resolving, and therefore for which an Expert System would be most useful, we are conducting user surveys. We have also used a number of descriptive techniques, such as interaction matrices, to help identify and pull together relevant information that will need to be included in the Expert System.

Figure 3 illustrates a technique we used to think about the factors that need to be considered when faced with the problem of a large bulk of wheat infested with grain weevil *(Sitophilus granarius)*. Initially all the options were identified, only some of which are shown in Figure 3. Then we attempted to determine under what circumstances each option would be recommended. This enabled us to identify the relevant qualifiers, some of which are shown in Figure 3. It should be clear from this how IF-THEN rules can be derived and included in the Expert System.

Conclusion.

Within our research programme at Silwood Park, Expert Systems are regarded as an additional tool for helping to analyse and resolve pest problems. While Expert Systems undoubtedly have a role to play in improving pest management, at this early stage in their application, it is not clear where their greatest contribution will lie: in giving advice to pest managers, in training field advisers, or in helping to identify applied research priorities.

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SIRATAC: a decision support system for cotton management

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Introduction

SIRATAC is an acronym for CSIRO and N.S.W. Department of Agriculture tactics for growing cotton. Chemical control of pests is essential for commercially successful cotton production in Australia. Apart from costing from $100 to $300 per ha, chemical control carries risks of pests developing resistance to insecticides and environmental pollution. The SIRATAC system is a computer-based dial-up crop management system that has been developed to assist cotton growers make good tactical decisions in the use of insecticides.

In the early 1970s, commercial cotton production ceased in the Ord River area and was threatened elsewhere because a major pest, *Heliothis armigera,* had become resistant to DDT. Cotton research was intensified with the aim of developing economically viable and ecologically stable systems of cotton production. Room (1979) constructed a prototype computer-based pest management system to synthesise the research results that began to accumulate into a practical integrated management system that made the best use of currently available information. The system has been progressively updated as further research results became available not only from Narrabri but also more recently the University of Queensland and the Queensland Department of Primary Industries.

The SIRATAC Pest Management System

The SIRATAC pest management program consists of several simulation models and a decision model. The HELIOTHIS model simulates the development of eggs and larvae using Room's (1983) temperature driven

* CSIRO Cotton Research Unit, Narrabri. It is a pleasure to pay tribute to the people, too numerous to mention in this brief article, from many organizations who have contributed to the development and application of SIRATAC.

functions. Mortality is estimated taking into account weather, beneficial insects and residual effects of previous sprays, using functions derived by Ives (pers. comm.), the data base and the toxicological studies of Wilson *et al.* (1983). Input is the latest counts of *Heliothis* eggs and larvae. Further egglaying is not simulated but the next day's egglay is assumed to be an empirically determined fraction of today's. Output is the predicted numbers of larvae in size classes on successive days. There is a simple TIPWORM model similar to the HELIOTHIS model.

The FRUIT model, described by Hearn and da Roza (1985), consists of three processes: fruit development, fruit shedding and square production. The rates of these processes are controlled by temperature, boll load and number of fruiting points. Input is all counts of squares and bolls to date, and output is the predicted daily numbers of squares and bolls to the end of the season and the number of bolls to be harvested.

The FEEDING model uses the functions of Wilson and Waite (1982) that describe feeding preferences of each age class of *Heliothis* larvae for each size class of fruit. The model includes the feeding rates for each class of larvae. Input is numbers of larvae and fruit in age classes, and output is number of damaged fruit.

The DECISION model supports two decisions: (i) whether or not to spray a pesticide; and (ii) if so, what pesticide to spray. In supporting these decisions the system observes several important pest management principles: (a) making maximum use of natural mortality of cotton pests; (b) utilizing the natural fruiting habit of the cotton plant which produces 2 to 3 times more fruit than it can mature and can compensate to a degree and replace fruit that are lost; (c) use of action thresholds which are pest levels above which the value of the damage they would do is likely to exceed the cost of control; and (d) using "soft" sprays whenever possible, which are not persistent and have a minimum effect on beneficial insects, killing a narrow range of insects, preferably only the target species.

In order to determine if an infestation needs to be controlled, the procedure first determines the appropriate action thresholds for each pest and then notes which pests require control because they exceed their thresholds either today or, in some cases tomorrow or the next day. Thresholds depend on the stage of the growth of the crop. For some pests, thresholds are step functions changing at specific phenological stages of crop growth.[1] For other pests, thresholds are dynamic and are a continuous function of the state of the crop relative to the course of crop development desired by the manager, provided the infestation is not likely to cause a yield loss or unacceptable delay.

In order to select an appropriate pesticide, the effect on the *Heliothis* population of each group of pesticides is simulated in turn, starting with the softest, until one is found that will reduce the population to 25% of the threshold. The procedure for other pests uses rules that embody the pest management principles, knowledge derived from the data base and from pest management practitioners.

The SIRATAC user collects and enters two sets of data regularly: (i) numbers of insects, counted every third day; and (ii) numbers of fruit (squares and bolls), counted weekly. Weather data are entered daily at the central computer. The user enters agronomic data such as variety and sowing date once at the beginning of the season.

The user runs the program each time he enters the insect data. The program first calls the FRUIT model to predict the development of the counted fruit and estimate the number likely to survive and be harvested. The model then predicts the production of further fruit, their development and likely contribution to harvest. The program then calls the HELIOTHIS model to simulate the development and mortality of *Heliothis* spp in order to estimate the numbers likely to be present tomorrow and the next day. the FEEDING model then predicts how many fruit *Heliothis* will damage before the next check in 3 days' time. The FRUIT model is then called again taking this potential damage into account in order to determine whether this infestation is likely to reduce the yield. The DECISION model is invoked to determine if a pest needs to be controlled and, if so, with what pesticide. The program concludes by providing the user with a choice of reports that document the recommended pest management

[1] phenology: science dealing with the influence of climate on the recurrence of annual phenomena of animal and plant life such as bird migrations and plant budding *(The Macquarie Dictionary).*

options, pest numbers, fruit numbers, a plot of crop development and crop prospects including an estimate of yield and date of crop maturation.

Application of SIRATAC

The area managed by the SIRATAC system has increased steadily from 10 hectares in 1976/77 to an average over 40,000 ha for the last three seasons (1984 to 1987), now representing 27% of the national crop. The first 5 years were mainly trials comparing SIRATAC management with conventional control; similar yields were obtained using SIRATAC and conventional control, but with marked reduction in the numbers and hardness of insecticide sprays used on the SIRATAC crops. The cost of sprays was reduced by 37% with a maximum of 72% (Hearn *et al* 1981; Ives *et al* 1984; Dowling and Cull 1982; Pyke and Twine 1983).

In 1981 the demand for SIRATAC was beyond the resources, and the terms of reference, of research. Growers formed a company, SIRATAC Ltd, to market SIRATAC as a commercial service to all growers. The company employs technical officers to promote SIRATAC and provide technical support. SIRATAC was initially developed in the Namoi Valley but it was progressively extended to all other cotton growing areas of eastern Australia in response to demand, linked to the SIRATAC computer through the public telephone system.

A central computer is preferred to individual microcomputers for SIRATAC because it allows updates of the system to be made instantaneously available to all users. Updates are sometimes made during the growing season when it is essential for them to be immediately available. The central facility also allows the data base, which has become an invaluable resource, to be automatically updated every time data is entered.

Most growers initially use SIRATAC because they expect to save money (Browne 1981). Subsequently they appreciate the objectivity of the system and value the database and the insights gained by monitoring the crop. Services available to users are expanding and include or will include: an irrigation scheduling; an information service on an expanding range of topics; water and nitrogen management; *Heliothis* population prediction; and economic optimization of decisions.

The SIRATAC system is dynamic; it is being continually updated in the light of research and experience, using the data base generated by the program. For this purpose, workshops with the users and research workers are held during the growing season and at the end of the season to consider changes. Viability of SIRATAC depends on the continued involvement of researchers, firstly in a support role for trouble shooting, education and program updating, secondly to strengthen SIRATAC in its existing scope and thirdly to expand the scope of SIRATAC.

SIRATAC as an Expert System

SIRATAC is a decision support system as defined by Belew (1985) having a database, a model base and a rule base. It is debatable whether SIRATAC as currently implemented is an expert system. Definitions of an expert system vary but most include these features listed by Alty and Coombs (1984): the inference engine must be separate from the knowledge base; knowledge representation must be rule based; and the system can explain its answers. The inference engine or control module decides in any situation which rules to invoke and in which order to invoke them. Such a definition implies a higher level language than FORTRAN in which SIRATAC is currently implemented. To this definition could be added the capability to deal with uncertainty in the input data and the resolution of conflict.

SIRATAC has the functionality of an expert system. From given facts, the system uses rules to reach conclusions which are offered as a recommendation to the user. SIRATAC uses the recognised procedure in expert systems of forward chaining from facts to a conclusion for the decision whether to spray or not, and backward chaining from a conclusion to the facts needed to support that conclusion that a particular pesticide ought to be used. SIRATAC has a limited explanation capability. The user can read the file that tabulates thresholds and actual and predicted pest populations to explain the decision to spray. To explain why a particular pesticide was selected, the user can read another file that tabulates the simulated effect on pest populations of each group of pesticides tried.

Because SIRATAC is implemented in

FORTRAN, the order of asking the rules is programmed into a rigid structure. The reasoning is all done by the programmer, not by the program during execution. The result is a decision tree that branches in answer to YES/NO questions to arrive at recommendations at the ends of the branches. The rules are the routes through the tree from node to node and can be represented in the conventional expert system format. In the *Heliothis* section of the tree, there were initially 8 questions giving 2^8 or 256 potential routes through the tree. Many routes were redundant and several branches lead to the same conclusion, so that there were actually only 7 conclusions in this part of the tree. Several years later, this part of the tree had 24 questions with over 16 million potential routes and 46 actual conclusions. As well as many branches leading to the same conclusion, by then the tree had, at several points in its structure, a number of branches leading to an intermediate conclusion from which further branching took place. The decision tree thus became intractable to further development, being increasingly difficult to modify with additional knowledge because of the convoluted and obscure structure.

At this point, it was realised the potential of the expert system software where the knowledge is separated from the structure. SIRATAC was originally developed using FORTRAN in isolation from the mainstream of software engineering and by scientists who were not computer professionals. SIRATAC is now being re-implemented professionally by the CSIRO Division of Information Technology in collaboration with Digital Equipment Corporation. As well as using expert systems software, the re-implementation will use other fourth generation languages for the database and the user interface. The new system will be more robust and user friendly with a more versatile and powerful database. The expert system will have an enhanced explanation capability, the ability to handle conflict and uncertainty, and be simple to modify.

Conclusions

SIRATAC uses computer technology to integrate many diverse research results and a wealth of experience to provide an extension and management tool. The progress SIRATAC has made has depended on the following criteria: the team of scientists was initially broad in individual interests and experience yet small in number allowing good communication; the role of development was recognised with trials done in the real world on commercial crops that would cost the grower money if bad decisions were made; the cotton growing industry is cohesive, supportive of research, with good communication between growers and researchers; and there was continued support by researchers after commercial release of the system.

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