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DECISION SUPPORT SYSTEMS FOR INTEGRATED CROP PROTECTION

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ABSTRACT

The use of decision support systems in integrated crop protection systems is discussed. Present and future trends in the development of decision support systems in this area are addressed with appropriate examples where available. The possible reasons for the relatively limited number of such applications are presented in terms of the problems that face the development of these system. An attempt is made to estimate the benefits that such systems can make toward improving crop protection in terms of financial return and reduced environmental impact.

INTRODUCTION

Decision support systems have been developed for and used in agriculture over the past 12 years or so in an attempt to improve all aspects of decision making and therefore management. At the same time continuing research into integrated crop protection has resulted in extremely large amounts of information being produced. This information, or knowledge, may take many different forms, for example, raw data contained within databases, qualitative experience of experts, simulation models of crops and pests and research reports. By definition, an integrated approach requires that all different methods of pest control should be considered when making a management decision. Whilst it is possible to make decisions, albeit poor ones, in the absence of information, in order to make the best possible decision it is necessary to be able to both understand and have access to all relevant information. The transfer of the wealth of information from researchers to practitioners is often a weak point in the process of improving integrated pest management, but it is an area where decision support systems can work particularly well.

Decision support systems can be made up of either a single component such as a database, geographic information system, expert system or simulation model or a combination of these (Knight & Mumford, 1994). They are able to aid decision makers by providing management options for a given set of conditions, clarifying the problem by predicting the likely future development of it or by explaining it in terms of past events. Decision support systems can also allow users to examine the consequences of making different decisions and therefore allow a variety of options to be examined. The idea of combining information from databases with simulation models and expert systems is not new, but the ability to do this quickly and easily has only really come about in the past few years with the widespread availability of cheap and powerful computers and software. Decision support systems are reliant upon the development of their component parts i.e. databases, models and expert systems. The development of these components should only be undertaken when it is appropriate to the problem. It is important that before any decision support system is developed that the problem has been rigorously defined and the requirements of the decision maker are fully understood.

A number of reviews of the use of expert and knowledge-based systems in agriculture and resource management have been carried out (Edwards-Jones, 1992; 1993; Warwick *et al.*, 1993) which highlight the subject areas that the systems cover and the number and type that have been described in the literature over the last 10-15 years. There has been a gradual move away from expert systems in the true sense toward knowledge-based systems and now decision support systems. The objective of the systems have remained the same, making better crop protection decisions, but the method of achieving this has shifted from the computer providing the definitive answer to the computer providing the user with all relevant information and some interpretation of that information to aid in the decision making process.

PRESENT AND FUTURE TRENDS

Decision support systems are used in many areas of crop protection including diagnosis or identification, prescriptive control and strategic control. The use of decision support systems for pest identification has led to a simplification of the identification process. Instead of traditional paper keys that are linear and require the user to work through the entire key in a systematic fashion, the computerised keys allow the user to choose a question about a particular character. The answer is used by the computer to eliminate all non-matching taxa. The user then chooses the next character and so on until an identification can be provided. These programs also have the ability to cope with the possibility of variability within the data set by using error allowance levels. An example of this type of key is DELTA (DEscription Language for Taxonomy (Dallwitz & Paine, 1986)) which is used in a program called INTKEY for the identification of beetle larvae and also grass genera. The advantage of this approach is that should a feature be damaged or missing the user can elect to not to answer questions about it. In a traditional dichotomous key it would be much more difficult to complete an identification under these circumstances. Another approach to this problem is CABIKEY (Computer Aided Biological Identification KEY(White & Scott, 1994)),which has the added sophistication of allowing users to have characters presented as pictures rather than pictures being purely in addition to text.

A common use of decision support systems is to provide an estimate of the probable damage that will occur to a crop with a given level of pests. In this case users are prompted by the computer to enter information that is necessary to run a model of the insect population development. The model can be of any type but is most commonly a simulation or a regression model. Once the data is entered into the system the model is run and a projection of the future population and consequent damage is made. The output from the model can be used along with information about the economic injury level to make an appropriate decision on control. There are many examples of this type of approach, for example, Berry *et al* , (1991); Knight & Cammell (1994); Perry *et al*, (1990);Stone & Schaub (1990); Wilkin & Mumford (1994). This strategic use of decision support systems is particularly useful since to use a model of pest populations without some guidance would be confusing for many users, by embedding the model in a user friendly interface and leading the operator through the process of specifying the values to enter into the model this particular problem is overcome. However, by hiding the model behind such an interface the user is less well able to understand how the system works and it becomes a bit of a black box. Therefore, a compromise between ease of use and transparency needs to be made.

The use of models in decision support systems allows users to experiment with different control strategies to see which achieves their objectives within a specific budget. For example, Grain Pest Adviser is being developed (Wilkin & Mumford, 1994) to contain models of mites and insects that infest grain, cooling and insecticide degradation. The system displays a graphic representation of the pest populations both with and without the use of control options so the user can judge which method provides the level of protection that the user requires. The inclusion of information about the costs of carrying out any of these operations, for example, the price of grain, cost of insecticide and the cost of electricity to cool the grain, allows the user to get an economic analysis of that strategy so they can make a decision based on both the success and cost of the control method. Since there is a level of uncertainty associated with any of these decisions because of changes in grain prices in the future the user is able to change the price of grain to see what effect it has on the chosen option. The 'best' option under one set of conditions may be very sensitive to changes in grain prices and therefore an apparently less good, but more robust, solution may be chosen because it is less susceptible to changes in price.

In order to implement increasingly complex integrated pest management programmes decision support systems are becoming ever more sophisticated and often comprise a knowledge base, a database and a model of some description, however, they can still be useful if they only contain one of these components and complexity for complexities sake is not a good thing.

ADOPTION OF DECISION SUPPORT SYSTEMS

It is perhaps surprising that the uptake of these systems has not become more widespread as pest management becomes more complex and decision support systems can provide a means of handling this increased complexity easily and at reasonable cost. There are a number of possible reasons for this.

The first point to note is that many of the early systems were produced to explore the potential of using this approach for the solution of pest management problems so were never designed to be widely used in the field. They were simply intended to show that it was possible to extract information from experts and the literature and create a decision support system suitable for use in pest management. The result was that decision support systems were found to be suitable for handling the type of problems that occur in pest management. The next phase was the development of systems intended for application in the field by farmers and/or advisers. Whilst some systems were widely adopted, for example, EPIPRE in the Netherlands (Zadoks, 1981), a system that provided information and advice on the timing of pest control in cereal crops, other systems do not appear to have been adopted on a large scale. The reasons for this low level of uptake by the farmers is not very clear but is probably due to a combination of factors. Firstly, farmers tend, by nature, to be risk averse and therefore behave conservatively. They are therefore not likely to adopt new technology until they are sure that it will provide a benefit to them over their present system. Decision support systems were not only new in that they provided advice and information in a new way, but also relied on the farmer being able to use, and probably own, a computer. This was undoubtedly a major hurdle to be overcome in the 1980's. Today, however, most farms have a computer for record keeping and farmers obviously have the ability to use them. The problem of fear of the unknown should no longer be an obstacle to the adoption of this technology. The way in which the information is presented to the farmer is probably still very important. The majority of advice comes from trusted advisers with which the farmers have developed a working relationship. The concept of using advice from a computer is quite a significant step and one which many other people may also be hesitant in taking. One way around this problem is to provide decision support to the adviser, who may otherwise be unable to advise on a particular problem, by tailoring the decision support system for his use. The farmer receives his advice from the adviser who can act as a bridge between the new technology and the farmer. In time the farmer may feel that he is happy to trust the computer output and use it himself.

Other possible reasons for the low level of adoption are that the programs have been developed in isolation from the farmers and they do not address the problems that the farmers or advisers feel are the most important. The decision support systems have grown out of an existing research project and are not always relevant. This particular problem can be prevented by getting farmer or adviser input at an early stage to identify and define the most difficult management problems. If the problem is suitable for solution by a decision support system then one can be built using input from the farmer and adviser. In this way the farmers feel they have some ownership of the system and are more likely to use it since they will have greater understanding of what the system contains and how it works.

Some of the reasons for the low adoption of the systems could be due to the poor marketing of the systems many of which have been developed within the academic community where there is little or no experience of marketing. This could lead to products being incorrectly priced, for instance, if the product is given away free the user may perceive the product to be of no value and not worth using. Conversely, if the product is priced too highly then the farmer will be unwilling to pay for the system when it may be cheaper to get advice from an adviser without any capital investment. This situation is also changing as free advice is becoming harder to get and the number of government advisers is being reduced making it more difficult to get advice at the time that it is required.

In order to improve the adoption of decision support systems the following points should be addressed; greater effort should be made to make them relevant to the farmers needs, care should be taken that the target market has the ability, willingness and hardware to use the proposed system and the benefits of the system should be clearly demonstrated to the user.

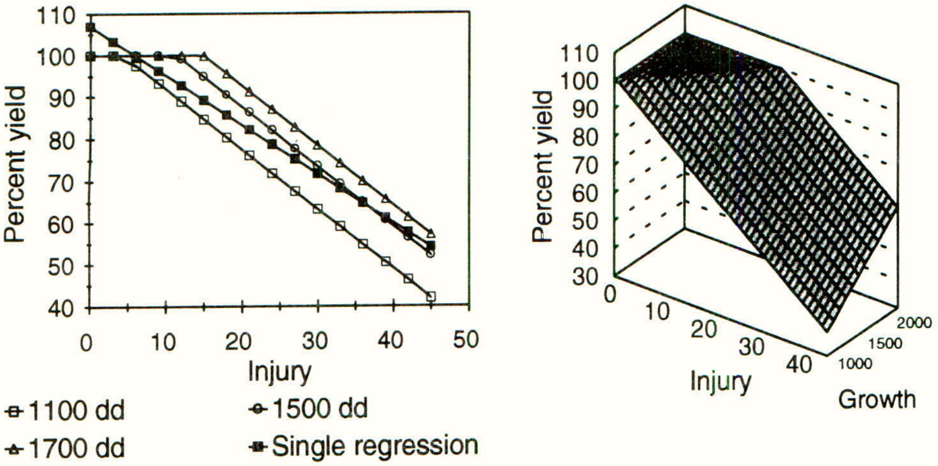
POTENTIAL BENEFITS OF USING DECISION SUPPORT SYSTEMS.

One of the main advantages of the decision support system is its ability to handle complex situations much more easily and efficiently than humans can. To demonstrate the potential advantage of using a decision support system over manual decision making a hypothetical example will be used.

The basis of most crop protection decision making is founded on the concept of the economic injury level as defined by Stern *et al* (1959). The objective of pest management is to reduce or maintain pest levels below the economic threshold and the concept is therefore valid for both preventative tactics and curative ones. The cornerstone of the economic injury level is knowing the damage function for the pest and crop in question and using this to calculate the economic injury level using the value of the crop and the cost of any control measures that may be used. If damage only occurs at a specific point in the crop life cycle then a damage function can easily be determined by a few relatively simple experiments. However, if the pest can attack the crop during many different developmental stages it is possible that the plant will be able to sustain more or less damage depending on when it is attacked. An example of this is the response of cotton (*Gossypium hirsutum*) to attack by the bollworm (*Helicoverpa zea*). During the early stages of development yields of cotton can actually be higher when the plant is attacked by bollworm than when it is not attacked because the plant over-compensates for the loss of any reproductive organs. At later stages of plant development the same level of injury will result in a much reduced yield since the plant will be unable to compensate for any losses. This particular problem means that for the economic injury level to be estimated with any degree of accuracy different damage functions should be used at different stages of development. The idea of using a different regression function for each growth stage of the cotton plant has been recommended by Stone & Pedigo (1972), with the assumption that the effect of insect injury on plant yield does not vary within the growth stage which is probably not true since the response will change gradually rather than at one specific point in time A refinement of this approach has been explored by Ring *et al.* (1993) by using a response surface for the damage function which illustrates that the economic injury level is not a static thing but is dynamic even when the value of the crop and control is constant. If the variability in crop price and the cost of control is added in, the variability in the economic injury level is even greater. It therefore becomes difficult to calculate the economic injury level manually and some sort of decision support system can be of great use.

Once the damage threshold has been determined in order to calculate the economic injury level the farmer has to know the cost of the control method. In the simplest terms the choice will be made by considering the efficacy of a particular treatment and the cost. The economic injury level can then be assessed and any action taken. Where there is a large range of control products the economic injury level may vary quite largely depending on the price of the particular control. The problem of which control method to choose and the consequent calculation of the economic injury level becomes even more complex if the environmental costs of the control is added into the equation. Attempts have recently been made to estimate the environmental costs associated with using a range of insecticides (Higley & Wintersteen, 1992) with a view to incorporating these into the calculation of the economic injury level.

In this example the crop is assumed to be worth $500/ha and the cost of control is $20/ha. Three scenarios are examined; firstly, using just one regression equation, secondly, using three regression equations for different growth stages (1100, 1500 and 1700 dd), and thirdly, using a response surface. The damage relationships are not real but could be representative of the sort of responses that can occur. The relationships are shown in Figure 1.



(a)

(b)

Figure 1. Damage relationships for a hypothetical crop: (a) a single estimate for all growth stages; separate estimates for 1100, 1500 and 1700 day degrees and (b) a response surface for all combinations of plant age and injury level.

It is assumed that the farmer checks his fields on three occasions (growth stages 1200, 1600 and 1800 day degrees) and finds injury levels of 7%, 15%, and 8% respectively. The farmer then has to make a decision to spray or not. The recommendations on whether to spray and the financial consequences of the actions are shown in Table 1.

It can be seen from the results that the use of the different methods can result in large differences in the financial returns to the farmer. The less sophisticated systems costing the grower more money. When the farmer also has to make a decision on which pesticide to use the economic threshold could change yet again depending on the cost of the method. The inclusion of the environmental costs into the calculation of the economic injury level increases the complexity of the decision still further. The above example is relatively simple but serves to demonstrate the point. Crops with variation in their responses to pest attack at different growth stages would be well suited to this approach.

Table 1. Comparisons of the economic injury levels and consequences of using them for a single regression estimate, three separate regressions and a response surface.

Method of calculating Economic Injury Level		Economic Injury level	Cost or benefit of method over response surface
Single regression	1200 DD	9.3	0.0
	1600 DD	9.3	33.5
	1800 DD	9.3	48.5
Three regressions	1200 DD	7.0	9.5
	1600 DD	14.2	9.0
	1800 DD	17.7	0.0
Response surface	1200 DD	8.9	-
	1600 DD	16.0	-
	1800 DD	19.5	-

CONCLUSIONS

Decision support systems are extremely useful and deserve to be used more widely than at present. For models requiring input, decision support systems can assist the user by reducing the need to have an extensive knowledge of the required values and the inner workings of the model. Similarly, the system can aid the user in interpreting results and suggesting decision options according to a wide range of scenarios. Decision support systems that include expert systems, geographic information systems simulation models and databases allow greater flexibility as they can be modified to take account of geographically specific parameters, assuming the required data is available. The process of specifying a system often helps to clarify a decision problem to both experts and farmers who are consulted during the procedure.

The increasing numbers of farm computers, the decline in traditional advisory services and improved user interfaces should help to improve the uptake of any new systems. It is interesting to note that systems for improving pest forecasting have been successfully deployed in Africa when it might be imagined that it would be more difficult than in developed countries. It is possible that the recipients in these countries have fewer preconceived ideas about what computers can and cannot do for them.

The ability of decision support systems to provide and interpret information for users is going to be of increasing importance as pest control becomes more and more complex with the balancing of a variety of control methods rather than just the traditional chemical approach. In addition, changes in crop protection legislation such as the potential need to include the environmental impact of any control decisions in the costs of control will also make the farmers task ever more complex and difficult.

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THE USE OF MODELS IN INTEGRATED CROP PROTECTION

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ABSTRACT

An examination is made of the role that mathematical modelling can have in developing integrated strategies, involving reduced dependence on chemicals, for controlling weeds, pests and diseases in crops. From a detailed survey of the application of models to weed control, it is concluded that modelling has fundamentally been concerned with answering issues that contribute comparatively little to our understanding of 'sustainable' systems of crop protection. There has been a strong concentration of effort on simulating the impacts of herbicides and on identifying 'threshold' levels for spraying. Issues such as herbicide resistance, weed-crop interference and integrated weed management systems have received scant attention. Nonetheless, given the complexity of the management systems involved in Integrated Crop Protection, mathematical modelling would seem to be a potentially valuable tool. In the case of some forms of control, such as biological and genetic, it is also arguable that modelling the consequences is imperative, given the potential risks involved.

INTRODUCTION

'Integrated Crop Protection' is not a new idea and, since the term was first coined, it has come to mean a variety of things. In its simplest form it is used to describe a pest, disease or weed control strategy in which a variety of biological, chemical and physical control measures are combined to give stable long-term protection to the crop. More recently, the term has been used to describe more biologically-oriented control strategies that have arisen following problems with solely using chemicals (Lockhart *et al.*, 1990; Swanton & Weise, 1991; Zimdahl, 1993). Equally, its underlying aims have been open to a variety of interpretations. Thus, when considered in the context of monitoring and forecasting pest, disease and weed infestations, the objective has often been seen to be pure profit maximisation (Cammell & Way, 1987). However, elsewhere Integrated Crop Protection has been seen as being concerned with the reduction of all inputs, as a means to safeguarding natural resources and minimising the impacts on the environment (Burn, 1987).

Nevertheless, if Integrated Crop Protection is to be seen as playing a pivotal role in the evolution towards 'sustainable' farming systems, then it seems more appropriate to accept the narrower definition of Burn *et al.* (1987), namely that it is the planned integration of a range of techniques to minimise the use of pesticides, herbicides and fungicides on the environment. As such, its aims are twofold:

i) to steer the use of chemicals away from from prophylactic towards selective use, while still achieving an economically justifiable outcome; and

ii) to minimise the use of chemical inputs and maximise the use of physical and biological controls for weeds, diseases and pests, so as to reduce environmental damage.

Thus, fundamental to devising an Integrated Crop Protection strategy is a sound biological understanding of the pest, disease or weed problem and the efficacy of different methods of control. On this depends the choice of the subsequent control strategy. Equally important is an understanding of the benefits and risks involved for the grower, as well as for the rest of society. On the surface, it should be possible to gain useful insights into these issues using mathematical models, where a 'mathematical model' is defined as either an equation or a set of equations that represents the behaviour of a system (France & Thornley, 1984). Thus, models of weed infestation, population growth and control have served as a framework for organising biological information on weeds and for developing weed control strategies (Mortimer *et al.*, 1980; Doyle, 1991). In particular, they have helped to identify information gaps, set research priorities and suggest control strategies (Maxwell *et al.*, 1988). Furthermore, their value has arguably extended beyond being simply useful research tools. Thus, several key questions in weed control cannot be answered using conventional field trials, because of the constraints of cost, time or complexity (Doyle, 1989). As such, models have come to serve as experimental 'test-beds'.

However, a review of mathematical modelling work in weed control (Doyle, 1991) suggests that it is concerned with addressing a range of questions, which are tangential to the main thrust of Integrated Crop Protection. Thus, there has been a very marked concentration on studying the mechanisms for *controlling* rather than *preventing* weed infestation and within the range of control mechanisms to focus on chemical control. Virtually, without exception, all the published models concerned with the population biology of weeds have confined themselves to projecting what happens, given an initial level of weed infestation. In contrast, the mechanisms by which weeds are spread and dispersed, an understanding of which is central to preventing infestation and certainly to biological and genetic control, has been seriously neglected by mathematical modellers. Equally, in response to the rising on-farm expenditure on chemical control, modelling efforts have concentrated on evaluating the critical weed infestation levels above which chemical control is justified.

At the risk of some simplification, it would appear that mathematical models of weed, pest and disease control have largely directed their attention to the scientific question 'what' rather than the practical question 'how'. Thus, weed management models have primarily addressed three questions (Mortimer, 1987; Doyle, 1991):

i) *what* is the relationship between the level of weed infestation and the crop losses;

ii) *what* is the level of any control measure required to contain the infestation or totally eradicate the weed; and

iii) *what* is the level of weed or pest infestation above which control measures are justified.

However, in respect of Integrated Crop Protection, these questions are subordinate to the more central issues of:

i) *how* is it possible to promote the more selective use of herbicides, while ensuring economically acceptable levels of weed control;

ii) *how* is it possible to minimise the environmental impacts of herbicides through the use of biological and physical control techniques; and

iii) *how* are the economic risks to growers of switching to non-chemical controls to be minimised.

As shown by Tait (1987), this 'mis-match' between the aspirations of Integrated Crop Protection programmes and the main areas of enquiry conducted using mathematical models is not unique to weed control, but is evident in respect of pest control.

A ROLE FOR MATHEMATICAL MODELS ?

This apparent inapplicability of much past modelling work to the study of Integrated Crop Protection has led to widespread disillusion with so-called 'hard' quantitative models (Tait, 1987). This has been compounded by the fact that many crop disease, weed and pest problems are developing very rapidly and, by the time that models have been developed and potential solutions generated, the solutions have often ceased to be relevant. For mathematical modelling to make a contribution to sustainable systems of crop management, there is a need:

i). to re-focus the areas of enquiry, so as to address more directly the issues raised by Integrated Crop Protection; and

ii) to move away from modelling specific applied pest or weed problems to studying more strategic issues in relation to chemical resistance and the mechanism of biological controls.

To illustrate the type of scientific issues that need to be addressed and to assess the contribution that mathematical modelling can make to these, the case of Integrated Weed Management is considered.

In terms of future research on Integrated Weed Management systems, it is generally agreed (Swanton & Weise, 1991; Gressel, 1992; Wyse, 1994) that the key objectives are to identify:

i) how to lower dependence on herbicides;

ii) how to prevent or delay the development of herbicide-resistant strains of weeds;

iii) how to use crop-weed interference techniques; and

iv) how to integrate several weed control techniques, including selective herbicides.

Lowering chemical dependence

One of the primary aims of sustainable farming systems is to lower the use of chemical inputs. For a considerable period now, mathematical models have been used to examine ways of reducing the frequency and application rates of herbicides (Doyle, 1989; 1991). In these models, attention has mainly focused on modelling low weed infestation densities with the aim of identifying the minimum or 'threshold' density that justifies expenditure on weed control Specifically, the threshold density occurs where the cost of chemical control is equal to the net benefit in terms of enhanced crop yields. In estimating, the threshold levels for weed species, several existing models have taken account of the benefits in subsequent years (Doyle *et al.*, 1986; Mortimer, 1987; Doyle, 1989). This is important because chemical applications may affect not only the present weed population, but also indirectly future populations by preventing a build-up of seed in the soil. Clearly, this is directly relevant to a study of *sustainable* cropping systems.

Nevertheless, the primary motive behind these models has been to improve the *cost-effectiveness* of using herbicides, rather than reducing adverse 'environmental' impacts (Doyle, 1991). Nonetheless, they provide an existing body of knowledge, which can be applied to studying the opportunities for reducing the level of herbicide usage. Nor is it difficult conceptually to see how environmental impacts could be incorporated into such models by treating losses of biodiversity or water pollution as 'costs' associated with herbicide use. The inclusion of such environmental costs would then merely modify the threshold density at which herbicide use would be justified.

However, 'threshold' models have come under attack in recent years on four counts. First, they are dependent on experimental evidence regarding weed-crop competition. In many instances, the experiments are conducted at weed densities that are of limited relevance to the determination of economic thresholds (Dent *et al.*, 1989). Second, virtually all the threshold models developed have assumed that the weeds are uniformly distributed across the field. However, many weed species exhibit a marked tendency to cluster, leaving large areas of a field relatively free of infestation. Compared with a field in which the weeds are uniformly distributed, the crop yield loss will be less (Dent *et al.*, 1989; Brain & Cousens, 1990) and the consequent threshold density will tend to be higher.

The third criticism of threshold models is linked to the existence of uncertainty (Auld & Tisdell, 1987). In weed control, there are three principal sources that may modify the perceived optimal threshold density for spraying: i) the potential weed density; ii) the form of the crop loss function; and iii) the form of the herbicide dose-response function. A major factor in decision-making about whether to use a herbicide is the size of the weed population. Where a pre-emergence herbicide is to be used, then there must be some uncertainty about this. In the second place, although the general form of the crop loss function may be known, its precise shape varies with location and agronomic factors (Reader, 1985; Cousens *et al.*, 1988). Thus, the economic threshold for spraying will vary accordingly. Finally, the efficacy of a given herbicide in controlling weed infestation is sensitive to site and management practices (Zimdahl, 1993). Not only do these factors mean that the economic threshold density for a weed is subject to uncertainties, but the very existence of uncertainty is known to modify grower behaviour (Auld & Tisdell, 1987; Doyle, 1987; Pannell, 1990). If farmers are risk averse, then they are more likely to use herbicides in a prophylactic way and to apply them annually as a security against weed invasion The consequence of all this is that specific weed threshold densities become less relevant.

The other major conceptual problem with threshold models is that, in practice, treating the damaging external environmental effects of herbicides as a cost is not really workable. Apart from the problem of whether environmental damage, such as loss of plant and species diversity can be measured in 'economic' terms, the resultant threshold densities may be unacceptable. Basically, the effect of increasing the overall costs of applying chemical control is to increase the threshold weed density at which spraying is justified. It is conceivable that the inclusion of environmental costs raises the threshold to a level at which significant crop losses occur and which the grower would not be prepared to tolerate. Thus, in the absence of alternative means of controlling the weeds, the credibility of the predicted thresholds is subject to attack.

Accordingly, even to be useful research tools, threshold models will need to be adapted to take account of the four problems identified. This will require more information on: i) crop yield responses to low levels of weed infestation, ii) the patchiness of weed distributions; iii) the apparent variability of yield and dose responses between sites; and iv) the effect of uncertainty on the behaviour of growers themselves. In addition, if they are to be used to explore 'sustainable' weed control strategies, they will need to extended to include consideration of non-chemical means of control.

Managing herbicide resistance

However, the search to lower dependence on chemicals should not be allowed to mask the underlying problems. First, as Gressel (1992) and Wyse (1994) have observed, if crop producers had not had a fixation with weed-free fields and weed science had not concentrated so single-mindedly on chemical control, then the development of weed species with herbicide resistance would not now exist and the constant search for new and more powerful herbicides would not be necessary. For a long time it was assumed that, because weeds have relatively long life cycles and the same chemical is not used repetitively on the same land, weeds would not develop resistance to herbicides in the same way as insects have to insecticides. However, over 100 cases of herbicide resistance have now been reported in one or more of 15 herbicide chemical families (Zimdahl, 1993). As a result, understanding the evolution and dynamics of herbicide resistance in weed populations has now become a major issue in weed science. Arguably the complexity of the the biological processes which influence herbicide resistance dictates a research approach that focuses on the interactions between life history processes and population genetics. Mathematical models can serve such a function and can provide a tool for evaluating management tactics.

However, the vast majority of mathematical models developed to study weed control strategies are fundamentally empirical. That is to say they can describe the response of the weed population to a given herbicide dose, but they cannot explain the mechanism by which reduction in weed numbers occurs. To do this, it is necessary to develop *eco-physiological* models of weed growth and development which simulate key physiological processes, such as photosynthesis and partition of photosynthate. Only in the last two or three years have such models begun to emerge for a limited range of weed species (Kropff & Spitters, 1992; Cousens *et al.*, 1992; Weaver *et al.*, 1993). The primary constraint has been, and continues to be, shortage of detailed experimental data on weed physiology.

Therefore, studying herbicide resistance by means of mathematical models has remained more an aspiration than a practical reality. Nonetheless, Maxwell *et al.* (1990) did make a serious attempt to address the issue using a simulation model, based on gene flows. Basically, the flow of genes is seen as directly altering the proportion of herbicide-resistant and non-resistant alleles in the weed population. Herbicide-resistant genes are introduced into the population both by immigration of pollen and seed and by genetic drift within the existing population. Attempts to manage herbicide resistance then involves two distinct strategies, namely i) the use of alternative herbicides to remove 'resistant' plants and ii) the manipulation of the non-resistant type gene to increase its incidence in the population. The authors conclude from the modelling exercise that the latter strategy may be more cost effective.

Modelling crop-weed interference

However, a reduction in herbicide requirements is only the first step towards 'sustainable' systems of crop protection. The need is to develop non-chemical methods, which may be used in conjunction with low levels of herbicides to control weeds. Crop interference with weeds is one of the primary non-chemical methods of weed control (Wyse, 1994). Most of the cultural practices adopted by growers, as part of their production systems, are designed to create an environment that allows the crop to interfere with weeds to the greatest extent possible. However, the complexities of crop-weed interference mean that mechanistic models, such as the so-called *eco-physiological* models referred to previously, are required. The reason for this is that it is through the mechanisms of competition for water, nutrients and light that the crop interferes with weed development. Most of the weed control models surveyed in Doyle (1991) purely rely on empirical relationships based on plant densities to determine competitive effects between the weed and crop. Typical of such models is the one by Firbank & Watkinson (1985) in which the density of both weeds and crop plants (D), together with the corresponding yields per individual plant (Y), are presumed to be subject to density-dependent mortality, which can be represented by a non-linear reciprocal model of the type:

$$\begin{aligned} D_1 &= D_0[1+\alpha_0(D_1+\alpha_1 D_2)]^{-1} \\ Y_1 &= Y_0[1+\alpha_2(D_1+\alpha_3 D_2)]^{-1} \end{aligned} \qquad (1)$$

where α_0 to α_3 are constants and D_0 and Y_0 denote the initial plant densities and the mean yield of isolated plants respectively. This model depicts the density (D_1) and yield (Y_1) of the crop as a function of the densities of both the weed and crop species. If the weed density is very low, then the crop yield is projected to be a linear function of the crop density. However, at higher densities, the total crop yield becomes constant, that is to say independent of the density of the crop. The argument for this is that, as weed competition becomes more severe, the combined biomass yield of weeds and the crop becomes restricted by the total availability of resources in the given habitat. While this model 'describes' biological reality, it is clearly not capable of explaining the mechanism by which the weed interferes with the crop, through competition for light, water and nutrients.

At the same time, it is rare for a crop to be invaded by a single weed species. As such it is better to envisage a weed population as comprising a multi-species assemblage (van Groenendael, 1988). Although this concept has little place in the modelling of weed-crop competition, it is central to neighbourhood models used for studying ecological competition among plants (Pacala & Silander, 1985; 1987). The basic idea is that the performance of an individual plant can be determined from the number, distance and type of neighbours. For each individual plant, it is possible to identify a neighbourhood area within which there is interference from neighbours and outside which such effects are negligible. However, from a practical standpoint, the use of neighbour models in weed management for situations involving more than a few species is likely to prove computationally expensive (Doyle, 1991). Although Swinton & King (1994) have tried to overcome this, it is arguable that they have achieved it only at the expense of losing all the 'mechanistic' properties of the model.

Modelling Integrated Weed Management

While the search for more sustainable farming systems focusses attention on alternatives to chemical control, Integrated Weed Management is fundamentally concerned with studying how a variety of control methods, including herbicides, may be combined to produce acceptable levels of weed control (Swanton & Weise, 1991). Defined as such, Integrated Weed Management has been studied only to a limited extent using mathematical models, despite the obvious potential (Pandey & Hardaker, 1995). Some early attempts, including studies by Cousens *et al.* (1986) and Doyle *et al.* (1986), did investigate the implications of cultivation techniques and straw-burning on economic thresholds for herbicide spraying for winter wheat. However, they were not primarily concerned with evaluating the possibilities for integrating different control techniques. Only in the last few years have models of weed systems, which explore combined control techniques, been developed. In many cases, the impetus has come from an interest in assessing the economic risks and benefits associated with biological and genetic control methods (Pandey & Medd, 1990; Volker & Boyle, 1994). However, there have been one or two attempts to use models to explore the interactions between cultivation practices and herbicide usage as a way or reducing dependence on chemical controls in arable systems (Frank *et al.*, 1992; Rasmussen, 1992).

What is strikingly absent is any attempt to use mathematical models to explore the social, physical and economic risks of non-chemical weed control techniques. As Pannell (1990) demonstrated using a model, risk considerations may lead to on-farm practices deviating from weed management recommendations. Thus, models can help to reveal inconsistences between recommended practices and the needs and circumstances of growers. This is especially the case, where integrated control methods are being proposed, often involving complex management decisions in the field. For biological and genetic control techniques, there are additional ecological and environmental risks and Gibson (1994) has shown how useful models may be in assessing these, before the technique is introduced into practice. However, in terms of Integrated Weed Management, these are all uncharted areas as far as modelling is concerned.

CONCLUSIONS

Thus, from a general survey of modelling work centred on weed control, it is evident that, although there is a general acceptance of the potential for using models to assist in the development of Integrated Crop Protection, the reality falls far short of the potential. Issues critical to the development of more sustainable crop protection systems, such as an understanding of the mechanisms for delaying herbicide resistance, the use of crop interference techniques and of integrated control systems, have not formed the basis of mathematical models. The reasons for the gap are fourfold. First, models of weed, pest and disease control in crops have concentrated strongly on simulating the impacts of chemical control and within that on identifying the threshold level of infestation for spraying. Thus, non-chemical control methods have received scant attention, as has the notion of combining different control methods. Second, the criteria used to determine the 'optimal' method of control has been 'cost effectiveness'. Other criteria, like minimising envionmental damage have been largely ignored. This has encouraged the selection of chemical methods of control. Third, models are only as good as the data on which they are based and, while a large body of data exists on herbicide response, much less data exists on the impact of other forms of control. There is also an acute shortage of information relating to the physiological processes involved in the growth and development of weeds. In consequence, currently it is often not possible to develop mechanistic models, which are needed if some of the alternative methods of control are to be explored. Fourth, the need for Integrated Crop Protection programmes often arises from the fact that control of more than one species of pest or weed is required. However, the techniques so far developed for simulating multi-species competition and control are computionally expensive, limiting their use. Nonetheless, given the complexity of the management systems involved in Integrated Crop Protection, mathematical modelling would seem to be a potentially valuable tool. Moreover, in the case of some forms of control, such as biological and genetic, it is also arguable that modelling the consequences prior to practical application is imperative, given the potential ecological and environmental risks involved.

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