An approach to modelling and evaluating alternative management strategies for insecticide resistance in the Australian cotton industry

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Abstract:

The issue of insecticide resistance to *Helicoverpa* insects is of increasing concern to the Australian cotton industry. In this paper we begin to consider this issue using bio-economic modelling and analysis. We develop management strategies at the farm level within an integrated resistance management framework. Because of our emphasis on resistance, we first discuss an index of resistance risk that can be applied to chemical and other strategies. After this initial filter is used, the resulting strategies can be evaluated in a bio-economic framework. The Helicoverpa Armigera and Punctigera Simulation (HEAPS) model can be used to evaluate the entomological impacts of alternative strategies for insect control. The method of analysis proposed involves dynamic optimisation techniques based on predicted stock and flow outcomes from the simulation and other models.

Key Words: Cotton, Insecticide Resistance, and Economics

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1. Introduction

Cotton is a capital-intensive high-value crop and insect pest control is one of the major costs in cotton growing. Intensive use of chemicals has increased insecticide resistance within insect populations such as *Helicoverpa armigera* and *punctigera*. Continued increases in resistance will increase future insect control costs and also cause negative impacts on the environment. Adamson *et al.* (1997) estimated that the total economic damage and management control cost of *Helicoverpa* in cotton in Australia was around $124 million per annum. They also estimated that if the insecticide resistance level increased there would be an effective loss of $934 to $1,139 million per annum.

Brief History of Development of Resistance[1]

The first serious resistance of *Helicoverpa* to DDT and DDT-toxaphone was recorded in the Ord River valley in the early 1970s. Resistance to chlorinated hydrocarbons developed after only 10 years of commercial use in cotton (Wilson 1974). Eventually cotton production collapsed in the Ord in 1974 due to these factors. By the late 1970s the main commercial insecticide groups were organochlorines, cyclodienes and organophosphates. But when these were found to be prone to resistance and environmentally disruptive they were replaced by the pyrethroids. In 1983 pyrethroids failed to show the satisfactory performance to control of *H. armigera* due to development of resistance at Emerald in Central Queensland (Forrester, Cahill, Bird and Layland 1993).

H. armigera resistance to some of the carbamate insecticides (methomyl and carbaryl) has been known since 1983. But no resistance to thiodicarb was identified at that time. As resistance to pyrethroids and endosulfan increased, growers tried to use alternative chemicals such as thiodicarb. However, in early 1993, severe thiodicarb resistance was found in sweet corn and maize crops. A small-scale resistance was also identified in cotton in NSW and Queensland (Gunning 1994).

Implications of the Problem

If insects develop resistance to chemicals then the efficacy (or effectiveness) of sprays is reduced, so that extra sprays are applied with progressively smaller effects. These cost more, have disruptive effects on the environment and may decrease the susceptibility of other insects. Australian cotton growers are well aware of the economic consequences of increasing insecticide resistance.

Field populations of *H. armigera* have developed levels of resistance to almost all of the current chemical groups. Monitoring of field populations of *H. armigera* through the

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[1] A discussion of the main chemical groups and classes is given in the Appendix.

1990s suggested that the status of pyrethroid resistance has continued to deteriorate and in most areas resistance frequencies are above 80% for fenvalerate (Holloway and Forester 1998). A study by Gunning *et al.* (1999) showed that resistance frequencies of *H. armigera* to carbamates in the Macquarie Valley of NSW were getting close to 100% within five seasons of use. Other chemical groups such as organochlorines (endosulfan), organophosphates, carbamates, fenvalerate and bifenthrin also showed an increasing trend of resistance frequencies.

A ten year interval comparison study (Holloway and Forester 1998) in the Namoi region showed that average spray numbers per season have increased substantially, nearly doubling over the period. Average sprays per season increased for pyrethroids from 3.2 to 6.3, for organophosphates from 1.9 to 3.2 and for carbamates from 0.4 to 0.7. Insecticide resistance management strategies delayed the resistance of *H. armigera* in some instances, but the level of resistance has gradually increased. This trend is a threat for insect control. If the industry loses one chemical, replacement is very expensive and it is also difficult to register a new chemical. The Ord Valley experience may be repeated if resistance management is not addressed.

What has been done so far

Insecticide resistance management (IRM) is a comprehensive program of alternative management strategies, which can be applied to minimising the development of insecticide resistance. Growers and scientists have been concerned about increasing resistance to some chemicals since the early 1970s and field and laboratory research has occurred since then. Within six months of the reported pyrethroid failure in January 1983 (Gunning 1984), a strategy aimed at containing the resistance problem had been formulated and ratified for use in the following season (Forrester *et al.* 1993). This strategy aimed to manage resistance not only to pyrethroids, but also to other major chemical groups such as endosulfan and the organophosphates/carbamates. A different approach was used for each chemical group, depending on the severity of the resistance risk and predicted selection pressure (Hoque *et al.* 2000). This was the start of implementing a curative resistance management strategy. Preventive insecticide resistance management to delay the resistance also has been working for last four years through the use of Bt transgenic cotton.

The IRM strategies have been developed and reviewed by the Transgenic Insect Management Strategy Committee (TIMS), which is convened by the Australian Cotton Growers' Research Association (ACGRA). TIMS also established a sub committee (the TIMS Troubleshooting Committee or TTC) to lodge the requests to vary the Strategy temporarily for specific regions (Shaw 2000). TIMS organises meetings of industry groups (which include representative of growers, consultants, researchers, resellers, agrochemical industry and aerial operators) to finalise the strategies. They start the process at the end of each season and try to finalise by early July so that the agrochemical industry has sufficient time to organise stocks for the following season.

Relationship between IRM and IPM

IPM is a crop protection system, which is structured to use a variety of pest control procedures rather than relying only on chemical insecticides (Smith 1971). IRM is a comprehensive program of alternative management strategies, which can be applied to minimise the development of insecticide resistance for different chemicals. IPM is a combined approach of different pest control techniques including mechanical, cultural, biological and chemical methods, which are used to minimise environmental and economic risks (National Farmers Federation 1997). IPM for cotton is a system that integrates all means of managing pest populations with the aim of reducing insecticide use whilst maintaining profitability. IPM helps to manage resistance, by reducing overall use of synthetic insecticides and selection pressure on *H. armigera*. IPM and IRM strategies are therefore complementary (Mensah and Wilson 1999).

Aims of the Paper

Growers are interested in maintaining the susceptibility of *Helicoverpa* populations to certain chemicals, and IRM strategies have been developed at the grower level with this purpose. IRM in the past has been mainly about chemical strategies, but it is now evolving more into IPM. That is, there are a number of ways of achieving IRM goals, which may include both chemical and non-chemical options. Alternative strategies can be developed based on entomological and biological criteria, including genetic characteristics and different modes of action. In this paper we discuss an approach to evaluating alternative IRM strategies based on both resistance risk (a biological type of criterion) and economic returns. We discuss the development and evaluation of some alternatives to current strategies. Firstly we propose assessing each strategy based on a potential resistance risk index (RRI) and then we outline an economic approach to the evaluation of alternative management strategies. This paper reports on the first stage of a work program relating to IRM in the cotton industry. Once this approach has been developed and discussed, the entomological and agronomic models necessary for the analysis will be refined and the bio-economic analysis undertaken.

2. Characteristics of the problem

Several generations of insects in each season

In Australian cotton growing regions *Helicoverpa armigera* typically have between 4 and 6 generations per season over spring and summer. *H.armigera* also over winter in most cotton growing regions by entering into a state of pupal diapause. This over-wintering population emerges as adult moths in the following spring and seed subsequent generations. These over-wintering individuals are the survivors of the previous season’s spray regime, and they are the sole carriers of resistant genes from one season to the next. Further, *H. armigera* moths have high fecundity – each female can lay up to 1500 eggs (Fitt 1989). The combination of high reproductive rate and short generation times is favourable for the evolution of resistance when successive generations are exposed to mortality factors like pesticides.

Area-wide management and insect mobility

Area Wide Management (AWM) is a cooperative approach to managing groups of neighbouring properties to achieve a uniform goal. It has been used in programs such as Landcare to manage natural resources through water and salinity management. It has become an important issue in cotton IPM because of the mobility of the insects. For cotton, AWM is the combined effort of a number of farmers and their advisers to manage pests using all the tools available with minimum impact on either beneficial insects, the environment or neighbours (MacPherson and Coulton 2000). This concept of pest management has captured the attention of growers as a means of managing pests in a coordinated manner, reducing the over-all costs of pest control and helping to manage insecticide resistance in *H. armigera* (Shaw 2000).

Interest in AWM is increasing within the Australian cotton industry due to increasing costs of chemical control, increasing levels of resistance to conventional chemistry and an awareness of the potential impacts of sprays on the neighbouring environment. AWM is an approach that acknowledges the mobility of pests and beneficial insects and that the management regimes to control pests imposed on a given field are likely to alter the abundance of beneficial organisms and levels of insecticide resistance in the surrounding locality (Dillon and Hoque 2000). An example of this approach is the use of trap crops to attract *Helicoverpa* eggs during spring and autumn and therefore suppress the overall population within a region.

There is not strong evidence of great success of AWM but some AWM groups have worked well together to achieve desirable outcomes. There has been a spirit of cooperation in many groups, but ultimately participants will need evidence of benefits to maintain their enthusiasm for AWM. What is needed now is to further develop the currently ‘rudimentary’ AWM into a strategy that delivers reliable season-long suppression of the *H. armigera* population (Murray, Miles and Ferguson 2000).

Resistance to several chemical groups

H. armigera have developed some degree of resistance to many of the current chemical groups available. Levels of resistance have steadily increased in most areas. For example resistance frequencies are now above 80% for fenvalerate (a pyrethroid) (Holloway and Forester 1998) and approaching 100% for carbamates in one cotton growing valley (Gunning 1999). Other chemical groups including organochlorins (endosulfan), and organophosphates, also show an increasing trend of resistance frequencies.

New technologies on the horizon – 2-gene technology

Bacillus thuringiensis var. *kurstaki* (or Bt) is a protein, which is toxic to *Helicoverpa* spp. on ingestion. Several commercial products containing Bt have been used by the Australian cotton industry in the last 20 years as selective foliar sprays for control of *Helicoverpa* species. The latest development in the use of Bt in cotton is in the form of transgenic cotton varieties (INGARD®) expressing the single protein CryIAc (P1) delta endotoxin, which have been commercially available in Australia for the last 4 seasons (Holloway and Dang 2000). Over that period it has showed a significant achievement in reducing the insecticide sprays (by 40-60%) for *Helicoverpa* or other Lepidopteran pests such as tipworm (Fitt 2000*a*).

To avoid the risk of insecticide resistance to Bt, the area of INGARD® varieties is restricted by regulation (currently 30% of cotton planting per valley). Mandatory management strategies pertaining to refuges, planting windows and pupae destruction are also imposed. Growers need to register and pay a licence fee on an area basis to grow INGARD® varieties. Most growers have had some experience with this INGARD® technology and the area under Bt has increased to the allowable proportion of total cotton area (Shaw 2000).

The INGARD® experience in Australia has shown that efficacy is not consistent through the season. Efficacy decline begins during flowering stage and supplementary *Helicoverpa* control is required for INGARD® crops, particularly during the last third of the growing season (Fitt 2000*a*). To improve the efficacy and for better resistance management of INGARD®, a two-Bt-gene variety is under development. With the two-gene variety, any larvae having resistance to one gene will be killed by the actions of the other gene. This approach gives a 10 to 20 fold increase in predicted time before resistance will occur (Constable 1998). Large-scale field trial and laboratory studies have shown that two-Bt-gene varieties are capable of providing highly effective control of *Helicoverpa* and substantially reducing the number of pesticide sprays required. Provided effective refuges are maintained, the advent of two-gene cotton will allow much larger proportional area of Bt cotton to be grown (Fitt 2000*a*).

Characterisation as an Economic Problem

Insect control costs and their impact on profits are important in spray decisions. Alternative spray management strategies have both short-term and long-term economic impacts. Short-term economic impact includes loss of profits within a particular season. If the spray strategy of one period affects the spray decision of the next period then there is a longer-term economic impact.

Broad-spectrum (harder) sprays kill both *Helicoverpa* pests and beneficial insects, and also have greater environmental impact in terms of potential damage to humans, fish, bees and other wildlife. They are less costly on a unit basis, but are used in greater quantities (giving a greater total cost) and are more likely to contribute to increases in resistance in insect populations.

In the case of a softer spray strategy, paddocks are sprayed selectively (targeted at *Helicoverpa*). These sprays are more expensive per unit but have less impact on beneficials and other wildlife. They may have a lower chance of success but do not aggravate resistance, rather they improve or maintain susceptibility in the insect population (Hoque *et al.* 2000).

Budgetary comparisons can investigate the short-term costs and benefits of harder versus softer spray strategies and other IRM approaches associated with spray decisions. The marginal benefits of extra unit of spray can be calculated for each type of season.

Economists are also interested in questions that are characterised by problems requiring the management of stocks of resources over longer time periods in the presence of uncertainty of outcomes. This interest is in representing the management problem for a decision-maker, which must decide between alternative actions, each with a number of possible outcomes (depending on probabilities) and each outcome represented in terms of a pay-off in monetary terms. The decision-maker's main objective is assumed to be maximisation of profit or minimization of costs over time. The problem is termed dynamic if the stock can be characterised by a consequential relationship between actions or decisions in one period and stock levels in a subsequent period. The stock level in the future is unknown at the time of action, and depends on specific actions and on other (eg climatic) occurrences (Hoque *et al.* 2000).

Decision-makers need to understand how the biological system works so that reliable predictions can be made about outcomes when particular tactics or strategies are followed. Simulation helps in making these predictions, attempting to represent the system being considered with sufficient detail to make reliable predictions. Once the simulation models are constructed and validated then it is possible to combine the economic and biological knowledge into a framework that can be used to answer important questions.

The Helicoverpa Armigera and Punctigera Simulation (HEAPS) model will be used as a means of predicting insect population numbers and susceptibility levels associated with alternative insect control strategies. Dillon, Fitt and Daly (1994) describe how the HEAPS model simulates the genetics of resistance in regional *Helicoverpa* populations. Yield prediction can be derived using the OZCOT model (Hearn 1994) or from agronomists' best predictions. A dynamic economic programming approach can be followed with the integration of insect population outcomes and yield prediction to assess alternative IRM strategies.

3. The question posed

Our focus is on applied decision-making for cotton growers (ie a farm-level issue). From the grower's perspective, the management issue is one of controlling insect pests in the current crop. Also known is the measured resistance to certain chemicals and/or chemical groups currently being used in the industry (Gunning 1994). Growers are looking for a forward plan or strategy to deal with current decisions, while accounting for the implications of these decisions on future levels of resistance. In effect the grower's aim is to maintain the susceptibility of *Helicoverpa* populations to specific chemicals and/or chemical groups.

The aim in this work is to develop and evaluate some alternatives to current strategies at the farm level. The general question is how vulnerable the chemical groups are to the evolution of resistance by *Helicoverpa*. There are two stages of analysis proposed. First, each strategy will be assessed in terms of an index of potential resistance risk developed in conjunction with this project. This is a biological/genetic assessment that relates to an evaluation of the potential for resistance to develop if the strategy is followed. We call it a Resistance Risk Index (RRI). This is discussed in the next section.

Once a ranking of potential (including current) strategies is made based on the RRI, the second stage or question will involve an economic or financial evaluation of the alternatives. A comparison of the rankings based on RRI versus those based on profit per hectare will then be used as a basis for policy decisions on spray strategies, and also in terms of guiding future research.

Another potential question involves the economic cost of resistance. This question is less relevant in our current context. The 'cost of resistance', if calculable, can be useful information when the question is one of the size of the problem and allocation of scarce R, D & E resources to address the issue given other competing funding priorities. For on-farm decision making the more relevant question concerns relative costs and benefits of changing between strategies. This is the appropriate question once the funding decision has been made.

4. An index of resistance risk

Chemical groups and the strategies that govern their patterns of use will be characterised in relation to the level of risk that over time *Helicoverpa* will evolve high levels of resistance to them. The Resistance Risk Index (RRI) will be assessed on the basis of four characteristics:

(1) the degree of target specificity of each chemical, whether broad spectrum (with resultant negative impacts on beneficial insect populations) or more specific to *Helicoverpa* (neutral or minimal impacts on beneficial insect populations);

(2) the efficacy of each chemical, which determines the degree of selection pressure to which populations are exposed. High efficacy creates a narrow bottleneck of genotypes in the overall population.

(3) the persistence of the chemical which influences the proportion of the population exposed, because individual insects may reside in sheltered positions or exist as un-laid eggs at the time of spray application, but may become exposed to chemical residues on the crop later; and

(4) the pattern of use in relation to dose rate and the number of consecutive sprays of each chemical. In the absence of resistance higher doses and repetition rates increase chemical efficacy, but thereby also increase the selection pressure for resistance to evolve.

5. The entomological simulation model

An overview of the Helicoverpa armigera and punctigera simulation model (HEAPS) is described by Dillon and Fitt (1997). The model tracks the densities and demographics of multiple populations of *Helicoverpa* within a user-defined explicitly spatial landscape. Each patch within the landscape can support a sub-population of *Helicoverpa*. The model runs on a daily time-step, and cohorts of *Helicoverpa* progress through their development cycle at a rate dependent on daily temperatures. The movement of moths over the landscape, and their subsequent mating and egg laying is simulated. Mortality rates are applied to each sub-population each day, and can include a natural ‘background’ level of mortality as well as simulated applications of chemical pesticides.

The HEAPS model allows a user to define a number of chemical types and give them each a name. The chemicals then influence the model in three ways (Dillon *et al*. 1990). First each chemical has a user-defined table of efficacy against each life stage of *Helicoverpa* (eggs, and very small, small, medium and large larvae). Second, each chemical can have a function describing how its efficacy decreases over the days after an application (residual activity period). And third, for any simulation run one of the chemicals can be set so that it has different efficacies against susceptible (SS), heterozygous (RS) and homozygous resistant (RR) genotypes of each life stage. Therefore the frequencies of the genes for resistance (R) and susceptibility (S) to that chemical can be tracked within the regional populations being simulated. The model can set to apply simulated sprays of sets of chemicals to any or all of the sub-populations in response to *Helicoverpa* densities that may exceed user-defined thresholds, and/or on a regular ‘calendar’ basis. In this way complex spray regimes can be simulated, and the frequencies of resistance genes to one of the chemicals can be tracked over time.

6. Prediction of production outcomes

There are a number of crop simulation models available to predict the production outcomes with response to different crop management decisions (Hearn 1994). An Australian crop simulation model (OZCOT), was constructed by linking a simple temperature-driven model of the fruiting dynamics to the widely used Ritchie (1972) soil water balance model. This model incorporated some other original models, such as a fruiting model, a leaf area generator model, a boll growth model and an elementary nitrogen model. It responds to different climatic situations, crop physiological characters, agronomic variables and management decisions. It is a decision support model for cotton production that has been validated in the cotton growing regions of Australia, and will be used to obtain the predicted yield outcomes.

7. Previous economic studies

The issue of deriving management strategies to best control biological pests in economically important crops has been considered and reported over a relatively long period. Because of the nature of the problem optimisation approaches have been used (Tabashnik 1986, 1990). In this review only selected studies are referenced.

Shoemaker and Onstad (1983) reported an optimisation analysis of the integration of biological, cultural and chemical control of alfalfa weevil in New York State. The optimal policies depended upon pest and parasite densities, weather, length of planning horizon, and on a number of parameters describing population dynamics. A stochastic dynamic programming model was used to analyse the integrated control of alfalfa weevil. The models used were a decision model (using an optimisation method) incorporating decision and state variables, and a population model including simple difference equations of both weevils and parasites. This analysis did not consider the issue of maintaining susceptibility to control chemicals within the weevil population.

Gutierrez, Regev and Shalit (1979) specifically modelled pesticide resistance into a realistic economic optimisation model of the interaction of Egyptian alfalfa weevil populations and alfalfa. The model had four components: the population dynamics of the weevil; the dynamics of the crop; pesticide-induced mortality; and the evolution of resistance in the weevil population. Two cases were evaluated – the standard optimal pesticide application schedule (derived for a single season with resistance not present), and an informed single season optimal policy when the level of resistance and the pest density is known at the start of each season. Optimal pesticide usage, infestation levels, frequency of the resistance gene and profits over time were derived in each case. Differences in patterns of pesticide use and frequency of resistance gene were noted. Both these management cases were myopic in that they ignored the long-term implications of resistance, which are complex and difficult to analyse. The results showed the potential of the approach to model and predict resistance outcomes in insect populations.

Dudley, Mueller and Wightman (1989) reported an application of dynamic programming for guiding IPM on groundnut leafminer (GLM) in India. A simulation model of the population dynamics of GLM was built in conjunction with an IPM project for this pest. It was linked to a dynamic programming model, which was used to indicate the number of insecticide applications needed to optimise income over ranges of natural mortality and host-plant resistance. Also included were the effects of initial level of GLM population, mortality caused by insecticides to natural enemies, the efficacy of insecticide application, and groundnut prices. The results were used to indicate where future research should be focussed in terms of 'how much' of each control component should be employed in integrated pest control.

Gorddard, Pannell and Hertzler (1995) investigated the issue of resistance development in weeds, and how to manage an agricultural system in the presence of weeds and weed resistance. The range of options for weed control is wide, with non-chemical control options being available in many cases, and weed control is expensive for farmers. They used a dynamic optimisation model for weed control under the threat of herbicide resistance, which integrated decisions about optimal chemical dosages and optimal levels of non-chemical control. They identified an economic balance between the current control of herbicide-resistant weeds and future development of resistance. There is an economic trade-off between the two, which has implications for weed management. The inclusion of non-chemical control was shown to have a major impact on the optimal strategy for herbicide use and on the extent to which resistance can profitably be delayed.

8. Economic approach and model

General approach

Our interest is in alternative strategies to impact future insecticide resistance in *Helicoverpa* moths in cotton, and the approach proposed will be similar to Gorddard *et al*. (1995). It involves managing stocks of resistant and susceptible *Helicoverpa* moths over time, based on predictions of changes in those stocks from one decision period to the next. Those changes depend on management strategies used and other factors.

Decision periods

Consider a continuous cotton rotation, ie cotton-fallow in a summer-winter cropping system. The decision period will be annual, that is, each strategy evaluated will involve a set of management decisions over the whole of one crop-fallow sequence. Thus a strategy could include chemical controls applied to the cotton crop (including number of applications and types of chemicals used) and the use of stubble management and other IPM strategies (use of refuges, Envirofeast etc). The annual decision period includes a number of insect generations within any crop. We need a process that models or predicts the insect outcomes over this time period.

Stock variables

We assume resistance is expressed in a single gene. Three stock variables can therefore be used:

- the density (number) of susceptible *H. armigera* (SS);
- the density (number) of heterozygote *H. armigera* (RS); and
- the density (number) of resistant *H. armigera* (RR).

These variables need to be specified at a point of time during the decision period and the number of each type at the start of each period is used. At present the entomological model is coded to only track resistance to a single type of chemical pesticide, and other types of chemical are not considered in terms of resistance – although other simulated chemicals do affect mortality.

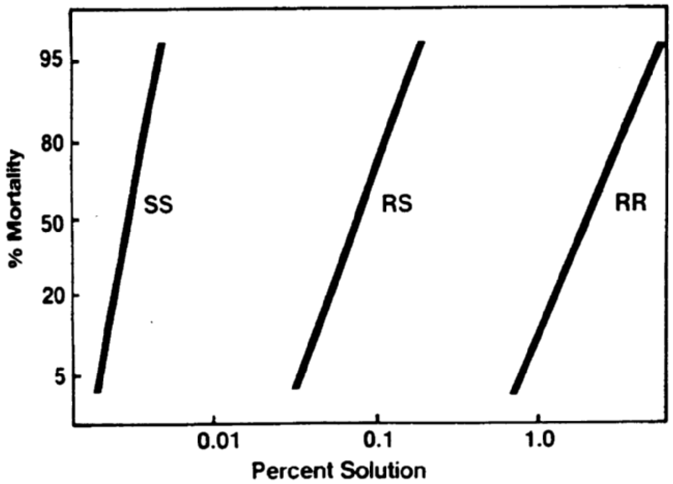

Figure 1: Typical dose response for the homozygous susceptible SS, heterozygous RS and homozygous resistant RR (after Roush and Daly 1990)

The diagram in Figure 1 based on Roush and Daley (1990) is the basis for those stock variables. On the X-axis is percent solution or dosage rate and on the Y-axis is percentage mortality. For our modelling purposes it is deemed reasonable to assume a single level of mortality for each genotype. The level of heterozygote mortality relative to

SS and RR genotypes is then an indication of dominance. The interaction of these factors determines whether resistance in the moth population is dominant or recessive.

We have doubts about explicitly modelling different dosage rates. In practice, *Helicoverpa* moths sprayed within a crop will be exposed to a range of dose rates because application coverage is not uniform within individual plants and across the field. A proportion of the larvae is in sheltered locations and may not emerge for a few days, and environmental factors influence coverage and persistence (wind, rain, UV radiation etc). Therefore the strategies will focus on numbers of applications of chemical types at a set rate.

Decisions or control strategies

Possible annual decision strategies need to include:

- use of 'softer' or 'harder' spray options in the cotton crop (ie type of chemical);
- use of these spray options with variations according to thresholds applied (ie number of applications influencing selection pressure);
- strategies used during fallow and other IPM strategies must also be specified;
- perhaps one IPM strategy to consider could be a beneficial activity index that indicates background *Helicoverpa* mortality rates and that is affected by a field's previous spray history.

Roush and Daley list alternative techniques for manipulating selection pressure in IRM strategies. These are divided into two groups, one involves reducing fitness of resistant individuals when insecticide is applied, and the other involves reducing the total amount of selection pressure applied. We will discuss and refine the management alternatives used in our analysis, but they need to be aligned with the types of inputs that can be specified in HEAPS.

State transition equations

The reason for using dynamic solution procedures (optimal control or dynamic programming) is that the process of resistance gene transmission is 'dynamic'. That is, we can explain the level of a stock at any point in time by a particular type of relationship (a differential equation called a state or stock transition equation). This relationship specifies that the stock level and decisions in the previous period, and other interim factors (eg climatic or other random factors), determine the level of the stock in any period.

Define the density of susceptible, heterozygote and resistant *Helicoverpa* at the end of any period *t* (where t goes from 0 to *T*) as SS_t, RS_t and RR_t respectively. Also represent the decisions in period *t* as U_t (incorporating chemical type), *M* as mortality of *H.armigera* from beneficial insects, O_{SS}, O_{RS} and O_{RR} as egg laying (oviposition) of new *Helicoverpa* eggs and I_{ss}, I_{rs} and I_{rr} as immigration of new *Helicoverpa* moths during the period. Then the state transition equations can be written as:

$$SS_{t+1} = f_{ss}(SS_t, RS_t, RR_t, U_t, M_t, O_{sst}, O_{rst}, O_{rrt}, I_{sst}, I_{rst}, I_{rrt}) \tag{1a}$$

$$RS_{t+1} = f_{rs}(SS_t, RS_t, RR_t, U_t, M_t, O_{sst}, O_{rst}, O_{rrt}, I_{sst}, I_{rst}, I_{rrt}) \tag{1b}$$

$$RR_{t+1} = f_{rr}(SS_t, RS_t, RR_t, U_t, M_t, O_{sst}, O_{rst}, O_{rrt}, I_{sst}, I_{rst}, I_{rrt})\,. \tag{1c}$$

In these equations f_{ss}, f_{rs} and f_{rr} represent the HEAPS model which specifies the density (ie population) outcomes for each type of genotype given the populations of *Helicoverpa,* decisions, mortalities, reproduction and immigration levels in the previous period. We also need to specify some initial levels of these stocks at the start of the decision period when $t = 0$.

Yield outcomes

Cotton yield outcomes *Y* are also specified in each period. The yield prediction is of the form:

$$Y_t = g(U_t, A_t, SS_t, RS_t, RR_t, \varepsilon_t)\,. \tag{2}$$

In this representation U_t are the decisions on chemical use and IRM strategy, A_t are other input decision variables such as seeding rate, fertiliser applied, irrigation strategy and the like. We consider that the yield also depends on the populations of *Helicoverpa* at the start of the period. The last factor ε_t is a random variable, which depends on temperature and rainfall factors during the crop period. The yield predictions according to *g(.)* could be derived from a model such as OZCOT (Hearn 1994) or from best estimates of agronomists.

Profit function

Net revenue from the cotton crop is represented as:

$$R_c = P_c Y - C_u - C_o - C_f \text{, where} \tag{3}$$

R_c = revenue from cotton ($/ha)

P_c = price of cotton ($/tonne)

Y = yield of cotton (t/ha)

C_u = costs involved in decision alternatives *U* ($/ha)

C_o = other variable costs (eg nitrogen, irrigation) of the crop ($/ha)

C_f = costs during the fallow ($/ha).

The fallow costs C_f exclude the costs involved in fallow strategies associated with decision alternatives *U*, which would be included in C_u.

The pest control problem

The grower's insect control problem can be written as:

$$\underset{U_t}{Max}\sum_{t=0}^{T} R_{ct} \big/ (1+r)^t \tag{4}$$

subject to:

$$SS_{t+1} = f_{ss}(.) \tag{5a}$$

$$RS_{t+1} = f_{rs}(.) \tag{5b}$$

$$RR_{t+1} = f_{rr}(.) \tag{5c}$$

and $SS_0 = SS(0), RS_0 = RS(0), RR_0 = RR(0)$. (6)

In (4), *r* is the time discount rate applied to future earnings and the discount factor applying to a dollar earned in period *t* when discounted back to time zero is $1\big/(1+r)^t$. The problem is to choose decisions in each time period that maximise the discounted sum of revenues deriving from those decisions. Then (5) can be expressed as the probability of moving from any particular state-space interval in year *t* to any other interval in year *t+1*. This information would be derived from the HEAPS model. The state transition equation (5) can be a set of probabilities of moving between states over successive periods depending on the decisions taken, the levels of stock in the first period, and on other random factors. Initial density levels of each type of moth are given by

$SS(0), RS(0), and RR(0)$.

Types of results

Gorddard et al. (1995) shows the types of results that can be derived from this type of analysis. The expected net present value of returns from cropping one ha of land using alternative IRM strategies can be derived. For any initial level of the stocks, the time path of the stock levels when following optimal decisions U^*_t can be plotted in a diagram. The nature of the optimal decisions U^*_t can also be discussed.

9. Discussion

In this paper we have set out the problem for farm-level decision-makers concerning insecticide resistance management in the Australian cotton industry. Further discussion is required in developing the decision alternatives, and in considering how the simulation models can contribute. Development of the analysis will progress in stages, the dynamic programming analysis will be specified initially for the agronomic outcomes (yield) due to insect population control without considering the genetic (resistance) effects. Once this formulation is satisfactory the resistance component will be included.

The well-known issues concerning dynamic programming associated with large numbers of state and decision variables, in terms of computing capacity, will need to be addressed as the analysis develops.

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Appendix

Chemical Groups

A wide range of insecticides is used in the Australian cotton industry. Based on their chemical structure and modes of action, insecticides are categorized into different chemical groups. Australian cotton production is mostly reliant on traditional or older chemical groups. New chemical groups are also available which are more effective in maintaining insecticide resistance and beneficial insect numbers, and in reducing the environmentally disruptive effects.

Although a wide range of insecticides has been registered for the control of insect pests of Australian cotton, current management is heavily dependent on insecticides from five classes or sub-groups. These are single representatives from the organochlorine (endosulfan) and formamidine (amitraz) classes, and several from the carbamate, organophosphate, and pyrethroid classes (Holloway and Forrester, 1998). Several new classes of insecticides such as the avermectin, biological (Bt), chloronicotinyl, diacylhydrazines, fipronil, imidacloprid, neonicotinoids, oxadiazines, phenylpyrazoles, pyrroles, spinosyns, sulfite ester, synergist (PBO) and thiourea are also now available. These insecticides have new modes of action and are likely to be more compatible with IPM and IRM (Holloway and Forrester, 1998; Shaw 2000; Fitt 2000*b*). As most of the new chemicals are comparatively expensive, growers will spray more selectively which will help to reduce the resistance risk. A list of different insecticides and their chemical groups followed by the Cotton Pest Management Guide 2000/2001 (Shaw 2000) is presented in Appendix Table1.

Appendix Table 1
The major chemical groups and insecticides used for cotton production

Chemical group	**Insecticide**
Carbamate	Aldicarb, Carbosulfan, Furithiocarb, Methomyl, Pirimicarb, Thiodicarb
Pyrethroid	Alpha-cypermethrin, Beta-cyfluthrin, Bifenthrin, Cypermethrin, Delta methrin, Esfenvalerate, Fenvalerate, Lambda-Cyhalothrin
Organophosphate	Azinphos Ethyl, Chlorpyrifos, Dimethoate, Methidathion, Monocrotophos, Omethoate, Parathion-Methyl, Phorate, Profenofos, Thiometon
Organochlorine	Dicofol, Endosulfan
Avermectin	Abamectin
Formanidine	Amitraz
Biological	*Bacillus thuringiensis*, Spinosad
Insect growth regulator	Diafenthuiron
New family	Imidacloprid
Synergist	Piperonyl Butoxide
Sulfite ester	Propargite

Source: Cotton Pest Management Guide 2000/2001 (Shaw 2000).