used to decide on the optimum management practices to adopt to regulate the nematode population. The model was further modified to include the effects of nematicides on population increase.

In a detailed study, Rabbinge (1976) presented an explanatory model of the population dynamics of the fruit tree red spider mite (Panonychus ulmi Koch) and one of its natural enemies, the predatory mite Amblyseius potentillae. Predatory mites are now widely used as biological control agents in glasshouse vegetable crops and in fruit orchards (Gruys and Minks, 1980). The simulation study was undertaken to explain the regulatory potential of predatory mites and to derive guidelines for management. In these models of acarine systems, the gut content of the predatory mite plays an important role in governing the predation behaviour of the predatory mite. Special submodels have been developed to deal with the dynamics of gut content and the corresponding predatory behaviour. These submodels are based on detailed models in which searching behaviour of individual predators is included. This searching behaviour is largely affected by motivational state. On the basis of the simulation studies a ranking of phytoseiid mites with regard to their prospective use in biological control is possible.

Another important phenomenon introduced in models of acarine systems (Sabelis, 1981, 1983) is the distribution of prey mites in space and the effect of clustering in webs. These phenomena are introduced in the models and their effect on biological control is evaluated. Some phytoseiids (e.g. Phytoseiculus persimilis) prefer to search in webbed areas whereas other predatory mites (e.g. Amblyseius potentillae) are hampered in their monitoring activity due to the presence of webs.

4.3 Models of plant diseases

An early entire plant disease epidemic simulator was that of Waggoner & Horsfall (1969). Their simulator, EPIDEM, employed a number of weather factors; temperature, relative humidity, windspeed, sunniness and wetness. Thus the system is more complex than invertebrate models where temperature is usually regarded as the main driving variable and the effects of other factors, usually known to play some role in the system, are not quantified. EPIDEM is updated every 3 hours and simulates many of the processes occurring in a disease epidemic. Although Waggoner and Horsfall found that much of the relevant data was already available from the literature, several important components had not been measured before. These included: the speed with which a germinated spore penetrates the leaf, the washing-off of spores by rain, and the fertility of the spore-bearing conidiophores. Hence, the simulation model helped direct experimental research along certain lines.

The disease they were concerned with, early blight of tomato and potato caused by Alternaria solani, is rather a complex disease with different optimum weather conditions throughout its life history.

Although the correspondence between model output and field results was not complete they were sufficient to demonstrate clearly the relationship between the weather conditions and the different life history stages. Waggoner and Horsfall also performed sensitivity analysis which indicated that the fertility of the conidiophores was very important to the final outcome of the simulation. They hoped that their model could form a basis for other diseases with similar life histories to A. solani.

Waggoner, Horsfall & Lukens (1972) produced a simulator EPIMAY for southern corn leaf blight caused by Helminthosporium maydis a fungal disease which caused much yield loss in the U.S.A. in 1970. Their approach to the problem was almost identical to that which they had employed for EPIDEM. The step length employed (3 hours) is the same as used in EPIDEM. Much of the similarity between the two models is due to the similarity between the life histories of the two fungal species. Again, when they tested their model they did not compare output directly with field results. One reason for this is the lack of detailed field observations especially at the start of the epidemic which is needed for input to the model. They do indicate however that their model was used in 1971 as an aid for forecasting corn leaf blight.

Shrum (1975) has developed a model (EPIDEMIC) to simulate the growth of stripe rust caused by Puccinia striiformis, West. on wheat. The model is hierarchal and comprises three layers, (cellular-organismal-population). This, Shrum claims, is an attempt to produce a flexible simulator which can be used for other plant diseases. It will be some time, however, before this statement is accepted by other disease modellers. He claims to have entered all important factors, but by introducing so much detail in one single model there is a danger of number-grinding rather than correct simulation. He goes on to list the uses of the model if developed further; i.e. prediction, estimation of effects of partial resistance, and the effects of fungicide on an epidemic. It would be unwise, however, to use an unvalidated model for management and this should always be avoided.

Kampmeijer & Zadoks (1977) and Zadoks & Kampmeijer (1977) have developed a model, EPIMUL, to determine the effect of crop populations on the course of an epidemic. This is a theoretical attempt to model disease epidemics on a time and space scale. It is, therefore, a general model and is used to study the properties of a disease. The model (written in FORTRAN) has a time step of one day compared to the 3 h of the models of Waggoner and Horsfall. This is an arbitrary choice but acceptable as the model is meant, not for actual disease situations, but purely as an academic exercise. It should however be realised that since van der Plank's equation (a logistic growth formula with a latent period delay and a finite infectious period) is applied for the different compartments, the relative growth rate of this equation dictates the time coefficient. Therefore, the time step should be adapted if another relative growth rate is applied. To introduce the spatial component, a large square (a field, a country, a continent) is divided into a number of smaller square compartments. Basically the model applies the same logistic growth equation with time delay to all compartments and used a Gaussian distribution curve to spread the spores over the different compartments. The dispersion of spores is assumed to take place according to this function. The model thus presumes a certain nature of dispersion rather than calculating it on basis of the geometrical and physical characteristics of canopy, spores and their interrelations.

Effects of host development are neglected in this model since the size of the model in space (20 x 20 = 400 compartments) limits the dynamics of the model in time. Nevertheless the model throws some light on the effects of spore dispersal. It indicates that the focus of a disease expands radially at a constant speed, and that the daily multiplication rate has little effect on the rate of displacement of the disease front. Also, the model indicates the importance of the initial spore pattern in determining the speed an epidemic moves through a crop. They warn however that the validation of the model is purely qualitative due to the artificial nature of the model and the inadequacy of published data.

5. Discussion

Although the models in the examples mentioned have been developed independently they are, in general, remarkably similar. This is a reflection of the similarity of the biological processes in populations of pest and disease organisms and also the shared aims of builders in trying to produce a model for prediction purposes. The most important aspect of this is the accuracy of the model, but as we have seen most models are poorly validated. Modellers compare their model output with field results and usually comment that the agreement between the two is reasonable. No effort is made to use stringent quantitative statistical tests and so the accuracy of the models is difficult to determine. Thus their reliability is uncertain and, as Way (1973) has pointed out, their impact in pest control has been limited. Some of the distrust that the field worker has against the modeller is the lack of the latter's practical experience. This is being remedied in studies in England (Carter et al., 1982), the Netherlands (Zadoks et al., in press; Rabbinge et al., 1979; Sabelis, 1983) and New Zealand (Teng et al., 1980). Detailed field experiments are performed to test the model outcome by comparison with the results of independent experiments. This test phase has been completed by several pest and disease models, so that the next step to simplified and summary models is being made. These summary models form the backbone of the pest and disease management system EPIPRE implemented in intensive wheat cultivation in the Netherlands. Pesticide usage in agriculture seems high and more supervised systems of pest and disease control should be developed in the near future in order to develop sound agricultural methods.

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HOW TO USE COMBINATION MODELS IN CROP PROTECTION

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1. Introduction

Pest and disease management requires knowledge of both the crop and the pest or disease system. The dynamic character of the interrelations urges a dynamic description of the substrate and environment of the pathogenic organisms. The emphasis in most pest and disease management studies is reflected in Ruesink's review (1976); most studies emphasize the description of pest and disease population dynamics sometimes with stochastic submodels that simulate the infection and spread of the pathogenic organisms. The models have proved to be reliable predictors of pest or disease development but their value as quantitative predictors of injury to the crop is limited. For that purpose, combination models of the population dynamics of the pest or disease organism and of the growing crop are needed. Such combined models have been developed for situations in specific crops, such as cotton, alfalfa, apple and wheat (Gutierrez *et al.*, 1976; Rabbinge, 1976; Rabbinge *et al.*, 1981; Rabbinge *et al.*, in prep.). In some cases, these comprehensive simulation models have led to simplified economic models for decisions about spraying or praying, but their reliability is low and their value is still limited.

2. Types of models

Multivariate regression models of the type developed by Thompson (1969) Pitter (1973) Bridge (1976) are often more reliable. With proper 'tuning', such models accommodate better to average field conditions since historical data include the variation in plant stand, diseases and pests, and nutrient and water supply, which may be the principal determinants of yield. Such regression models perform best in predicting the mean performance of a population of fields, whereas the dynamic models may work best with the individual field. Among the dynamic models, different levels of detail should be distinguished depending on the objective of the study. When an explanatory approach is aimed at, these dynamic models are based on a systems hierarchy in an effort to provide prediction of integrated behaviour from a more detailed knowledge of the underlying physiological and morphological processes (De Wit et al., 1978; De Wit & Goudriaan, 1978). Of course all such knowledge becomes descriptive at the ultimate level of reduction, but one may distinguish between descriptive and explanatory models (De Wit, 1982) on this basis. When damage assessment is the aim, less detail seems necessary as rough estimate of the effect of pathogenic organisms may suffice. However, when explanation is the aim comprehensive simulation models are needed to take into account the complex nature of the various interrelations between harmful organims and host plant. The most important characteristic of these explanatory models is their integrative capability. Knowledge from different levels of organization is brought together in such a way that it is used to explain the behaviour of crops and the pest or disease organisms in a variable environment. Some types of physiological information are readily extrapolated from lower to higher levels; others are not.

2.1 Development of models

In this paper we will discuss some simple examples of how combined plant-pest or disease models have been developed. The aim of this modelling effort is to obtain insight as to how pest or disease organisms affect crop growth and productivity. A complete understanding of the nature of the interrelations is not the objective, but enough basic knowledge on the physiological background is necessary when the final aim is a management system which requires a reliable prediction of the effect of damage-causing organisms in individual fields. Comprehensive explanatory simulation models are then indispensable as an integrative tool. By sensitivity analysis and simplification, models are developed which may be used in management systems. Thus we may distinguish three types of models which express different levels, or phases of development, of knowledge and insight. At the frontiers of knowledge, preliminary models are very common. They enable the quantification and evaluation of hypotheses and are useful as such, but seldom survive a long time. Many different hypotheses may be expressed quantitatively in these models and their consequences may be calculated and used for an evaluation. These models may help as guidelines in experimental research. Comprehensive models may be developed from these preliminary models as a result of scientific progress; more knowledge and insight become available and may promote the lucidity of the system studied. The third category of models comprises summary models. These models are derived from comprehensive models and serve as vehicles for communication, instruction and may sometimes be used for management purposes. Since summary models are derived from comprehensive models, different forms of these may exist depending on the objective and interest of its user.

Combination models of crop growth and pests and diseases may exist in each phase of model development. Some examples of preliminary models are given below.

2.2 Combination models

Few combination models in the literature are based on detailed plant physiological analysis. They are very often of a dualistic nature, combining a great deal of descriptive elements on one hand, and a great deal of experimental observations on subprocesses on the other. But if too many phenomena observed at the system level are introduced, very often the behaviour of the model is being governed merely by these descriptive relationships. Models which aim at explanation are then rapidly degenerating into sophisticated ways of curve-fitting. Some examples are given to illustrate the use of combination models. These examples should merely be seen as a way of calculating pest or disease effects on the canopy without regard for the nature of damage. In many cases, this approach suffices to get reliable estimates of crop losses due to the damage-causing organism and may serve pest management and decision making, but when explanation is the aim they are too simple and a more detailed study is needed, as demonstrated for the cereal aphid-wheat relationship (Rabbinge _et al._, 1981) and the cereal-stripe rust relationship (Rabbinge, in prep.).

3. Crop growth under optimal and suboptimal conditions

Much attention has been paid to develop calculation procedures based on the process of photosynthesis. Some review articles illustrate this considerable effort (Loomis _et al._, 1979; Penning de Vries, 1980). These calculation procedures form the backbone of simulation models of crop growth. Different classes of simulation models may be distinguished depending on the crop production level for which they are meant; a delimitation of growing crops proposed by De Wit (De Wit & Penning de Vries, 1982). This approach emphasizes dry matter production rather than morphogenetic development. Four levels of plant production may be distinguished.

Production level 1

Comprises the potential production level reached in conditions with ample plant nutrients and soil water all the time. The growth rate of the crop in these conditions is determined by weather conditions and amounts to 150-350 kg ha^{-1} d^{-1} of dry matter when the canopy fully covers the soil. In these conditions the absorbed radiation is often the factor limiting the growth rate during the growing season. In fact, this is quite a common situation in cool climates. Major elements in this class of system are the dry weights of leaves, stems, reproductive or storage organs and of roots, and the surfaces of photosynthesizing tissues; major processes are CO_2 assimilation, maintenance and growth, assimilate distribution and leaf area development. A situation with plant growth at this production level can be created in field and laboratory experiments while it is approached in practice in glasshouses and in the very intensive production of sugar-beet, potato and wheat on some Western European farms.

Production level 2

Growth is limited by water shortage at least part of the time, but when sufficient water is available the growth rate increases up to the maximum rate set by the weather. Such situations can be created experimentally by fertilization in temperate climates and in semi-arid zones; it is approached in practice in non-irrigated but intensively fertilized field, such as many Dutch pastures. The extra elements of this class of system are the water balances of the plant and soil; crucial processes are transpiration and its coupling to CO_2 assimilation and loss or gain of water by the soil through evaporation, drainage and run-off. The heat balance of the canopy needs consideration in detailed analyses at this production level because of its relation to the water balance.

Production level 3

Growth is limited by shortage of nitrogen (N) at least part of the time, and by water or weather conditions for the remainder of the growth period. This is quite a common situation in agricultural systems using little fertilizer, and is also normal in nature. Even with ample fertilization, N shortage commonly develops in crops at the end of the growing season. Important elements in these systems are the various forms of N in the soil and in the plant; important processes are the transformations of nitrogenous compounds in the soil to forms less or more available to plants, leaching, denitrification, N absorption by roots, the response of growth to N availability and redistribution of N within the plant from old organs to growing ones.

Production level 4

Growth is limited by the low availability of phosphorus (P) or by other minerals like potassium (K) at least part of the time, and by N, water or weather for the remainder of the growth period. Lack of P is particularly interesting because of its relation to the metabolism of N. Growth rates are typically only 10-15 kg ha^{-1} d^{-1} of dry matter during a growing season of 100 days or less. This situation occurs often in heavily exploited areas where no fertilizer is used, such as in the poorest parts of the world. Important elements of this class of system are the P or mineral contents of the soils and of the plants; important processes are their transformation into organic and inorganic forms of differing availabilities, absorption of minerals by roots, and the response of plant growth to their absolute availabilities. The availability of P relative to that of N is also important.

It is rare to find cases that fit exactly into one of these four production levels, but it is a very practical simplification of a study to reduce specific cases to one of them. It focuses attention on the dynamics of the principal environmental factor and on the plant's response. Other environmental factors can then be neglected, because they do not determine the growth rate; or rather, it is the growth rate that sets the rate of absorption or efficiency of utilization of the non-limiting factor. If, for example, plant growth is limited by the availability of N, there is little use in studying CO_2-assimilation or transpiration to understand the current growth rate. All emphasis should then be on N availability, the N balance and the response of the plants to N.

4. Effects of pests and diseases

Pests and diseases may affect the growth of a crop at all production levels. However, the nature of the relation between crop and pest or disease organism may be considerably different and the crop losses, both qualitative and quantitative, may also depend on the way crop growth is affected. In a detailed study on crop losses due to ceral aphids, Rabbinge *et al.* (in prep.) demonstrated that the effect of a similar aphid load on the plant was considerably different at different production levels. Yield loss (kg kernels/ha) was correlated with the maximum aphid density per kernel, normally reached at crop development stage milky ripe (decimal code 77). At a production level of about 5000 wheat/ha^{-1}, a maximum aphid density of 15 tiller^{-1} cau yield depression of about 250 kg ha^{-1}; whereas, the same population density at a yield level of 7500 kg ha^{-1} caused a yield loss of 800 kg. In the analysis of this damage relation, it was demonstrated that the major reason for the progressive damage relation was the relative importance of indirect effects on yield loss. The major reason for the considerable damage at higher yield levels is found in the effect of honeydew on photosynthetic rate and promotion of senescence of leaves (Rabbinge *et al.*, 1981). These effects are caused by the sealing of stomates and the depression of the activity of photosynthetic active enzymes.

This example has demonstrated the importance of defining the yield or production level at which the pathogen-crop relation is studied. Effects at production level 1 may be completely different from effects on production 2, 3 or 4. In the next part of this paper only effects of pests and diseases at production level 1 will be discussed. The effect of pests and diseases at other production levels may be different. It is demonstrated that pests and diseases of 'poor crops' and pests and diseases of 'rich crops' exist (Rabbinge, in prep.).

5. Simulation of crop growth

In the case of production level 1, computation of production is based on assumptions of a maximum photosynthetic activity and closed crop surfaces. Methods in which attention is spent on photosynthesis, respiration and partitioning between various plant organs are scarce. Based on knowledge about accumulation, distribution and redistribution of carbohydrates, quantitative aspects of respiration etc., Van Keulen (1976) derived a simple calculation method for potential rice production which can be applied, after some adaptation, to other crops (Penning de Vries _et al._, 1982) and is very suitable for interconnection with a population model of pest and disease organisms in order to study their effect.

5.1 Summary model SUCROS

The summary model (SUCROS) developed by Van Keulen comprises short cuts and descriptive tables for subprocesses, based on computations with a comprehensive crop growth simulator, BACROS, (De Wit _et al._, 1978).

Weight of shoot, root and ears (in the case of wheat) increases with a developmental stage-dependent rate. All organs grow from an assimilation stream, the size of which depends on the incoming radiation and the leaf surface participating in photosynthesis. Photosynthesis is diminished before partitioning between different plant organs by a rate-dependent growth respiration and a weight-dependent maintenance respiration.

Root and shoot may decrease with a rate which depends on size and a development stage.

a) Photosynthesis

The basis for the calculation of potential crop yield is the photosynthetic rate of the canopy. Assuming optimal growing conditions, De Wit's (1965) calculation procedure can be used to compute photosynthetic rates for closed green crop surfaces. Goudriaan & Van Laar (1979) demonstrate that on the basis of the photosynthesis-light response curve of a single leaf in ambient air of normal temperature and CO_2 concentration, a response curve of closed canopies may be calculated without further knowledge of the geometric characteristics of the canopy. Only the total leaf mass should be known. Effects of chloroplast distribution, nitrogen content of the leaf blade, age of the leaf and environmental conditions such as CO_2-concentration and temperature, can be found as changes in light-use efficiency or maximum photosynthesis rate of the simple leaves. In individual leaves light saturation is normally reached at values of 0.15 cal cm^{-2} min^{-1} (=104.7 J m^{-2} sec^{-1}), which is well below the values reached in the middle of a sunny day on a horizontal plane.

Goudriaan (1977) showed that it is reasonable to assume that the actual rate of gross photosynthesis is proportional to the fraction of the total energy intercepted by the canopy. To calculate this fraction an exponential extinction of the light intensity within the canopy using a fixed extinction coefficient seems reasonable (Van Keulen, 1976; De Wit, 1965; Goudriaan, 1977).

With the photosynthesis part of the comprehensive crop growth simulator BACROS (De Wit et al., 1978), Goudriaan & Van Laar (1979) calculated daily gross photosynthesis rate for completely overcast and clear skies for different geographical sites and different times of the year for a closed canopy. The actual daily gross photosynthesis rate (GFOT) in the summary model is now found by calculating the fraction overcast during a day (F), and multiplying the daily gross photosynthesis rate for overcast skies (PO) with this fraction, adding to this product the fraction clear multiplied with the gross photosynthesis rate for clear skies (PC): i.e. GFOT = (1.0 - F) × PC + F × PO.

The fraction overcast (F) is calculated according to the formula

F = (DTRS-0.2×HC)/(HC-0.2×HC), in which DTRS = actual incoming radiation in J m^{-2} s^{-1} and HC = incoming radiation when the sky is completely clear. The incoming radiation on overcast days equals 20 per cent of the amount of incoming radiation at clear days. PC, PO, DTRS and HC are introduced in the model as time and location-dependent variables. The gross photosynthesis rate of a crop GFT is now calculated from the gross photosynthesis of a closed canopy by multiplication with a factor that accounts for the extinction of the radiation in the canopy and thus only has considerable effect with low leaf area (LAI $<$ 3): i.e. GFT = GFOT×(1.0 - EXP(-0.6×LAI)). The LAI is not based on knowledge or measurements of the leaf area during crop development but computed from the weight of the above ground material assuming a fixed specific leaf weight of 0.5 kg m^{-2}, a figure which seems to be representative for small grains.

b) Respiration

To grow and produce new compounds, the energy fixed in the photosynthetic process is partly used, so that only a changing fraction is fixed in new compounds. Two main processes for which the just-fixed carbon is used can be distinguished.

1. Growth processes, i.e. the construction of structural plant material as proteins, fats, carbohydrates out of the primary photosynthetic products. Each of the newly formed structural compounds requires a further amount of primary photosynthetic products. In a detailed study of this growth respiration, and by means of a sophisticated way of bookkeeping of all the processes involved, Penning de Vries (1975) derived the efficiency of conversion for the different structural compounds in terms of weight, namely the production value.

2. Maintenance processes. The other sink for photosynthetic material is the maintenance of already existing cells. Their structure must be maintained and this involves the turnover of protein and the sustaining of ionic gradients and membrane structures. Again the composition of the material determines the energy required; the main variable

being the protein content. The complicated character of maintenance means that accurate quantitative estimates of these processes are rare. Although the size of maintenance respiration is low in comparison with growth respiration, its presence during the plant's whole life span makes its contribution to the total energy spent for respiration comparable with the costs of growth processes (Penning de Vries, 1980). Maintenance respiration is directly affected by temperature and seems to react to temperature according to a Q 10 value of 2-3.

Since maintenance of present structures has a higher priority than synthesis of new structural material, the computations are done in such a way that growth respiration is calculated after subtraction of the respiration needed for maintenance.

c) Development

To compute how, and at what rate, carbohydrates are partitioned, the developmental phase of a plant (crop) is of high importance. In most models of crop growth, development and morphogenesis are not considered. A major reason for this is that processes of development are poorly understood and explanation of, for example, the appearance of leaves, the distinguishing between vegetative and generative phases, and flowering and heading of plants is virtually absent. Still, the development of a crop heavily interferes with its growth and thus development should be considered in a realistic crop growth simulator. To circumvent the absence of reliable data on the process of development, a description of the development of the crop is introduced in the crop model. In most crops, development is affected by temperature and day length. These governing factors may be introduced to compute the rate with which the crop develops, this is usually done by defining crop development in terms of a temperature sum i.e. the product of average temperature and time. The vagaries and implicit assumptions of this technique are too numerous in many cases and, for this reason, a more flexible approach is chosen in which development is mimicked by integrating a temperature and daylength-dependent development rate. The input relation of this rate should be determined from crop development experiments in which the average development period (for example from germination until flowering) is determined at different temperatures. Often the inverse of this period has a linear relation with temperature and thus enables the application of the temperature sum as a measure of development stage, but also the other condition of instantaneous temperature reaction should then be fulfilled. Tests on this linearity are seldom executed, so its application should be done with care.

Besides partitioning and changes in temperature response, ageing and senescence of the various plant organs is determined by development stage. To determine the ageing and senescence rate, the life span of leaves, stem and other plant organs should be determined under various abiotic conditions. Based on these measurements, temperature- and development-stage-dependent relative ageing rates for stem and root of winter wheat have been introduced. Generally it can be stated that there is a considerable shift in partitioning after flowering. This may of course be different in non-determined growing plants such as beans.

5.2 Combining SUCROS with population models of pests and diseases

Three examples of damage-causing organisms have been chosen to demonstrate the different effects of a disease or pest according to its relation with the host plant. The input data in the crop model are based on winter wheat but can very easily be adapted to other crops so that this summary model is widely applicable. The calculations are all performed for a standard year, starting at 15 May and ending at 25 August. The chosen interrelations are such that the pest and disease organism dynamics are given with descriptive relationships rather than simulation with detailed population models. Mutilation of leaf mass, coverage of leaves, and leaf mass consumption are treated and each represents a group of pest or disease organisms. It is self evident that these three examples of host plant-pathogen relations are not exhaustive; many other interrelations are possible, but are not treated as they fall outside the scope of this bulletin.

a) Mutiliation of leaf mass

Many examples of leaf mass consumption by herbivores are possible. The influence of removers of leaf mass seems limited unless their numbers become very high, or their consumption rate is very considerable. For example, the effect of leaf hoppers on leaf mass is so high that sophisticated prediction and monitoring systems have been developed to prevent their disastrous effects. To demonstrate the effect of a leaf consumer on crop growth, a simplified description of population growth of the cereal leaf beetle has been attached to SUCROS and parameterised for winter wheat.

Larvae of cereal leaf beetles (*Oulema melanopus*) consume leaf mass and do this at a consumption rate of about 250 cm^2/day (= 2 g dry mass). Only the larvae consume leaves. After growth and development they pupate and form adults that may give rise to another generation. The rate of increase of the numbers of cereal leaf beetle larvae mainly depends on the immigration rate of the adult beetles which lay their eggs on the leaves. After hatching the larvae immediately start feeding. Their effect on crop growth is introduced as a drain on the shoot weight. This rate of decrease of shoot weight is assumed to be proportional to the number of larvae of the beetle, lumping all developmental phases of the larvae together. Consumption of leaf mass by the adults is neglected, and age and food-quality-dependent reproduction and development rates are not considered. The beetle population is introduced in a very simple way by distinguishing four morphological stages: eggs, larvae, pupae and adults. The adult population is assumed to be 50% males, so that after egg laying only 50% will grow up as females and contribute to the next generation. Reproduction of adult beetles is diminished when high larvae densities are reached, which depends on the larvae/shoot weight ratio.

Calculations with the model show that only when the population density of the larvae reaches a level of 15,000/ha or $15/m^2$ or 0.004/tiller at flowering is the effect on the yield more than 1% of the yield. It has also been shown that the time of introduction of the beetle is of high importance. A late and heavy attack of the beetles scarcely affects the final crop yield, but an early and steady attack may cause a severe decrease of the yield. For this reason it is important to determine the presence of the beetle at an early phase of crop growth and to prevent outbreaks.

b) Leaf coverage

Mildew, caused by Erysiphe graminis, is coupled to the wheat simulator to demonstrate the effect of a disease that covers the leaf surface and promotes leaf senescence. The fungus is simulated with a descriptive formula according to Vanderplank (1963) and Zadoks (1971).

Individual spores or pustules are not distinguished, but rather sites are simulated, i.e. the leaf surface is expressed in potential sites, each site representing the minimum size of a lesion (a field of 1 ha, LAI = 3, contains 10^{12} such sites). The increase of sites in course of time is simulated with the equation.

$$\frac{dN_t}{dt} = R\ (N_{t-p} - N_{t-i-p})\ (1 - \frac{N_t}{N_m})$$

in which N_t = number of visible infections at time t, R = number of daughter lesions per sporulating lesion per day, p = length of the latent period of the fungus, i = length of the infectious period and N_m = maximum number of possible infections. When the latent period approached zero and the infectious period goes to infinity the equation changes to that for logistic growth

$$\frac{dN_t}{dt} = R\ (N_t)\ (1 - \frac{N_t}{N_m})$$

in which N_m can maximally reach the value for the surface of the standing crop, in this case expressed as LAI.

Of course this representation of a mildew epidemic is too simple and a more detailed simulation model in which all morphological stages are distinguished should be used (Rijsdijk, 1978; Zadoks, 1971). However, for the present example the given equations suffice. The stimulation of respiration by the fungus is neglected and the effect of ageing of the leaves is not considered but can easily be introduced by changing the relative rate of ageing of the shoot, which is fungus-density-dependent.

Some results of the computations with the model show that the effect of leaf coverage is only of importance when the leaf area index of the crop is smaller than 3. Moreover, it is shown that a percentage of leaf area covered by mildew of 30% at early milky ripe results in a yield decrease of 10% or 700 kg of wheat. Of course these results should be considered with care as the other effects of the mildew are not introduced and high light intensities may mask these effects. A coverage percentage of more than 20% is very seldom in practice so that other damage effects are probably also very important.

c) Parenchyma cell consumption

This way of plant damage is probably best represented by mites. Plant mites can be considered as a major pest. Mites are found from the Arctics to the Tropics and frequently attack horticultural and agricultural crops. In many cases mites are considered to be secondary pests as they often become a serious pest when insect sprays are introduced. Predators (ladybirds, predatory mites, syrphids) probably regulated the numbers of the mites before that time, but were killed by the sprays, leaving the spider mites unharmed due to rapidly developing resistance (Huffaker *et al.*, 1970). Spider mites seldom cause severe damage in wheat, only in very hot spells does the two spotted spider mite *Tetranychus urticae* cause, very locally, rapid senescence of leaves and decrease of photosynthetic activity. The increasing usage of pesticides in winter wheat may lead to mite problems in wheat when abiotic conditions are favourable. Most plant mites cause this damage by injection of their stylets through the epidermis in the parenchyma cells and swallowing the contents. The attacked cells may die and the surrounding cells often show phenomena like suberization of cell walls, decrease of photosynthetic activity and increased maintenance respiration. The crop model is changed at two places to introduce these effects. Firstly the maintenance respiration is increased with a term that accounts for the mites. This respiration term is considered to be proportional to the mite density. Although this may be true at relatively low densities, this way of introduction overestimates the effects of the mites at high densities. Secondly, an effect of the mites on the photosynthetically-active leaf mass is introduced. This effect is also mite-density-dependent, the basis of these effects being derived from damage data of Sabelis (pers. comm.) on roses. The density of the mites is simulated by way of three age classes, lumping the different morphological stages together. A more realistic population dynamic model should consider the different morphological stages and the sensitivity of development rate to temperature and food quality (Rabbinge, 1976). This effect, and that of temperature and other abiotic factors on reproduction, mortality etc., are not considered. Computations with the model show that a minor change in the simulation of the maintenance respiration due to the presence of the mites causes a major effect on the growth of the canopy, and does interfere considerably with yield. The same holds for the effect on leaf senescence, an increase in average leaf senescence of 4 days results in a yield loss of 500 kg of wheat.

6. Use of combination models

The examples of combination models described are used as a research tool to obtain better insight and understanding of the effects of a pest or disease on its host. When necessary, detailed models of the population dynamics of the pest or disease organism can be combined with detailed models of crop growth. An example of such a detailed study is given by Gutierrez *et al*. (1976) and Rabbinge *et al*. (1981; in prep.).

The detailed population-dynamic crop and combination models themselves are seldom used for actual decision-making in crop protection. Their role is to test hypothesis, to gain insight and to pin-point the most decisive variables for the rate of development of pests and diseases. They are used to compute the range of acceptable disease or pest levels according to the weather, the crop production level and the condition and developmental stage of the plants. These calculations have been made for different diseases and pests in winter wheat and have resulted in simplified summary models and/or decision rules, which are used to determine whether control measures are needed.

In the Netherlands these results are used in a supervised control system called EPIPRE (EPIdemics PREvention) (Rijsdijk *et al*., 1981). EPIPRE is developed for wheat farmers. It works on a field-by-field basis and gives recommendations for every individual wheat field included. This was done in 1979-1980 by a team of research workers for 1000 fields and based on field information. This information is stored in a data bank and includes data on location, sowing time, cultivar, a few simple physical and chemical soil characteristics, herbicide application and nitrogen (N) fertilization. The information per field is updated whenever additional information is supplied by the farmer or the research team.

This information is used to run the simplified combination or the decision-rule models to obtain recommendations that are then sent immediately to the farmers. This EPIPRE supervised control system is now operational in several European countries and has led to an improved economic plant protection system with reduced pesticide use and with optimal economic results. This optimal yield may be different from maximum yield as cost-benefit analyses are used as the basis for advice.

At present this supervised control system of pests and diseases in winter wheat does not supply information and advice on supervised weed control or on N and P fertilization. Reliable simulation models on N in soils and crops are gradually becoming available, and may be used in future to advise on the timing and amount of N added to winter wheat. The same holds for weed control. In this way an integrated crop protection system may be developed, in which costs are reduced and economic yields are optimized.

7. Conclusions

An introduction on combination models of pests and diseases and crop growth has been given. The examples presented are still of a preliminary nature but serve as an illustration of how these models can be used. Specialists from different fields, such as entomologists, phytopathologists, plant physiologists and crop ecologists, may contribute to the further development of combination models. Both comprehensive and summary models are needed in this process of gaining knowledge and insight in the pathogen-crop relationship. These efforts are indispensable for the development of supervised control systems.

The need for supervised crop management studies lead to the rapid development of this type of model. interdisciplinary effort of plant pathologists, agronomists and extension people will help to achieve reliable crop management systems in the near future.

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A DECISION ANALYSIS/MODELLING APPROACH TO PEST AND DISEASE MANAGEMENT

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1. Introduction

Despite the considerable effort devoted to using modelling techniques in crop protection, Way's challenge made in 1973 - that systems analysis and modelling had "....not yet proved their practical value in controlling pests..." (Way, 1973: p. 137), is still largely unanswered. One possible reason for this is that much modelling effort has not been primarily concerned with answering practical, crop protection problems. As Hall & Norgaard (1974) disconcertingly put it - "...we never meant for our model to be 'applied'."

The view expressed in this paper is that modelling techniques are only likely to be of practical value in crop protection when aimed at providing relevant information for decision making, whether this be at the research, the extension, or at the farm level. Consequently, systems analysis and modelling is seen to be of greatest value when employed to address specific choices that arise from the initiation of a research programme through to the implementation of crop protection practices. With the decision problem identified, the modellers' problem is then to choose or develop a technique relevant for this specific purpose.

At the farm level, decision making in crop protection can be usefully divided into strategic and tactical decision making. Strategic decisions are concerned with long-term planning and design options, such as the layout of an orchard, the choice of spraying machine, or whether to opt for prophylactic or adaptive pest control. Examples of models that attempt to address strategic questions are given by Norton et al. (1983) and Cussans & Moss (1982). By contrast, tactical decisions are more concerned with short-term options, such as should I apply a spray this week or not? The EPIPRE system (Rijsdijk, 1982) is a good example of a modelling approach that tackles a tactical decision problem.

In this paper, I will not discuss the practical value of models at this level. This is not because this role of modelling is unimportant but because systems analysis and modelling techniques probably have a far more important role to play in research and extension decision making, at least for the present. It is this problem that the remainder of this paper addresses.

In responding to practical crop protection problems, research and extension organisations clearly have to undertake experimental and empirical studies, aimed at understanding the processes involved, developing control methods and practices, and testing them in the field. However, in all cases, the decision problem involved is which particular line or lines of research and extension should limited resources be allocated to, and how should this be carried out. Assuming that the ultimate aim is to improve practical crop protection, these research and extension decisions will be taken on the basis of the contribution made to this end. It is to provide an aid to this decision making process that a research and extension screening procedure has been suggested (Norton, 1982). The purpose of this screen is to provide a systematic and yet flexible means of focusing on those ecological, technical, socio-economic, and institutional features of the problem that are most likely to affect a successful result. An outline of this procedure is given in Fig. 1.

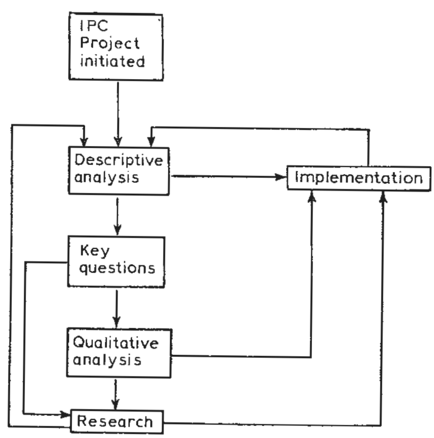

Fig. 1. The role of modelling in research and extension decision making

2. Descriptive analysis

The purpose of the initial descriptive analysis is to obtain a clear definition of the problem. To start with, why does the problem exist? Is it the result of certain constraints at the farm level, such as a lack of machinery know-how, or information? Each of these problems clearly will have to be tackled in a different way. Where information is lacking at the farm level, is this because the information is not being disseminated to the farmer or is it because the information does not exist? If the information exists but is not being disseminated, the implication may be that better synthesis and interpretation of information is required, or that extension services should be improved. Where the information does not exist, the implication is clearly for research, or other forms of data gathering, to be developed.

It should be evident from this that a major emphasis of the descriptive analysis is to identify the problem at the farm level. Therefore, one aspect on which the descriptive analysis should focus is to describe the decision process at the farm level. In many cases, this should involve a survey, either an exploratory survey or a more formal survey, to help identify the major components of the on-farm decision problem. In particular, surveys should attempt to determine:

i) present crop protection practices,

ii) the objectives that farmers' have in employing these practices, particularly their goals and risk attitudes,

iii) farmers' perceptions of pest attack, pest damage, and the effectiveness of crop protection measures,

iv) on-farm constraints, including capital, labour, machinery and information,

v) the sources of information used by farmers.

The problem of crop protection on the farm is unlikely to remain a static one however. The problems that most research and extension workers face is that the target for their efforts is a moving one. Thus, research being undertaken at present should be addressing the problems of the future rather than the problems of today. It is to obtain some idea of how future developments in agricultural policy, cropping practices, application machinery and chemicals, are likely to affect future pest problems and their control that a regional level description is required. The major components of this system are outlined in Fig. 2. The purpose at this level of description is to obtain some insight into the history of pest development, the important factors that have affected this development in the past and so obtain some idea of likely future developments.

At the farm level, the descriptive analysis consists of two major components, as shown in Fig. 3. The ecological component is divided into a structural description, identifying the major components, and the design of the cropping system. The dynamic description is concerned with changes in these components over time and how they interact. The management component is concerned with understanding why farmers are carrying out the crop protection practices they do, and how their perceptions, objective and constraints, affect their decision.

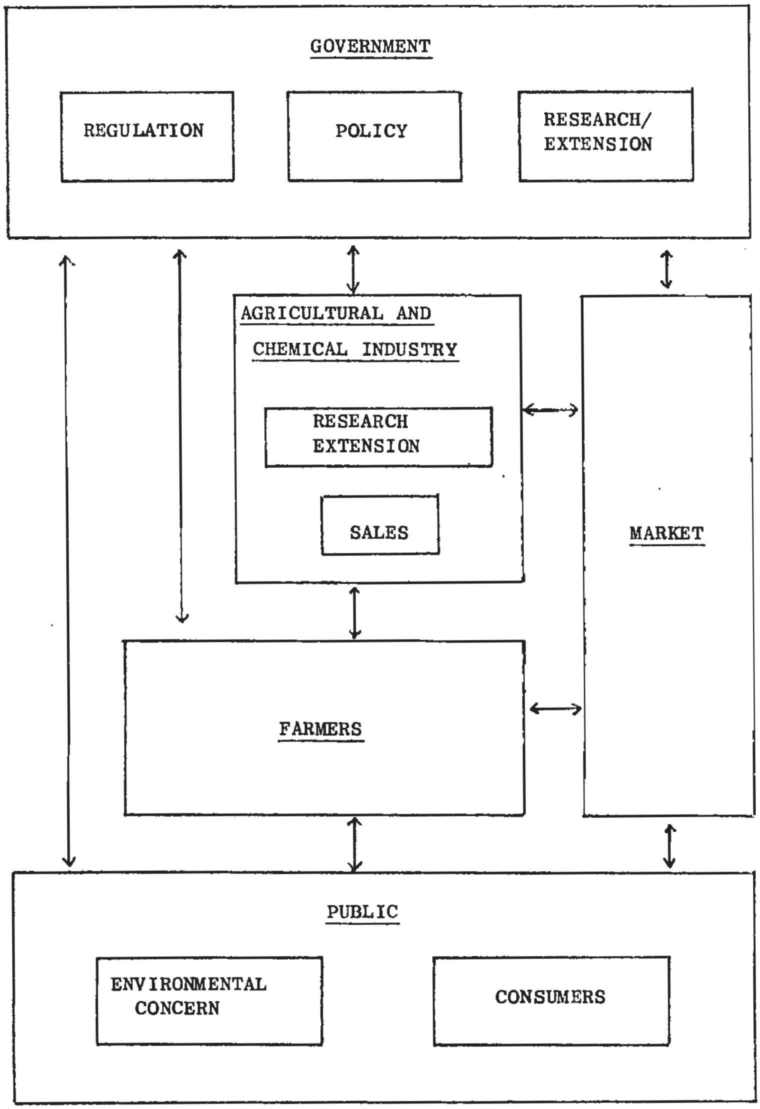

Fig. 2. Regional factors influencing crop protection problems.

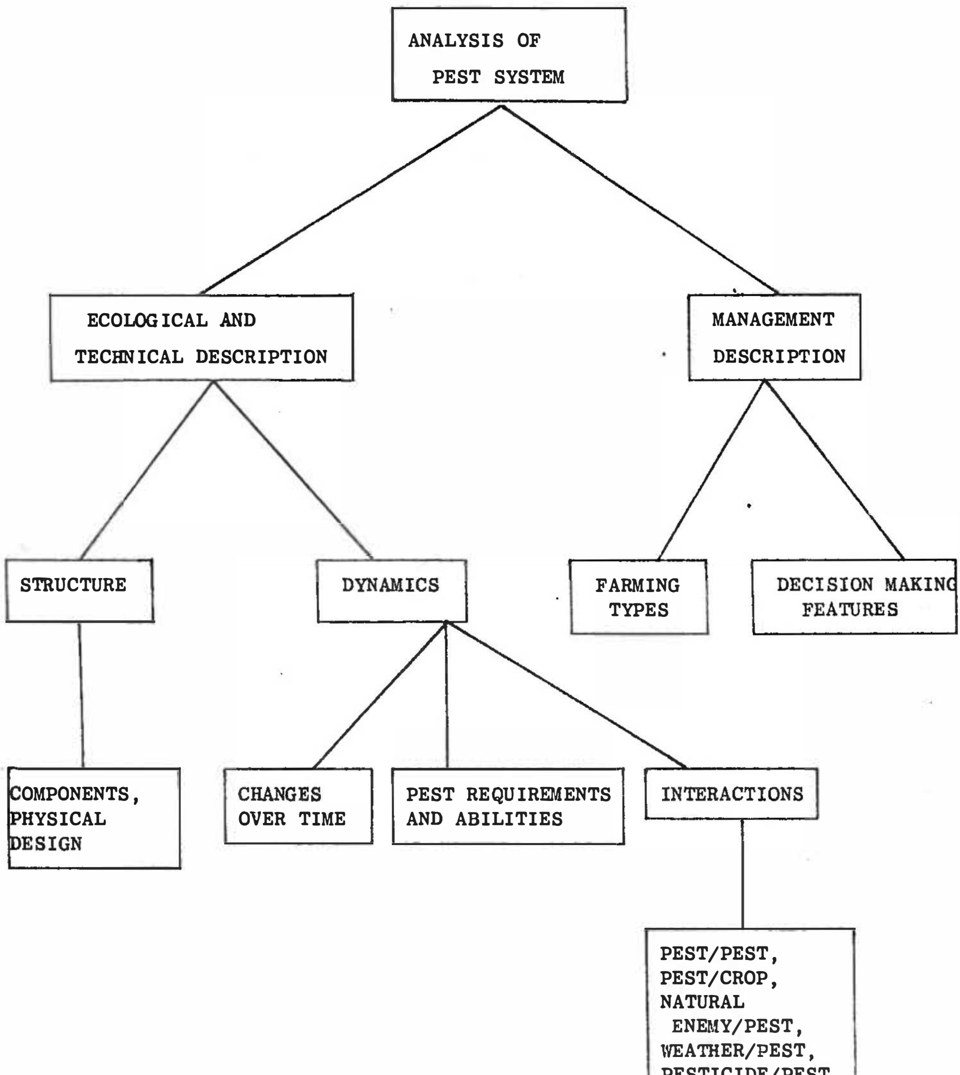

Fig. 3. Descriptive analysis of a crop protection problem.

This descriptive analysis phase, will, in many cases, be best conducted within a structured discussion group, involving representatives of government research institutions, universities, the chemical industry, and other interested and informed parties. To help focus discussion and to facilitate greater communication between disciplines, overlay mapping techniques, interaction matrices, graphs, and other simple displays, can be usefully employed. To illustrate, a damage matrix, indicating where an interaction occurs between different insect and disease pests on various apple tree components is shown in Table 1. By checking through this table, each possible interaction can be considered by the group, and certain or likely interactions identified. As shown in Fig. 3, predator and parasite/pest, weather/pest, and pesticide/pest interactions, are also likely to be considered.

The description of the system achieved in this way is, in effect, an agro-ecosystem model, albeit a very crude one, especially when compared with the simulation modelling approach. However, apart from the fact that the descriptive model can be achieved quickly, the aims of these two approaches is different. The purpose of the descriptive model is to identify important relationships, to raise key questions, and to provide a relevant context within which more detailed modelling can be used to investigate spe[illegible] questions.

3. Key questions

Having undertaken a descriptive analysis, a whole series of key questions are likely to be raised (Fig. 1). These key questions will have arisen from describing the regional factors that affect the problem as well as the on-farm description, and will consist of questions concerning missing information, on ecological, technical, and decision making processes, and speculative questions, concerning problems such as "what would happen if...". Clearly, for certain types of information the obvious next step is to conduct empirical or experimental work to obtain this information. In other situations, and particularly for speculative questions, the way in which these can best be investigated through empirical or experimental studies is by no means as obvious. It is here where qualitative modelling techniques can be of value.

4. Qualitative analysis

Using general theories, principles, concepts, and models of pest control, the purpose of qualitative modelling is to refine and "tease-out" certain key questions identified in the previous stage. It is concerned with identifying key parameters and variables involved in these questions, enabling relevant research programmes to be identified. To some extent, this qualitative analysis phase can be regarded as a hypothesis generating process, serving to complement the existing research policy and design process by allowing hypotheses and speculations to be investigated in some

Table 1. Damage matrix: the effect of pest components on the tree and fruit. Each * indicates an interaction which is detrimental.

Tree components	Codling/ Tortrix	Winter moth	Sawfly	Rosy apple aphid	Woolly aphid	Mites	Mildew	Scab	Nectria	Phytophthora	Gloeo-sporium	Fireblight
Vegetative buds				*			*					
Leaves				*	*	*	*	*				
Wood									*	*	*	*
Fruit buds		*		*			*					
Blossom trusses	*	*		*	*	*	*					
Fruitlet	*		*					*				
Fruit	*							*	*	*	*	
Fruit in storage								*	*	*	*	

detail. For instance, where several possible research lines are being considered, an important initial contribution that a qualitative analysis may make is to identify the best line to follow. Projects may be rejected on the grounds that they are unlikely to meet farmers objectives or constraints, or because the information required would be impossible or extremely expensive to obtain.

To illustrate how qualitative analysis can be useful, consider the following key management question that often arises in crop protection - "Under what conditions will a monitoring and spraying strategy be better than calendar spraying?". A simple "decision model" provides a useful framework for discussing the issues surrounding this question. An outline of the problem is represented in Fig. 4, where the net revenue associated with three strategies - no spraying, calendar spraying, and monitoring and spraying - is expressed as a function of the level of attack in a particular crop season. Note that this particular model is only relevant for an exogenous pest that migrates, or is wind borne into the crop each season. The dynamic aspects associated with endogenous pests, such as weeds and nematodes, that complete their life cycle within the farm agro-ecosystem, are not accounted for in this model.

Some of the biological, ecological, technical, and economic factors involved in estimating the form and relative positions of the curves shown in Fig. 4 include:-

1. The damage relationship, which determines the shape of the net revenue curve when no spraying is undertaken;
2. The effectiveness of each crop protection strategy, which affects the slope of the other two net revenue lines;
3. The cost of calendar spraying and the cost of monitoring which determines the point at which the net revenue curves interset the vertical axis when pest attack is negligible.

As well as identifying the information required for constructing Fig. 4, this model provides the context within which the implications of a variety of factors can be considered. For instance, within this framework an investigation of the implications of new monitoring techniques and spraying machinery, future pest scenarios, growers' objectives, and changing market prices, can be made in an explicit fashion.

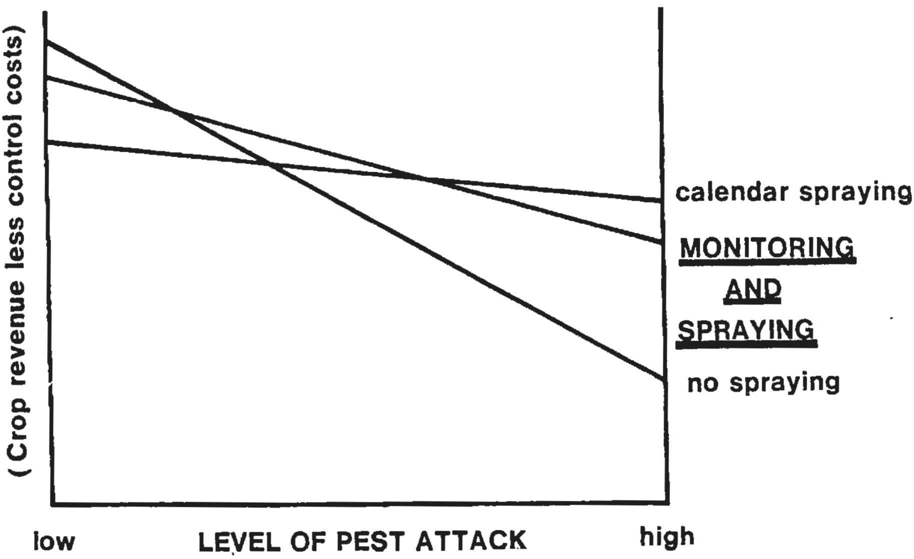

Fig. 4. Diagrammatic representation of a decision model concerning the choice between calendar spraying and monitoring and spraying.

Other examples of modelling techniques that could usefully be employed at this qualitative analysis stage are given by Holling (1978) concerning management strategies for spruce budworm in Canada, Comins (1977a, 1977b) on the ecological features affecting pesticide resistance and strategies for delaying it, and Southwood & Norton (1973), Anderson (1979), and Hassell (1980) on factors affecting the feasibility and efficacy of biological control.

5. Discussion

This paper set out to demonstrate how a decision analysis/modelling approach to pest and disease management could be of practical value in crop protection. While this approach undoubtedly has an important role to play in the implementation of certain crop protection practices, this particular application is likely to be limited. What is likely to be of greater value for a wide range of pest problems is the use of modelling techniques at the descriptive and qualitative analysis stages. This approach is likely to be particularly important when employed in workshop sessions during the early stages of a research programme. Far from being in conflict with essential empirical/experimental research, descriptive and qualitative analysis can be complementary or catalytic, providing the tools by which the gap between pest control theory and practice might be bridged, and, more importantly, providing a basis on which more multi-disciplinary research in crop protection might be achieved.

How this approach can be operated in practice is another matter. Since pest problems are diverse and research programmes vary in terms of the finance, time, and expertise available, a flexibility of approach is vital if it is to be of practical value. Perhaps the greatest challenge in attempting to employ modelling techniques of practical value in crop protection is to create an institutional structure that will allow it to be achieved.

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THE STATUS OF MODELS IN CROP PROTECTION; AN ANALYSIS USING DATA BASE SYSTEMS

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1. Introduction

A decision of the joint EPPO/IOBC Conference at Paris in 1976 (Jeger & Rabbinge, this bulletin) was to produce an inventory of crop protection models, at various stages of development, but restricted to fruit, grapevine, hop and cereal crops in western and central Europe. The inventory was compiled by questionnaire (Butt, 1983) and offered a unique opportunity to assess the status of models, both published and unpublished, in crop protection; albeit, disregarding models concerned with important crops such as potato and sugar beet. This chapter is concerned with an analysis of the models submitted by December 1981, using, unless otherwise stated, the chapter by Jeger, (this bulletin) as a reference point, and will discuss the technical means employed in the analysis, and the accessibility of such information to those working in crop protection. It is not intended to identify or discuss individual models; the full and updated inventory will be published as an IOBC Bulletin (Butt, 1983).

2. Methods - the use of computer-based Data Management Systems

Fifty-eight completed questionnaires were received and the data from each were classified, coded and punched as a computer file. Each return was teated as a RECORD; within each record, each category of answer was defined as a FIELD, each field having one of a number of possible VALUES. It is important to note that the classification used in this exercise did not exactly correspond to the questionnaire structure. RETRIEVALS from the file were made by extracting all or part of a record. Fields within a single record or a number of records were retrieved either in their entirety or for specified values. Records were sorted into order of a selected field or fields (multiple sorts). The fields and values defined for each record are given in Appendix A. Values were coded for computer entry as combinations of one, two or three alpha or alpha-numeric strings. Data were punched onto paper tape in fixed format. Two data management software packages, GRASP and dBASE II were used to make retrievals from the file. A version of GRASP (Appendix B) was available on the ICL System-4 mainframe computer at Rothamsted Experimental Station and accessed from interactive terminals at East Malling. A version of dBASE II (Appendix C) was implemented on a microcomputer, in the Fruit Breeding Department at East Malling, used for the establishment of a fruit genetic resources data base; data were transferred to this machine and retrievals made immediately. Experience has shown that dBASE II has advantages over GRASP in this exercise and gives a dedicated single-user system of great power and flexibility. More modern, reliable and versatile mainframe machines also offer powerful data management systems, if access is readily available. Full technical details of the two management systems and their implementation in this exercise are available from the second author.

3. Results - analysis of models

The classification of the information obtained by questionnaire was, broadly, of administrative, biological, model and managerial detail. Administrative information on the models is summarised in Table 1 and, in each case, relates to the first author cited. There was sometimes ambiguity in the author's affiliation, and this was interpretated according to experience in the United Kingdom. Most models originated in the United Kingdom or in West Germany, predominantly in universities or colleges, and were designed by biologists or agriculturalists rather than by service-based modellers.

Biological information is summarised in Table 2. Most models were concerned with cereal crops, especially wheat, and the splash-dispersed diseases were well represented although the range of pests and pathogens modelled was quite extensive. The aspect modelled showed an even split between the individual events within the disease or pest life cycle, such as infection or dispersal, and the overall progress of disease or pest in time and in space. More specialised aspects, such as the relation between disease progress and yield loss, host resistance and pesticide insensitivity were less common. Models were mostly concerned with two interacting populations (pathogen and host) only; there were few examples at higher (community) or lower (individual plant) levels of integration.

Modelling information is summarised in Table 3. The purpose of the model corresponded to the terminology used by Jeger (this bulletin) and the author's stated intentions were interpreted accordingly. Most models were designed to forecast, and most were linear or multiple regression equations although, often, these involved a considerable amount of careful biological forethought. Quite a number of models purported to explain natural phenomena, although this was taken with some caution due to differences in terminology found in the questionnaire responses. At least one model was claimed by its designer to be both explanatory and descriptive! The modelling approach taken was almost equally holist or reductionist (Jeger, this bulletin). Very few authors were prepared to consider the term

Table 1. Number of models classified according to country, organisation and discipline of first author.

Country		Organisation		Discipline	
United Kingdom	22	University	26	Biology/Agriculture	44
West Germany	17	Research Institute	17	Physics/Climatology	10
France	8	Weather Service	8	Statistics/Economics/ Mathematics	4
The Netherlands	7	Government Advisory	7		
Other	4				

Table 2. Number of models classified according to crop, pathogen or pest, and aspect of reality modelled

Crop		Pathogen/Pest		Aspect of reality	
Wheat	21	*S. nodorum*	7	Components of disease/ pest life cycles	24
Barley	7	*P. herpotrichoides*	6	Epidemic development/ population dynamics	21
Cereal	5	*V. inaequalis*	3	Disease/damage - yield loss relationships	5
Apple/top fruit	9	Powdery mildews	5	Resistance	3
Grapevine/hop	7	Downy mildews	4	Ancillary*	5
Unspecified	9	Leaf rusts	4		
		Other	9		
		Aphids	4		
		Moths	2		
		Other	9		
		Ancillary*			

* Crop model useful for combining with pest or disease model

Table 3. Number of models classified according to the purpose of model, the techniques used in modelling and programming language

Purpose of model	
Forecasting	27
Explanation	15
Exploration	10
Description/ standard of comparison	5
Optimisation	1

Techniques		
Time -dependence	Yes	27
	No	31
Stochastic elements	Yes	7
	No	51
Optimisation procedures	Yes	2
	No	56

Language	
Non-computerised	27
FORTRAN IV	14
FORTRAN (special features)	13
Simulation language	4

'description' as an adequate objective in modelling. Only one model was designed for the purpose of optimisation. Techniques used in modelling were almost equally time-dependent or not; the former usually corresponding to dynamic models based on differential or difference equations, the latter to static models involving regression equations. Almost half of the models required the evaluation of a table, diagram or nomogram rather than access to a computer. Where access to a computer was required, the most popular language by far was FORTRAN IV, although many programs included features that would not necessarily be available at every installation and create problems in portability. The simulation language, with one exception, was CSMP (Brennan & Silverberg, 1968).

The input and output sets used in classifying the models were quite detailed (Appendix A). The frequency distribution of the number of input or output variables for each class of information over all 58 models is given in Table 4; for example, 10 models required three weather variables as part of their input set, 6 models generated three disease or pest variables as part of their output set. The extent to which models required inputs, or generated outputs from more than one class of information is given in Table 5; for example 13 models, required two classes of input information (usually weather and one other), 12 models generated two classes of output information (usually disease/pest and crop). The majority of models were weather-dependent and the range of variables covered corresponded to that proposed by Müller in his report to the working group at Versailles in 1980 (see also Franquin & Rijks, 1983). A few models required multi-location sensing that might present problems for an eight channel automatic weather station. A larger number of models required biological monitoring of pest, pathogen or disease and the crop. Integration of such data with weather data may present considerable problems in data management, thus requiring specialist packages (Eisensmith et al., 1980). Very few model outputs were an unambiguous recommendation or other directive (e.g. spray/don't spray). Most output required further interpretation before a management decision could be made.

Managerial information is summarised in Tables 6 and 7. A large number of models were considered by their author(s) to be validated, or of proven operational value (Jeger, this bulletin) although it was not always clear whether the value was for the model designer, researcher or user. The model designer's statements were taken at face-value here and were not interpreted according to Jeger (this bulletin). Interestingly, many of the models were published before they had developed past the testing stage, i.e. before they were of proven operational value. Models are readily accessible either from publications or directly from the designers. Using the authors' responses to questionnaires, half of the models were designed to be used for management. Of these, most were of a statistical form (Rabbinge & Carter, this bulletin) and for day-to-day tactical decision-

Table 4. Number of models classified according to inputs and outputs, and the number of variables within each class of information

Class of information		Number of variables 0	1	2	3	4	5	> 5
Input set:	weather	16	9	9	10	4	4	6
	soil	53	4	1	-	-	-	-
	husbandry	45	8	3	1	-	-	1
	pathogen/pest	24	12	6	5	2	3	6
	crop	35	16	2	1	2	2	-
Output set:	pathogen/pest	9	29	9	6	1	1	3
	crop	46	6	2	3	1	-	-
	other	48	10	-	-	-	-	-

Table 5. Number of models classified according to the number of classes of information required for input or output

	Classes of information 1	2	3	4	5
Input set	26	13	15	2	2
Output set	46	12	0	-	-

Table 6. Number of models classified according to stage of development, publication and availability of models

Stage of				Availability	
development		publication			
Planning	1	In Press	3	Not available	13
Construction	7	Preliminary report/ abstract	4	Computer listing:-	
Testing	29	Proceedings/book/thesis	11	designer	18
Operational	21	Scientific journal	27	publication	6
		Unpublished	13	Equation etc.:-	
				designer	6
				publication	15

Table 7. Number of models classified according to intended use, limitations on use and actual use of models

Intended use		Limitations on use		Actual use	
Non managerial	29	Not realistic/interpretable or testable	15	Unused	5
Managerial:-		Unavailability of data	12	Designer only	21
tactics	23	Specificity	8	More widely in research	13
strategy	6	Lack of fundamental knowledge	6	Government agencies	16
		Detailed data collection	4	Farmers/growers/co-operatives	3
		Sophisticated apparatus	2		
		No limitations	1		
		None given	10		

making rather than for longer term strategic decisions. There was a wide range of perceived limitations on the use of the models; a large number were considered either not practicable (due to non-availability of data), interpretable or testable, and the objectives or motives of the model designers must be in question here. Surprisingly few authors considered models to be limited through a lack of fundamental knowledge. Very few models had developed to be of practical use in pest or disease management. Most models remained the property of the designer and immediate research associates.

The 'one-way' analysis of models described above was facilitated by data management on a computer, but could have been achieved without. Data management facilities became essential with multiple classification and the preparation of multiway tables. Even with a small number of models the task becomes daunting. For example, 15 fields limited to three values per field gives 105 possible two-way tables with 9 cells per table, and 455 possible three-way tables with 27 cells per table. This section is concluded with some examples of the more complex retrievals (Tables 8, 9, 10).

The retrievals were done within the broad classes of information (Tables 8, 9) or between classes (Table 10). There were proportionately more disease models for the cereal crop than for crops overall, and these were more concerned with the individual events within the disease cycle (Table 8), reflecting the predominance of models concerned with splash-dispersed or wetness-dependent, fungal pathogens. Table 9 suggests several reasons why models do not develop to practical uses. Of the models that were unused, none were originally intended, according to their authors, for management use and that fact alone seems to have determined their fate rather than any particular limitation on their use. Similarly, very few of the models that were in the hands of the designer, or researcher, only were intended for management and these were limited, in particular, by being impracticable, not interpretable or untestable. The models that had found some practical use, either by the advisory services or directly by farmers, were virtually all conceived for use by management and in particular (although not shown separately in Table 9) were limited by the availability of local rather than regional data (Rabbinge, this bulletin). Finally, Table 10 reveals much on the present status of models in crop protection and the attitudes of those involved with modelling. Virtually all models claimed to be explanatory were concerned with overall epidemic development (or with the population dynamics of pests) and were not intended for direct management use. On the other hand, most forecasting models were concerned with individual events within an epidemic and were intended for management. It can be concluded that explanation was not, in general, considered a prerequisite for management, that techniques for forecasting the overall time-course of disease or pest development were poorly

Table 8. Number of models classified according to crop, disease or pest and aspect modelled (omitting the five crop models)

	Cereal (31)		Fruit (13)		Other (9)	
	A	B	A	B	A	B
Component of disease/ pest life cycle (24)	11	2	5	2	3	1
Epidemic progress/ population dynamics (21)	9	4	3	2	2	1
Special topics (8)	4	1	1	-	-	2

A, disease model (38); B, pest model (15).

Table 9. Number of models classified according to intended use, limitations on use and actual use of models

	Unused (5)		Designer/ Research (34)		Government (16)		Farmers (3)	
	A	B	A	B	A	B	A	B
Not practicable/ interpretable/ testable (27)	2	-	10	7	-	7	1	-
Specificity (8)	1	-	3	-	-	3	-	1
Lack of knowledge (6)	1	-	3	1	-	1	-	-
Detailed data collection/ sophisticated apparatus (6)	-	-	3	1	-	1	-	1
No limitations/ none given (11)	1	-	3	3	1	3	-	-

A, non-managerial use (29); B, managerial use (29).

Table 10. Number of models classified according to the aspect modelled, the purpose of the model and the intended use of the model

	Explain		Forecast		Explore		Describe	
	A	B	A	B	A	B	A	B
Component of disease/pest life cycle (24)	2	-	1	16	1	-	4	-
Epidemic progress/ population dynamics (21)	9	1	3	5	2	1	-	-
Special topics (8)	-	-	-	2	3	2	-	1
Crop model (5)	3	-	-	1	1	-	-	-

A, non-managerial use (29); B, managerial use (29).

developed and that management was seen as primarily concerned with day-to-day problems during the season.

4. Conclusions

It seems clear from this analysis that few models are being developed to practical ends in crop protection. Those which have found some use are mainly for forecasting individual events within the epidemic and are based on regression equations, although these can have a good deal of biological sense associated with them. There are few examples in the 'Inventory of Models' of comprehensive explanatory models that are developed, evaluated and subsequently simplified to some more practical form (Rabbinge & Carter, this bulletin; Rabbinge, this bulletin). The most important factors in determining the eventual management uses of a model are the original intentions of the model designer, the contact with empirical evidence at all stages of development, and the consideration given to the local conditions where the model is to be used.

The analysis also demonstrates the potential usefulness of a data management system for models in crop protection. A data base can be established and accessed so that modellers are aware of all activities and developments within a particular area. This argument has been extended by Bloomberg (1980) who calls, not only for information on models and model construction to be more widely available, but also for models to be constructed in a modular fashion so that parts may be exchanged and fitted togerher for the immediate task at hand. There is a certain attraction in this argument, but it does ignore the need to develop models for practical use, and procedures for evaluation in such a context. The question of accessibility of models and free exchange of information does, of course, become important when crop protection services based on models are operational and paid for by customers, but that is not the immediate concern of this bulletin.

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APPENDIX A: Classification scheme for 58 models in 'Inventory of Models'

Name

1.
2.
3.

Country

United Kingdom
West Germany
France
Holland
Other

Organisation

University/College
Research Institute
Weather Service
Government Advisory

Discipline

Biology/Agriculture
Physics/Climatology
Statistics/Economics/Mathematics

Crop

Wheat
Barley
Cereal
Apple
Grape/Hop
General

Pathogen

Leaf rust
Powdery mildew
Downy mildew
S. nodorum
P. herpotrichoides
V. inaequalis
Other fungal
E. amylovora

Pest

Aphid
Mite
Moth
Nematode
Other

What aspect of reality is modelled

Components of disease/pest life cycle
Epidemic development/population dynamics
Initial disease/pest levels
Host resistance
Disease/damage - yield loss
Non-disease/pest aspects

Hierarchical level of problem

Community
Population
Organism
Sub-organism

Purpose of model

To explain
forecast
optimise
generate hypotheses
provide standards of comparison
explore (= "investigating")
describe

Is the modelling approach

Reductionist
Holistic
In between

How is the problem modelled

With time-dependence	Yes/No
With stochastic elements	Yes/No
By optimisation procedures	Yes/No

How is the solution to be used

Non-managerial
Managerial - tactics
strategy

What are the perceived limitations on usage

Data unavailable
Detailed data collection
Sophisticated apparatus
Lack of fundamental knowledge
Not realistic, interpretable or testable
No limitation
Specificity

Stage of model development

Planning
Construction
Testing
Operational
Automated

Model availability

Not available
Equation, table, graph
  designer
  publication
Computer listing/tape/cards
  designer
  publication
Hardware specification
  designer
  publication

Model language

Non-computerised
FORTRAN
FORTRAN with special features
Simulation language

Stage of publication

Unpublished
In press
Preliminary report
Scientific journal
Proceedings/book/thesis

Actual usage

Unused
Designer only
More widely used in research
Government agencies
Farmers

Weather inputs

temperature
relative humidity
leaf wetness
dew
rainfall
sunshine
wind

Soil inputs

type
condition

Husbandry inputs

- sowing date
- fertiliser
- fungicide
- plant spacing
- field size
- other

Pathogen/disease inputs

- initial inoculum
- spore release/dispersal disposition
- virulence
- disease assessment
- components of partial resistance

Pest/damage inputs

- initial population
- population counts
- multiplication rates
- developmental rates
- asymptotes
- competition/predation/parasitism

Crop inputs

- development/growth stage
- plant part
- physical characteristics
- physiological parameters
- potential yield
- susceptibility
- uniformity

Pathogen/disease outputs

- component of epidemic
- disease development
- final disease level
- other

Pest/damage outputs

- population density
- final density
- other

Crop outputs

- growth/development
- crop quality/yield
- crop damage
- physiological response

Other outputs

- control recommendation
- economic threshold

APPENDIX B: GRASP

GRASP is an acronym for Geological Retrieval And Synopsis Program. It was designed to provide interactive access to earth-science data bases (mostly oil and gas data). It is written in FORTRAN and was designed to be machine independent and has been implemented on IBM, CDC, DEC, Hewlett-Packard and Honeywell Multics computers at over 25 installations in 14 countries.

APPENDIX C: dBASE II

dBASE II is an interactive, relational type data management system for micro-computers and is available from most suppliers of micro-computer software. Two versions of the software are available; the full version, and a version which allows the user to try out the product on a small data base (up to 15 records) for trial purposes on a sale or return basis. At East Malling it makes use of the following hardware and software:-

- Z.80 based microprocessor system
- 64K bytes of memory
- CP/M 2.2 operating system
- Dual 8" floppy discs (approx. 1 Mb/disc)
- Cursor addressable CRT
- Printer
- 10 Mb Winchester disc (so far not used)

dBASE II main specifications:-

Records per data base field	(maximum)	65535
Characters per record	"	1000
Field per record	"	32
Character string length	"	254 chars.
Command line length	"	254 chars.

CONCLUSIONS AND RECOMMENDATIONS

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We have identified three main areas in which conclusions have been reached and we wish to make specific recommendations with regard to 'the development of models for practical use in crop protection'. These areas are the need for interdisciplinary approaches and problem identification, the sequence of model development, and the evaluation of models in a practical context.

When a farmer considers changing any agricultural practice, including disease or pest control, he does so in the context of his overall farming system, available labour and machinery, and in the case of crop protection, the relationship of the change with other disease or pest practices. However, it has often been the case that scientists investigating the biology and control of diseases and pests have become increasingly specialised in their approach. To some extent, this increased specialisation has become a constraint to the development of flexible and acceptable methods of control. In this context, systems analysis and other modelling techniques have an important role to play in promoting greater interdisciplinary work. There is a danger, however, that the modelling language and approach, while bringing different disciplines together, may then lead to greater, in this case modelling specialisation. Consequently, an equally important feature of modelling should be to correctly identify and define the practical problem of concern. Used in this way, modelling may be used to help direct research to tackling the key biological, technical and management questions that are crucial for practical improvements in crop protection.

This IOBC working group reflects the interdisciplinary nature of modelling. There is both mutual interest and a co-operative atmosphere, since participants are aware that models of different kinds, at varying levels of detail and based on different philosophies and techniques, serve a wide range of objectives. Nevertheless, it seems desirable to establish criteria which may help in deciding which modelling approaches are of most value, once the problem of concern is identified and the objectives adequately stated. Many simple models are of most value in providing insight, directing research and identifying key factors as part of the applied research process. However, where the mode of operation of a pathosystem is studied, comprehensive models are of most value in bridging the gap between detailed biological studies in the laboratory, or controlled environment chamber, and crops in the field. These models may then lead to summary models, or decision rules, for use in practical disease or pest management, and be compared with more direct forecasting techniques. The precise sequence of model development will, or course, vary depending upon the problem identified and involve different qualitative and quantitative phases and degrees of simplification, but the evaluative phase must operate at several points in the sequence.

The evaluation of models, at all stages of development from conception to implementation, is the most problematic of the three areas. It is unlikely that any universal algorithm can be developed and one is certainly not proposed here. However, the evaluation of a model's utility in a practical context remains the least developed process; perhaps unavoidably, due to the few examples of disease or pest models being used in practical management. The activities of this working group should advance the practical implementation of models; it is now important that the group actively pursues the financial and logistical means to provide the necessary evaluations where appropriate, and to do so in a climate of rapidly changing farm management practices.