An economic assessment of Insecticide Resistance Management strategies in the Australian Cotton Industry

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Abstract:

Cotton production in Australia is a high-value industry with about 90% of fibre produced being exported to Asia, primarily to Indonesia. One aspect of modern cotton production is the heavy usage of insecticide sprays to combat *Helicoverpa* insects. The high cost of sprays and the public view of the industry regarding its perceived impact on the environment have led to the development of integrated pest management strategies. The measurement of insecticide resistance within insect populations has also prompted the development of insecticide resistance management (IRM) strategies. The aim of the work reported here is to improve the understanding and adoption of IRM strategies by cotton growers. This is pursued by conducting an economic assessment of alternative IRM strategies, to be used in an industry extension campaign. A farm-level dataset is used to conduct an initial analysis of alternative (relatively 'hard' and 'soft') spray options. The use of entomological and yield simulation models is investigated to pursue other analyses which can more fully account for the multi-period and dynamic nature of the problem. A full social benefit cost analysis would ideally value the environmental off-site impacts of chemical use (albeit lower under IRM), however that task is not attempted here.

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1. Introduction

A major insect pest of the Australian cotton industry since its inception is *Helicoverpa armigera* (Lepidoptera: Noctuidae). This insect causes severe damage to the cotton plant, especially the fruiting parts (flowers, buds, bolls) but also to the leaves. Control of the pest has traditionally been through the use of insecticide sprays applied throughout the growing season. In the 1970s the main insecticide groups used to combat the insect were organochlorines, cyclodienes and organophosphates, but these were prone to resistance and environmentally unfriendly (Forrester, Cahill, Bird and Layland 1993). In the late 1970s these chemicals were replaced by the pyrethroids. These chemicals had many benefits including cost-effectiveness at very low dosage rates on a broad range of agricultural and public health pests, having no residue problems, being safe to mammals, having low environmental impacts and being immobile in the soil. They were regarded by many at the time as the almost perfect insecticide. In cotton they were particularly favoured because of their contact mode of action and good efficacy against previously resistant pests.

However, in January 1983 pyrethroids failed to give good field control of *H. armigera* at Emerald in Central Queensland, and this was shown to be due to the development of resistance (Gunning, Easton, Greenup and Edge 1984). This was of major concern to the cotton industry, and to other field crop industries for which the insect is a pest. Within six months of the reported failure, a strategy aimed at containing the resistance problem had been formulated and ratified for use in the following season (Forrester et al. 1993).

Since then the issue of insecticide resistance has become more pressing, despite the use of IRM strategies. These strategies in Australia aim to manage resistance not only to pyrethroids, but also to other major chemical groups such as endosulfan and the organophosphates/carbamates. A different approach is used for each group, depending on the severity of the resistance risk and predicted selection pressure. The IRM strategy was specifically designed to fit within a broader Integrated Pest Management (IPM) program. For example, pyrethroids are avoided in the early season (replaced by 'softer' insecticides such as endosulfan, spinosad and *Bacillus thuringiensis*), so that there is minimal disruption to the early season beneficial parasitoids and predators and also to avoid the potential upsurge of secondary pests such as mites, aphids and whitefly.

There were also a number of key strategy guidelines which recommended additional non-chemical countermeasures to reduce selection pressure (Forrester et al. 1993):

- grow early maturing crops to avoid dominant *H. armigera* populations late in the season;
- avoid growing certain alternative host crops (especially early maize and sunflowers) near cotton, as they serve as early season nursery crops for resistant *H. armigera;*
- avoid consecutive sprays of pyrethroids where *H. armigera* are emerging from neighbouring early season alternative host crops, as resistance levels will be exacerbated by selection of moths before mating;
- sample over-wintering pupae under cotton stubble and cultivate should they exceed threshold;
- target pyrethroids to egg hatch, to avoid selection of older established larvae;

- check crops frequently and thoroughly and spray on threshold. This can minimise the need for sprays and ensure their maximum effectiveness through optimum timing (especially important for shorter-residue organophosphates);
- utilise host-plant resistance wherever possible; and
- if a pyrethroid is used to control sorghum midge, do not follow up with a pyrethroid for *H. armigera* control, especially as the midge spray will have already selected for pyrethroid-resistant *H. armigera.*

This integrated approach was designed to vary mortality factors so that selection pressure would not be channelled to any one control measure. There has been almost universal adoption of the strategy from its inception, it is the world's first attempt at nationwide curative resistance management. This is noteworthy because it was, and still is, only a voluntary strategy.

Despite these efforts resistance among insect populations to chemical groups continued to grow because of heavy use of the insecticides. This is a world-wide problem. At present the cotton industry is in the 3rd or 4th year of using mixtures of chemicals. This strategy has only worked on a short term basis in other countries. The industry has worked hard to reduce sprays, especially early in the season.

There are a number of control options being used that maintain the balance between the *Helicoverpa* pests and their natural predators. These 'softer' options involve not interfering with the predators early in the season by using narrower spectrum insecticides. If broad spectrum chemicals are used then beneficial insects are lost, but the broad spectrums are less expensive to apply. An important question is whether these soft options can be used more widely.

There are a number of important aspects of the current situation. First is the advent of area-wide management groups which are operating because the insects are mobile. The spray program of an individual cotton grower may be negated if insects from a careless neighbour can re-enter to cause damage. In these area-wide groups the emphasis is on reducing the use of broad spectrum sprays early in the season and the use of trap cropping on a geographically-coordinated basis.

A second issue is the availability of new products on the market. These are new groups of chemicals which are very specific to *Helicoverpa* and so cause less ecological imbalance. They are environmentally-softer products which act as stomach poisons for insects, but they appear to be less effective. There are also products such as *Bacillus thuringiensis* and viruses which are not new to the industry, but which are being used again because other products have dropped off in effectiveness.

The third issue that can be mentioned is the recent introduction of genetically modified organisms such as INGARD (Bt) Cotton. Roundup Ready Cotton is also due to be released soon. Some possible problems for cotton growers with these include the price or technology fee set by the chemical company, the extra costs of checking by consultants of the live insect balance every day, the emergence of secondary pests that aren't normally a problem, and that because there is only a single gene there is a limit on the area that can be planted to these cottons on a per-farm (around 30%) and per-region basis. Dual gene products that are currently being developed can be planted in a greater proportion of the farm area.

Other complicating factors at present are the current low price of cotton and the generally low returns from the crop last year. These income pressures are adding to the problem for cotton growers of how best to continue production for business survival when:

- conventional ('harder' programs) involve a large number of sprays (costly due to the number of sprays) to control insects, with attendant risks of increasing resistance;
- softer approaches, with very selective sprays that don't disrupt the ecology, are individually more expensive, and they involve the use of trap crops and other practices which may reduce whole-farm income;
- there is a possibility that the pyrethroids may fall over soon due to resistance anyway; and
- the harder organophosphates are causing problems on an occupational safety and health basis, and are being phased out in other parts of the world.

An important issue for the industry is to avoid using harder products up to January. The related economic question is about the cost of using soft options up to mid January in an overall program context. These costs will also include the use of area wide management and trap cropping, together with the softer chemical options. Ideally this analysis should include the longer term implications for the level of insecticide resistance or susceptibility in the insect population.

The remainder of the paper is as follows. Section 2 contains a brief review of cotton production in Australia, the types of insects and the chemical and other methods used for control, and presents some evidence of insecticide resistance. Then Section 3 contains a discussion of alternate (hard and soft) management strategies as a basis for the analysis. The next section introduces the data that will be in the analysis. Two possible data sources are available for this paper. Then in Section 5 possible evaluation methodologies are reviewed. Section 6 contains the results of the analyses, then follows a summary and conclusion section which completes the paper.

This paper is aimed mainly at a presentation of the problem and an initial analysis with readily available data. Further and more detailed analysis will be undertaken when a number of biological simulation models can be linked to produce more refined entomological and agronomic predictions of outcomes from different management strategies.

2. Cotton production and insect species in Australia

2.1 Growth stages of cotton

Cotton is at once a fibre, food, and feed crop. The cotton plant is a warm-season woody perennial shrub which is grown as an annual field crop (Kohel and Lewis, 1984). Although cotton is now modified and adapted to grow in a broad range of environments, temperature during the growing season - in terms of both range and duration - has a dominant influence on sowing date, growth rate, fruiting, yield and fibre quality. Cotton therefore does best in areas with a long and hot season. The higher the average temperature, the faster cotton will grow and develop. The longer and hotter season, the higher the potential yield (Constable and Shaw 1988). Although low rainfall is preferable - it reduces the incidence of waterlogging, plant disease and fibre quality losses - a reliable supply of water is essential for a high yielding crop (CRDC 1995).

Cotton belongs to the Hibiscus family and the cotton plant produces abundant leaves. When the flower matures it becomes a boll, and when the boll matures and dries, it is automatically broken down and the cotton fibre comes out. Each plant produces on average 10 bolls which contain about 1.5 g of cotton fibre (lint). Cotton is harvested in Australia by mechanical cotton picker and compressed into a module (a block of 8-10 tonne of seed cotton). These modules are transported to ginning mills for ginning (separation of lint and seed). Lint cotton is packed into bales weighing 227 kg. This is the commercial form of cotton.

It takes between 150 and 180 days for the cotton plant to mature for harvest from planting. But this depends on the climatic situation and variety. The planting time varies from mid September to mid October but this also varies depending on location. Plant emergence is within 7 to 14 days, then follows 1 to 2 mm of growth per day. Squaring occurs about 42 days after sowing. Flowering starts after 65 days from sowing and the last effective flowers continue until 160 days from sowing. Boll opening starts after 63 days from flowering. The pre-harvest period is considered to be after 180 days of sowing and harvesting date depends on crop condition. The growth of cotton is generally described in terms of three stages. These are Stage I (up to 10 December), Stage II (up to 10 January) and Stage III (after 10 January). The growth of cotton by stages is shown in Figure 1.

2.2 Some history of insect pests in cotton production

Cotton yields increased dramatically after World War II with the introduction of cycliodine insecticides such as DDT. More recently DDT has been replaced by other groups of chemicals including the synthetic pyrethroids, organophosphates and carbamates (Pyke and Brown 1996). Most of these chemicals kill the beneficial insects and spiders as well as the pests. Unfortunately many insect pest populations have become resistant to insecticides because repeated applications have resulted in genetic selection which favours individuals capable of detoxifying the insecticide. Use of the chemicals still kills the beneficial species, and this has led to entire cotton industries in various parts of the world collapsing because it is impossible to make a profit by returning to unsprayed conditions and the associated low yields.

2.3 Harmful and beneficial insect species

There are a number of insect pests of cotton in Australia. The main species are listed in Table 1, together with a description of their impacts and modes of action. The most important insect pests are the two heliothis species, the native budworm, *Helicoverpa punctigera* (Wallengren), and the cotton bollworm, *Helicoverpa armigera* (Hubner), and spider mites (Pyke and Brown). The cotton aphid is also an important pest that often requires control in its own right, but is usually suppressed by the chemical control measures used for *Helicoverpa*.

There are a number of parasites and pathogens of *Helicoverpa* (Pyke and Brown). Parasites include the two-toned caterpillar parasite, the banded caterpillar parasite, the orange caterpillar parasite and the orchid dupe. There are also viral diseases (eg Nuclear polyhedrosis virus), fungal diseases and bacteria that affect the larvae of various cotton pests. Bacterial infections can generally be observed after artificial infection with *Bacillus thuringiensis* (Berliner), sold commercially as Bt sprays. Predatory beetles include ladybirds, the red and blue beetle, the green soldier beetle and the green carab beetle. Predatory bugs include the glossy shield bug, the predatory shield bug, the damsel bug, the bigeyed bug, the assassin bug, the brown smudge bug, the apple dimpling bug and pirate bugs. Other predators include green lacewings, the brown lacewing, the common brown earwig, hover flies, wolf spiders, lynx spiders, nightstalking or sac spiders, the tangle web spider, the redback spider, jumping spiders, flower spiders, crab spiders, orbweavers and ants.

2.4 Insecticide use in the Australian cotton industry

The chemical groups and insecticides shown in the 1998/99 season Cotton Pesticide Guide (Harris and Shaw 1988) are listed in Table 2. The traditional chemical groups have been carbamates, organophosphates, organochlorines and pyrethroids, but newer categories such as biological actions, insect growth regulators and synergists are included.

The current recommended Resistance Management Strategy is also contained in the Cotton Pesticides Guide 1998/99. For various regions of the industry, the strategy shows the types of spray and other activities recommended to control *H. armigera* and mites in the three stages of the crop. Post-harvest activities include cultivation to destroy over-wintering pupae as soon as possible after picking. The strategies incorporate insect thresholds, sprays/mixes and application rates.

2.5 Evidence of insect pest abundance and insecticide resistance

Trends in *H. armigera* abundance for the Macquarie Valley NSW are shown in Figure 2 (source Gunning (1999)). Abundance is defined as the percentage of all *Helicoverpa* sampled which are *armigera*. From Figure 2, sample trends over the last five cotton seasons show insect numbers rising over the course of each season, reaching 100% in 1998/99. In the last two seasons insect numbers have been larger in percentage terms, and for a longer part of the season, than in the previous two years. However, in 1994/95 there was a prolonged period of abundant insects. The current season has been one of a relatively cool start climatically, so the early season insect numbers may be reduced.

The resistance of insect populations to chemical groups are shown in Figures 3 to 7 for the Macquarie Valley in NSW. The resistance frequency is the percentage of the population that survive a discriminating dose. The resistance factor is a measure of how resistant a population is compared to a susceptible strain.

In Figure 3, the resistance frequency of *H. armigera* to carbamates (thiodicarb, methomyl) has trended up over the last 5 seasons, and is getting close to 100%. For endosulfan (an organochloride) the trend in Figure 4 is flatter, but with increasingly wider fluctuations within seasons. By the end of 1998/99 the frequency had dropped relatively low in a historical context. For the organophosphates shown in Figure 5, resistance in profenfos was under 20% prior to the last season when it rose to around 30%. The chlorpyrifos resistance frequency has remained at zero for the last two seasons.

Fenvalerate and bifenthrin are both pyrethroids. Fenvalerate resistance frequency levels in the Macquarie Valley (Figure 6) are very high - between 85 and 100% for the last two seasons. The resistance factor for fenvalerate is rising. The spray windows in each season (denoted by the bar) exhibit marked increases in resistance factor. Factors of 30 to 40 indicate that the populations at these times were 30 to 40 times more resistant to the chemical than a susceptible strain. Resistance frequency levels for bifenthrin have risen steadily in the last three seasons - finishing above 50% at the end of 1998/99. In general these Figures show worrying upward trends in resistance in this valley, and similar trends are apparent elsewhere in Australia.

3. Alternative management strategies for insect pests

3.1 Integrated pest management

IPM is a crop protection system which is structured to use a variety of control procedures rather than relying only on chemical insecticides (Smith 1971). It 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. Inherent in IPM is the recognition that pest control is a complex issue requiring the integration of agronomy and ecology with soil science, chemistry and engineering. Key tools for successful IPM include population monitoring of both pest and predator species (National Farmers Federation 1997).

Although there is no unambiguous definition of what IPM means in theory, or in practice, IPM strategies in Australia generally promote four key principles to farmers:

- whenever possible, use non-chemical control techniques (eg. biological, cultural and mechanical control measures);
- spray only when the level of pest infestation reaches a threshold of economic significance, or when climatic conditions threaten a disease outbreak;
- avoid using sprays in a way that limits the effectiveness of natural controls; and
- do not spray regularly with the one chemical, because this will induce the onset of resistance to chemical (Barr and Cary 1992).

3.2 Insecticide resistance management

Insecticide resistance management is a comprehensive program of alternative management strategies which can be applied to minimising the development of insecticide resistance. Resistance occurs when an insect, fungus or weed develops an ability to survive doses of an insecticide, fungicide or herbicide that would normally have controlled it. It usually develops after frequent uses of one class of chemical (National Farmers Federation 1997).

Pesticide resistance is the ability of an insect or mite (arthropod) to survive a rate of pesticide that other individuals in the population cannot survive. This characteristic is inherited and the survivors pass the gene(s) for resistance to the next generation. The more often spraying occurs, the faster are removed the susceptible individuals and the greater the selection for a population that has mostly resistant individuals.

Resistance management of insecticides is important in the future profitability in cotton. New registrations for products are difficult to obtain and costly to develop. Application of insecticides which do not provide adequate level of control wastes money, unnecessarily increases the overall pesticide load in the environment, and exposes other insects to these products (Brazzle *et al*, 1998).

3.3 Soft versus hard management options

The term ‘soft option’ is one that describes insecticide selection procedures that aim to maintain beneficial insects while achieving effective control of pests. It includes a combination of a restricted set of selective insecticides which have a relatively harmless effect on beneficial insects compared to the alternatives. Soft option decisions are more important in the early crop (ie. pre-flowering) phases when beneficial insects are more abundant. The significance of this type of strategy is to preserve the activities of beneficials and reduce the number of insecticide sprays. This is also important in achieving IRM objectives.

The IPM Guidelines, Supporting Document 1, contained in Mensah and Wilson (1999) categorises insecticides according to their disruptive effects on beneficial groups such as predatory beetles (ladybeetles etc), predatory bugs (big-eyed bugs etc), spiders, wasps and ants, and thrips. They rated the impact (percentage reduction in beneficials following application) as: very low (less than 10%), low (10-20%), moderate (20-40%), high (40-60%) and very high (>60%) based on extensive testing over several years. According to their table, the overall effects of Bacillus thuringiensis (Bt) and NP Virus (registration pending) on these beneficials are very low. Dicofol, Pirimicarb and Spinosad effects are also low and these insecticides can be used as soft options. But Endosulfan effects on beneficials are moderate.

‘Hard option’ chemical controls can be defined as a more conventional type of spray decision where the emphasis is on cost and efficacy and where the impact on beneficials is not considered. Deutscher and McKewen (1996) define a ‘hard option’ spray as one where the spray decision considers standard or lower thresholds and the full range of available chemistry. The IPM Guidelines (Supporting Document 1) (Wilson et al. 1999) categorised a number of insecticides which show very high or highly disruptive effects on beneficials. Use of these highly disruptive insecticides can be defined as a hard option in a spray decision. According to table 1 of those guidelines, pyrethroids have very high impact on all beneficials. Carbaryl, Methomyl, the Organophosphates and Thiodicarb also have high impacts on most of the beneficials.

Deutscher and McKewen (1996) investigated hard and soft options in experiments where they tried to analyse the performance of these different approaches. They conducted early season trials from 1992/93 to 1995/96. The aim of their soft option was to preserve beneficial insects for as long as possible, and to determine whether their impact on pest numbers was sufficient to reduce the total number of sprays. The insecticides for their soft option included Bacillus thuringiensis (Bt), Endosulfan, Chlorfluazuron (before it was withdrawn) and low rates of Thiodicarb. They excluded the chemicals belonging to the organophosphates and synthetic pyrethroid groups. Their result showed that using a soft option strategy when possible to control Heliothis was not only economically viable but a more sustainable approach to insect management where similar yields can be achieved with fewer sprays.

When comparing Deutscher and McKewen (1996) with current IPM guideline for Endosulfan and Thiodicarb use (Mensah and Wilson 1999), the changes of situation over the period can be seen. Deutscher and McKewen (1996) used Endosulfan and Thiodicarb as soft option whereas current IPM guidelines identify these two as overall moderate and high disruptive insecticides respectively.

3.4 Farming systems issues

Although we are mainly considering IRM strategies that impinge on resistance or susceptibility in the insect population, the broader IPM strategy is also important. This includes issues beyond which chemical to use to address a problem, issues such as crop rotation, tillage, the use of trap crops and the area wide management strategies.

In general when evaluating individual strategies that are embedded in a broader interactive farming system, the impacts of changing a strategy may have wider implications for economic returns. The analyst must be careful to fully include these implications within the economic analysis, if possible.

The farming system used by the cotton growers within the data set is described in the next section. However the analysis conducted in this paper is preliminary, and it has not been possible to fully incorporate the whole-farm implications at this stage.

4. Data sources available for this analysis

4.1 A farm-level data set

The farm-level data set utilised in this study is from an area-wide management group of irrigators in north-west New South Wales. The group consists of nine farmers with a total area of 5,800 ha developed for flood irrigation. The 1998/99 summer cropping program consisted of 85% irrigated cotton and 13% fallow following winter cereal and 2% fallow following winter pulse.

The soil type varies from heavy black clay to grey and brown clay. Soil pH is uniform and ranges from 6.5 to 7. These soils are well suited to irrigation and no salinity problems have been detected to date. The irrigation area is situated on the floodplain of a major river in the upper Murray-Darling basin.

Cotton crop development is primarily dictated by accumulated heat and measured in units known as Day Degrees (DD = (C°Max.- 12 + C°Min. - 12)/2). The accumulated daily day degrees from October (1^{st}) to March (31^{st}) is one measure of the suitability of seasonal conditions for cotton production. The 10 year mean of day degrees for this period for this location is 2240 and the 1998/99 season day degrees totalled 2190, suggesting seasonal conditions were about average.

Farming practices within the group are typical of current trends in irrigated cotton farming towards stubble retention and minimum tillage. All growers in the group attempt to optimise inputs of fertiliser and water. All growers use professional crop consultants to advise on agronomy and pest control decisions, the nine farmers employ 6 consultants.

Spray cost information (both chemical and application costs) varied in coverage and reliability between farms. These data were standardised using external sources such as a chemical reseller's price list, and application costs from Scott (1999).

4.2 Simulation models

Dillon (1991) and Dillon and Fitt (1997) have discussed the characteristics of *Helicoverpa spp*. and described the development of a model to be used as a research tool for simulating the dynamics of *Helicoverpa* populations on a regional basis. This is the Helicoverpa Armigera and Punctigera Simulation model (HEAPS). *Helicoverpa* moths are well adapted to exploit diverse agro-ecosystems and have complex seasonal dynamics influenced by various environmental and biological factors. In cropping areas of eastern Australia, *Helicoverpa spp.* complete four to six partially overlapping generations from September to April, with a diapause (period of spontaneously suspended growth or development) during winter. Both species are highly polyphagous, feeding on a range of crop and non-crop host plants, both within and outside the cropping areas. In addition both species are highly mobile. Adult movements may occur on several spatial scales: from one field to another, between areas within a region, or between regions, depending on local conditions and the presence of suitable winds. The high mobility of these moths means that modelling population processes in heterogeneous agricultural landscapes will be enhanced if the spatial and temporal arrangements of host patches are explicitly included (see Dillon, Fitt and Zalucki (1998)).

4.3 A ranking of insecticide regimes for relative softness and hardness

The data from the farm-level data set included the number and types of sprays used in each field in the last cotton season. To quantify the degree of impact that a given insecticide regime may have had on the beneficial predatory insects within a cotton field, a ranked score was allocated to each insecticide application. The total score for each field was tallied according to the number of sprays and the spray rank score. Scores for each type of insecticide were allocated on the basis of their overall impact on beneficial insects as documented by Wilson et al. (1999). These are shown in Table 3.

The total weighted score for each field was then used to categorise the field as one where hard or soft control options were used. The 93 fields from the data set were classified according to whether they had conventional or INGARD cotton. For INGARD cotton (totalling 39 fields), the median rank score was used to delineate the hard (> 50^{th} percentile) and the soft (< 50^{th} percentile) fields. For conventional cotton (totalling 54 fields) the 33^{rd} and 67^{th} percentiles were used to delineate into hard, intermediate and soft fields. This allocation is shown in Table 4.

5. Methodologies for evaluation

The question being asked in this paper is about the economics of various options to control insects (mainly *Helicoverpa*) in cotton production in Australia. From a cotton producer's point of view, the issue is of comparing alternative IRM strategies for insect control. IRM strategies involving the use of 'harder' versus 'softer' options, with respect to chemistry, are important issues for the industry.

This issue is being driven by growing resistance to chemical insecticides among heliothis populations, especially *H. armigera*. That resistance has meant increasing numbers of sprays, and total input costs, in commercial cotton production. The implications of this are reduced profitability to individual producers (especially in times of lower cotton prices), a threat to the survival of the cotton industry, and a concern in society about environmental issues flowing from expanded use of chemicals that have varying degrees of toxicity to humans, animals, fish and birds. In particular, the issue of endosulfan use adjacent to beef production and contamination of export beef has a great deal of significance for the cotton-beef industry relationship.

Parigi (1995) reviewed analytical techniques that can be used in measuring the on-farm economic impact of IPM. The approaches reviewed were economic threshold model, marginal analysis (optimisation) model, mathematical programming models, decision theory, systems approaches and budgeting. The methods discussed below fit into some of these categories.

5.1 Two approaches to the analysis

As an initial focus for this work two approaches have been pursued, according to availability of data. One involves using a data set available from a particular area of nine contiguous cotton properties that have operated in a Landcare group with a single agricultural consultant who has collected the data. The other involves a modelling approach which investigates the use of an entomological model to predict insect population numbers and susceptibility levels from the alternative insect control strategies.

The farm level data have been provided on the basis of anonymity. This data set must be considered as a case study approach for the industry, because no sampling procedure was followed to ensure representativeness - the data were available and deemed very suitable for the present purpose. However, although it is not derived from any formalised sampling procedure, the data set can be considered as fairly typical of the industry in north western NSW. Analysis of this data is undertaken in an ex post fashion and is conducted for a single year only.

The modelling approach is an ex ante analysis, ie projecting forward over time the effects of alternative strategies. The appeal of this approach is that it attempts to account for the carryover effects in the insect population of the management strategies being tested. These carryover effects are important in an environment of rising insecticide resistance, and are not accounted for in the ex post analysis.

These are preliminary analyses for a number of reasons. First, the degree to which the analyses can represent the full complexity of the cotton decision is limited. When the IRM strategy involves changing crop rotations, growing trap or refuge crops and controlling weeds, a whole-farm analysis should ideally be used. Second, because of the mobility of insect pests, area wide management programs have been developed to make the best use of IRM to maintain susceptibility of pests and the viability of beneficials within a localised area or region. The case study of nine properties used here is from such a management group, but the analysis will not be able to account for those issues. The entomological model used in the second approach is constructed as a spatial representation of a landscape to account for area wide issues. However, in this initial analysis it will not fully utilise the spatial capacity. The last reason why the analyses are preliminary is that a full dynamic representation of the cotton production system, which includes the impact of insects on crop yield, is not yet available. The entomological model outputs are expressed in terms of insect population and genetic susceptibility outcomes, but these are not translated at this stage into consequential cotton yield effects. When that representation is possible a fuller analysis will be conducted.

5.1.1 Simple budgetary comparisons

This dataset was used to compare insect control costs and gross profit (Gross Margin or GM) for hard and soft chemical control options. The data were assessed and a number of paddocks were selected as representative of each chemical control option. A comparison of the averages of paddocks in each option was then used to provide an idea of the costs and benefits in the short term of alternative management strategies. It must be emphasised that both options are still contained within a standard IRM strategy, as recommended to the industry, but the question is about the net benefit of moving from a more traditional to a newer approach.

The hard option is representative of paddocks where broad spectrum sprays were used. These sprays are likely to kill both *Helicoverpa* pests and beneficial insects, and also to have greater environmental impacts in terms of potential damage to humans, fish, bees and other wildlife. They are likely to be less costly on a unit basis, but would be used in greater quantities (greater total cost) and would be more likely to contribute to increasing resistance in the insect population.

The soft option involves using more selective spays and applications (targeted at *Helicoverpa*), which are more expensive per unit, have less impact on beneficials and other wildlife, and probably have a lower chance of success. They would not add to the resistance problem, rather they would improve susceptibility in the insect population. Both these options have been discussed in Sections 3 and 4.

The idea in this analysis is to see what the current situation is for cotton growers with respect to spray options, and to make some initial assessments of the short term costs and benefits associated with each strategy.

There are a number of weaknesses or shortcomings of this approach. These are:

- the farming system may differ between properties, therefore care must be taken in making comparisons. There may be differences in the overall IPM strategy, in seasonal pest presure, in fertiliser inputs, and other inputs between properties that may tend to confound the comparisons between chemical control options. These could include soil types, cropping history and previous IRM strategy used. Presumably climatic variability will be standard between properties due to their close proximity;
- this analysis takes no account of outputs in terms of insect populations or insecticide resistance levels in those populations, therefore it is only a partial response to the question;
- it takes no account of the impacts of growing trap crops under a softer strategy and the impact on whole-farm profitability of the hard versus soft question; and
- as mentioned above, this analysis takes no account of the gains from area wide management of the heliothis problem.

In general this approach ignores the spatial and temporal ramifications of using different options, and in a planning context it does not look forward in an ex ante framework. However, it still provides a useful first step for the analysis.

5.1.2 Simulating IRM strategies

Dillon, Fitt and Daly (1994) have described how the HEAPS model predicts the efficacy of alternative IRM strategies. In general this is not an easy task when seasonal conditions can vary within a broad range.

The incidence of resistance is intimately tied to the population dynamics of *H. armigera* both within and outside agricultural regions. *H. armigera* populations fluctuate in response to the availability of host crops, the levels of natural and applied mortality, the proportion of resistant individuals and the rates of immigration and emigration. Resistance levels increase whenever insecticide controls exert differential mortality, by killing susceptible insects but allowing a higher number of resistant individuals to survive. Those survivors will promote resistant genes into the next generation, and they may spread resistant genes to populations in other areas. Resistance levels decrease only when non-selective controls are used and the frequency of resistant genes is diluted by immigration of susceptible individuals.

The HEAPS model simulates insecticide resistance by keeping trace of the allele and genotype frequencies in each of the sub-populations of *H. armigera* within the region being simulated. Separate tallies are kept for each life-stage. Genotype frequencies may change whenever each of the following events occur: (i) differential survival follows a simulated insecticidal control, (ii) movements of adult moths between sub-populations, and (iii) moths mating and producing new batches of offspring. The initial frequencies of each genotype for each life-stage within each sub-population must be provided by the user. The resistance module within HEAPS incorporates the following assumptions:

1. resistance is controlled by a single gene locus with 2 alleles, R (resistant) and S (susceptible). Thus three genotypes are possible, RR (homozygous resistant), RS (heterozygous) and SS (homozygous susceptible);
2. each *Helicoverpa* life stage of each genotype has a specific survivorship in relation to a given insecticide application and its residual effects. This results in differential survival of each genotype following a selective spray;
3. the relative “dominance” of the resistant allele is controlled by the survivorship that the user attributes to each genotype and life-stage combination; and
4. mating is random, so the allocation of offspring into each genotype is calculated on the basis of the allele frequencies within the parent population. Because the parent moths may have mixed origins, it is unlikely that a Hardy-Weinberg equilibrium will be maintained.

The HEAPS model has been designed as a flexible research tool. To run a simulation, the user must first define the scenario within which the model will operate. The spatial representation of the landscape within the region being simulated is described in terms of the type and size of each host patch and its distribution in space and time. Over the host patches are spread sub-populations of *Helicoverpa*, each with their own densities, demographic make-up, and initial genotypic frequencies. As the simulation runs, the model needs to be able to access weather data as this effects the development and movement of the pests. The incidence and rate of immigration into the region, and the genetic make-up of the immigrants must also be defined. The user must also define the efficacy of control applications and set rules that the model will use to trigger their use.

5.2 Another approach

Economists have long been interested in questions that are characterised by problems requiring the management of stocks of resources over extended periods in the presence of variability. Their interest has been in representing the problem as observed by a management decision maker, who must decide between alternative actions, each with a number of possible outcomes (depending on probabilities) and each outcome represented in terms of a payoff in money terms. The decision maker has an objective, usually assumed to be to maximise profit or minimise costs in a commercial framework. The problem is termed dynamic if the stock being managed 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.

In general the economic decision is an optimising one, the objective is to make as much profit (or to minimise costs) over some decision period. This is based on an assumption that these objectives are representative of real-world managers. This can be contrasted to a simulation approach, which attempts to represent the system being modelled in sufficient detail to make reliable predictions possible. The issue for applied economists who want to formulate 'best bet' decision rules for a particular management issue has been to get reliable biological or other predictions to include in the economic analysis.

In turn scientists have more often been interested in conducting R&D to improve the understanding of how a biological or other system works so that reliable predictions can be made about outcomes when particular tactics or strategies are followed. This is a basic requirement of the R&D process in understanding living systems. Once the simulation models have been constructed and validated there is an opportunity to combine the economic and biological knowledge into an analysis that will answer important questions.

The approach used by economists to answer these questions has often been dynamic optimisation. This includes optimal control theory and dynamic programming (Kamien and Schwartz 1991). Dynamic optimisation models are economic in terms of the objective function, but they are distinguished by an equation of motion or transition function. This is a biological or physical relationship which expresses the difference in stock levels between decision periods as a function of the initial stock level, the decision made and other external influences operating within a period.

5.2.1 A literature review of dynamic optimisation applied to insecticide resistance management

In this section a number of studies are reviewed regarding decision making for insecticide usage in crops when resistance is an issue. The studies are mainly by economists and address the issue of using economic optimising methods to characterise and analyse decisions by farmers with respect to pesticide applications with and without resistance being an issue.

Shoemaker (1973) discussed the optimisation problem for an agricultural pest management issue. In considering an agro-ecosystem with crops and insect life that exists in their shelter, she formulated a control model with an economic criterion (the minimisation of cost). She categorised factors within an ecosystem model, with just one crop, into those of first priority (weather, major pests and their biological control agents) and of secondary importance (insect age distribution, pesticide residue, resistance, soil moisture and nutrient levels). The state vector consisted of the pest density, parasite density and crop biomass. The various methods to control pest damage were included in the control vector (eg, amount of pesticide applied, amount of microbial pesticide applied, number of sterilised males released, amount of irrigated water used and amount of fertiliser applied). She defined *n* stages of equal length and developed a difference equation to describe the current effects of the control policy on the stock in the next period. A dynamic programming model was formulated by discretizing the state space and utilising Bellman's principle of optimality to set up and solve numerically the model by backward recursion. Storage requirements and the issue of dimensionality were also discussed.

Hueth and Regev (1974) discussed the incorporation of pest resistance into pest management models and illustrated the close relationship between the economics of pest resistance and the economics of exhaustible resources. Biological capital was viewed as the total susceptibility of a particular species to currently developed pesticides, susceptibility being defined as the negative of resistance. The optimal application of pesticides implies 'conjunctive management of both the pest and its associated stock of susceptibility' (p. 543). They assumed that pesticide may be applied at any one of an arbitrary large number of times, allowing for consideration of the dynamic properties of the economic threshold. They developed a standard discrete time optimal control problem to characterise a simplified biological model.

Hueth and Regev's interpretation of the co-state variable from their problem was that pesticide use was determined by the marginal value of pesticide use in plant growth and pest control compared to the marginal unit cost of insecticides plus the marginal cost of their use in reducing the stock of susceptibility. This latter is the marginal user cost, which changes the future costs of controlling the pest as a result of a decision to apply chemicals in the current period. This is an opportunity cost of current production, and analogous to the meaning as employed in natural resource economics. The authors showed that the economic threshold (defined as the level of pest population at which pest control is initiated) varies over time and under certain circumstances increases with time so that, the closer the harvest time the higher is the level of pest population that will be tolerated before controls are applied.

Norgaard (1976) discussed economics and IPM. Economics can enter the design of IPM strategies in three inter-related ways: (1) the pest management goals of farmers are largely economic; (2) as a science of resource allocation, economics can aid in selecting optimal quantities and combinations of pest management inputs; and (3) the economist's understanding of the incentives underlying farmer's behaviour and the effect on these incentives of alternative social institutions can speed the adoption of new pest management practices. He noted that economists are interested in the science of economics, in optimisation and economic behaviour, and that variables over which the decision maker has some control are different for the farmer, for agricultural institutions, and for society.

Norgaard developed the basic neoclassical marginalist conditions for profit maximisation, and then discussed the economic threshold concept. Noting that pesticide applications are almost always discrete, the concept of the threshold splits into two components: (1) at what pest population level should control be initiated; and (2) by how much should the pest population be reduced. It is important to distinguish the relationship between the damage threshold (the pest population level above which any economic loss occurs) and the economic threshold. The marginalist conditions require that the level of control be set at the economic threshold, since the damage threshold level may involve marginal costs exceeding marginal benefits.

However, the situation becomes more complex when it is realised that the damage threshold, which is integral to the economic threshold concept, can itself be raised by crop management using economic inputs. Management options such as changing planting dates, improve timing of irrigation and cultural practices, and use of resistant varieties, affect the economic thresholds through the damage threshold. Therefore pest management decisions are likely to become less and less separate from crop management decisions in general - the agro-ecosystem concept.

Norgaard also discussed the importance of risk aversion for agricultural decision makers, a criterion that must be weighed against profit maximisation in the long run. He referred to a widely held view that a substantial proportion of total pesticide applications occurs for insurance purposes and that perceived risk and risk aversion are the major determinants of whether or not farmers adopt new pest management strategies. He also discussed possible regional strategies which arise because of the important relationships between farmers in pest control due to pest mobility, and the likelihood of regional pest management strategies being developed if suitable institutions can be designed.

Talpaz, Curry, Sharpe, DeMichelle and Frisbie (1978) used a simulation model of the interaction between the boll weevil insect subsystem and the cotton plant subsystem in an optimising procedure to detect the optimal policy for pesticide application under deterministic conditions. Dynamic nonlinear optimisation techniques were used to solve for the optimum. The algorithm used calculated the gradient vector and the Hessian matrix numerically by repeated evaluations of the cotton-boll weevil simulation model subject to restrictions on the dose-response relationship and the economic objective function.

This approach was not concerned with resistance and did not use dynamic optimisation to solve the model. It used a dynamic simulation model and static economic optimality conditions to derive a solution.

Shoemaker (1984) presented a procedure for calculating optimal integration and timing of biological, chemical and cultural methods for control of a univoltine pest population in a random environment. She used a stochastic dynamic programming model with four state variables and a more detailed differential equation model describing the effect of management and weather on population demography and crop yield.

Onstad and Rabbinge (1985) showed how dynamic programming could be used to determine optimal solutions to models for crop disease control. They related these solutions to sets of dynamic economic injury levels which make crop management more efficient. The ability of dynamic programming to solve efficiently the sequential decision problems commonly involved in pest management systems was the primary reason for its use.

Zacharias and Grube (1986) developed a stochastic dynamic programming model to determine approximately optimal management strategies for control of corn rootworm and soybean cyst nematode in Illinois. They analysed the case of more than one crop and more than one pest being simultaneously controlled, however without considering the resistance issue. They showed that the solution to the multiple pest problem is tractable

Moffitt and Farnsworth (1987) also considered thresholds for chemical control of agricultural pests in a dynamic ecosystem. They noted that development of pest management advice was generally in terms of an insect population threshold, consisting of a rule of thumb linking pesticide treatment decisions to the pest population. Decision rules developed for farmers need to be simple and practical enough to be implemented. The action threshold is determined empirically as the minimum population level for which it is profitable to apply a pre-specified and fixed amount of pesticide (normally the recommended or label dosage rate).

They developed a simple algebraic model of a competitive farm firm to identify the action threshold, which is of the form: if the population is above the threshold then treat with the label dosage rate, if it is less than or equal to the threshold then don't treat. Potential shortcomings of this approach are that it is not necessarily derived with regard to profitability, and that it has been derived in a static framework.

Moffitt and Farnsworth then derived an approach to develop optimal advice utilising an expression for expected profit that incorporates the discrete choice nature of advice based on an action threshold, but which emphasises economic efficiency using a pesticide to manage a pest in a dynamic ecosystem. They did this by extending the action threshold concept to multi-period decision making, and included stochastic influences and an assumption that uncertainties regarding the level of stochastic factors could be captured by a probability density function. They used a conditional static rather than a dynamic model.

Regev, Gutierrez, DeVay and Ellis (1990) used dynamic programming to analyse the time evolution of pathogen density and virulence for optimal management of Verticillium Wilt in cotton in California. They used deterministic and stochastic versions of the model to analyse four different control treatments and utilised sensitivity analysis to study the economic value of controlling Verticillium Wilt in cotton.

Knight and Norton (1989) discussed the severe threat to agricultural productivity posed by pesticide resistance among anthropods. They noted that reductions in pesticide efficacy from pest resistance has major economic, environmental and human health implications, and that understanding the economics of resistance at the farm and beyond-farm levels will allow the optimal use of pesticides over time. Solutions to the problem require coordinated efforts among different groups. Pesticide resistance can influence costs and yields, and hence individual farm income, but because of pest mobility pest-control actions by one farmer affect other farmers. Pest-control activities also have significant environmental and distributional impacts on society as a whole. For economic analysis of farm-level issues, Knight and Norton identified two main types of studies - those exploring the optimal use of pesticides in light of the dynamic nature of resistance, and those examining the choice of alternative pest management strategies. Both types of analysis are concerned with the effects of resistance on pesticide productivity, or efficacy. Because of the potential for resistance, future as well as current productivity must be considered. They noted that much of the literature on economics of pesticide resistance includes dynamic optimising models which implies management of both the pest and its associated stock of susceptibility. A number of those studies (some reviewed here) were of a theoretical or simplified analytical nature. Economic analyses that incorporate spatial aspects (the possibility of pest migration) seem rare. The inherent complexity of the biological processes, and hence the mathematical complexity of the model, has constrained empirical applications, although Archibald's (1984) economic analysis of resistance in California cotton appears to be an exception. Knight and Norton state that because of the nature of the problem, a stochastic dynamic model is the preferred approach for in-depth analysis of both the optimal level of pesticide use and the choice of pest management alternatives given the existence or potential for pest resistance to pesticides.

Cox and Forrester (1992) conducted an ex post evaluation of an insecticide resistance management strategy for *Heliothis armigera* in Australia. They also discussed the susceptibility of insects to insecticides as a natural resource with unique features that are not found in other economic topics. One is non-renewability, and the other is the notion of common property. An insecticide resistance management (IRM) strategy is one that tries to delay an increase in the frequency of resistant genotypes. An issue in the analysis of IRM is the reconciliation of the conservation criterion of keeping the stock of susceptible genotypes intact with the present value criterion of economic efficiency. They emphasised the fact that a positive discount rate implies that susceptibility should be harvested at a rate that is greater than that which sustains the level of susceptibility indefinitely (ie, a responsible IRM uses up susceptibility).

The common property nature of the susceptibility resource arises because the development of resistance to a particular chemical in a pest population is an external effect associated with pesticide use, the costs of resistance are not borne by individual decision makers because insects are mobile. The use of the stock of susceptibility by one producer reduces the stock available for another producer, increasing the chances of a spray failure. Susceptibility is a common property resource which needs to be managed for the total benefit of all growers, and to the wider community. There are other kinds of externality associated with pesticide use, including environmental pollution and information about the stock of susceptibility.

Cox and Forrester defined two types of IRM in Australia, curative IRM (which aims to contain pyrethroid resistance and prevent reselection of historical endosulfan resistance), and preventative IRM (which aims to avoid any future problems with organophosphate or carbamate resistance). They described the economics of curative IRM and used two models for generating the economic benefit from investment in IRM in Australia. These were an economic surplus model and an input-saving model, both using a net present value criterion. Their results were that there were significant economic benefits to Australia from the use of the IRM strategy. They described IRM as a social technology because its impacts are felt by the whole community.

In terms of preventative IRM, they noted that a different approach is needed because of the uncertain temporal displacement of the benefits. Cox et al. (1991) used a simulation model in an 'optimisation by experimentation' approach to undertake the economic evaluation of thresholds in Phases 2 and 3 of the cotton crop growth in Australia. The SIRATAC fruit and *Heliothis* feeding models were used in the analysis to determine the optimal *Heliothis* pest thresholds defined in different ways. They noted that their procedure did not make use of a formal optimisation procedure to preselect the search space. They tested the effects of letting the pest thresholds to vary in Phase 2 of the development of the cotton crop, and showed a substantial increase in cotton gross margin. Issues such as compensation and *Heliothis* population dynamics needed to be further investigated to overcome some of their reservations of their results. They anticipated that simpler decision-support tools could be developed and calibrated from these more complex models to assist users in evaluating recommendations.

5.2.2 A future analysis

Peck and Ellner (1997) investigated the effect of economic thresholds and life-history parameters on the evolution of pesticide resistance in a regional setting. They explored the dynamics of alleles conferring insecticide resistance in agro-ecosystems in which economic thresholds are used to manage insect populations. Their single-field model results indicate that economic thresholds may have important implications for pesticide management strategies, because resistance evolution is no longer independent of the growth process.

The issue of investigating alternative management strategies with a particular economic focus is one that is being pursued in this analysis. Dynamic Programming will be used with changes in levels of insect stocks and insecticide resistance over time being predicted by the HEAPS model. A simplified analysis (in terms of management strategies, spatial scale and farming system) will initially be undertaken as an exploration of possibilities. This analysis will be undertaken assuming that cotton yields are not affected by heliothis damage, because the yield impacts have not yet been incorporated into the modelling process. Subsequent work will incorporate yield effects.

6. Analysis and results

6.1 Budgetary comparisons of hard and soft options.

The main results and budgetary comparisons are presented in Table 5. Averages for the hard and soft groups for conventional and INGARD cotton varieties are presented. For INGARD fields, cotton yield was 7% higher under soft than hard chemical options, for conventional fields there was virtually no difference. The rate of nitrogen application showed little difference between groups of fields. Average spray costs were 21% lower under soft chemistry in both the conventional and INGARD crops, respectively.

After accounting for variable costs according to the information in Scott (1999), the average GM of soft option was higher by 5 and 25% for the conventional and INGARD crops respectively. Average gross margin and yield was higher in INGARD fields than conventional fields. These trends provide a broad indication that spray costs decrease and profits increase in the soft management strategies compared to the hard strategies.

6.2 Insect pest pressure

Average *Helicoverpa* egg density for each field over the whole season provides the best relative measure of pest pressure experienced by fields in each category. Figure 8 plots the distribution of egg densities per metre experienced by fields in each of the five pest control categories within the study site in Northern NSW. The error bars denote the standard error for average densities in each category.

The mean egg densities in Conventional Hard, Conventional Soft and INGARD Hard fields were not significantly different. Conventional Medium fields had average egg densities per check that were significantly higher than the other categories, and INGARD Soft fields had significantly lower average egg density than all other categories ($p < 0.0001$). There was no evidence of clustering or spatial correlation in average egg densities experienced by each field.

It is evident from the distribution of egg densities that some individual fields experienced much higher or lower egg pressure than average. These fields will be identified and examined closely in the future to determine if their use of pesticides was appropriate. In general the spray rank categories appear to be justified with the exception of four INGARD fields that had very low pressure, and yet received pesticide ranks that placed them into the INGARD Hard category.

It is interesting that most fields experienced average densities per check of between 3 and 5 eggs per metre (Average = 4.29), and yet fields in this band applied vastly different pesticide regimes. Fields that had egg pressure in this band are represented in each of the five spray rank categories. Our preliminary results suggest that gross margins are likely to be better under softer pesticide regimes, and so it may be that there is room for improvement in the management of some fields that experienced this intermediate level of egg pressure. However we acknowledge that other factors may also affect the pesticide regime applied to individual fields. These include secondary pests – which have not been considered in this analysis, and differential pest pressure at different stages of the season. Weather conditions, previous spray history and other factors affecting the logistics of spray applications may also have a strong influence on the choice of pesticides for each application.

7. Summary and conclusions

Cotton production in Australia is heavily reliant on the use of insecticides to control a range of pests, especially *Helicoverpa*. The high cost of sprays, and increasing levels of insecticide resistance within *Helicoverpa armigera* populations have prompted the development of insecticide resistance management strategies and integrated pest management strategies.

A fundamental component of these management strategies is to reduce the amounts of pesticides applied, and to utilise pesticides that are primarily ‘targeted’ at the pest and have minimal impact on beneficial insects (predators and parasitoids). However such ‘soft’ chemicals tend to be expensive or to have lower efficacy than traditional ‘hard’ broad spectrum pesticides. Deciding the optimal pesticide to use when pests exceed economic thresholds is difficult and wrought with uncertainties.

In this paper we review the issues surrounding pest management in Australian cotton systems. We report on a preliminary analysis to determine the current situation for cotton growers with respect to pesticide options, and to make some initial assessments of the short term costs and benefits associated with alternative strategies. An area wide management group containing 9 contiguous farms was selected to avoid major agro-ecological variability. The field level data set (n=93 cotton fields) was considered as a case study approach for the Australian cotton industry as a whole.

A ranked score was allocated to each insecticide application according to the likely impact on beneficial insects, and each fields management strategy was categorised as soft, intermediate or hard. Fields containing INGARD cotton are analysed separately to conventional cotton fields. The resulting 5 management strategy groups are then compared on the basis of overall yield, pest pressure, pesticide costs and gross margins.

With respect to cotton yields, INGARD crops had higher yields under soft options. There were no significance yield differences in conventional crops that had hard, intermediate or soft pesticide regimes. But in all cases softer options showed substantially higher gross margins.

There are likely to be some differences in farming system, IPM strategy, previous cropping or IRM strategy history, and trap crop performance which have not been considered in this analysis. However the analysis conducted in this paper is preliminary, and it has not been possible to fully incorporate the whole-farm implications at this stage. Future work will involve more detailed budgetary and simulation modelling analyses. Resistance management strategies will also be evaluated using longer term and dynamic methods.

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Table 1
The major insect pests of cotton

Insect pest	Description
Native budworm (*Helicoverpa punctigera*) larvae cause early to mid season damage to terminals, buds, flowers and bolls	This is a key pest species. All spray programs are based on controlling this pest. It bores into fruiting parts causing them to drop off or rot. Larger bolls can be completely hollowed out.
Cotton bollworm (*Helicoverpa armigera*) larvae cause mid to late season damage to terminals, buds, flowers and bolls	This is a key pest species. As for native budworm. This species has developed resistance to chlorinated hydrocarbons, pyrethroids and some carbamates
Rough bollworm (*Earias huegeli*) larvae cause early to late season damage to terminals, buds, flowers and bolls	It attacks terminals and leaf axils in young plants causing malformation. Later, it attacks by boring into squares or bolls. Fungal or bacterial rots may aggravate damage
Spider mite (*Tetranychus urticae Tetranychus ludeni*) nymphs and adults cause mid to late season damage to terminals and leaves	It is present from seedling to emergence, although generally in low numbers with populations increasing from mid to late season. It feeds mostly on the undersides of leaves causing loss of photosynthetic area. Leaves often develop red pigmentation and bronzing. Cotton mites are resistant to organophosphates, but control is still possible with certain organophosphates.
Thrips (*Thrips imaginis*, *Thrips tabaci*) nymphs and adults cause early season damage to terminals and leaves	They feed by lacerating soft tissues and sucking up plant juices. Leaves become distorted and silver on the underside: terminal buds become blackened and die. Damage is greatest when dry weather in spring forces thrips off their normal hosts onto cotton seedlings.
Aphids (*Aphis gossypii*) nymphs and adults cause early to late season damage to terminals, leaves, buds and stems	They feed by piercing and sucking. Outbreaks sometimes occur on seedlings causing stunting. Heavy infestations at the end of the season produce copious amounts of honeydew which can foul lint. Female aphids lay only live young.
Tipworm (Crocidosema plebeiana) larvae cause early season damage to terminals and stems	Newly hatched larvae graze on the terminals, then later tunnel down the stem. Their main damage is to delay maturity, which may or may not be a significant problem depending on seasonal and agronomic factors. Tipworm problems are correlated strongly with the prolific winter growth of its host marshmallow, *Malva parviflora*.
Whitefly (B-type Bemisia tabaci) adults and nymphs cause mid to late season damage to terminals, leaves and stems, and contamination of lint	B-type *B.tabaci* detected in Australia. This pest can cause problems in cotton and is a serious pest in other countries (eg Pakistan and USA) where it can degrade lint into honeydew and can carry a number of cotton viruses. No infestations have yet been found in cotton, but this pest has been found on nursery lawns in some cotton towns of NSW and Queensland.

Source: Cotton Pesticides Guide 1998-99, Shaw (1999).

Table 2
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 Pesticides Guide 1998-99, Shaw (1999).

Table 3
Score ranking of insecticides used in cotton production

Insecticide	Overall impact	% reduction in beneficials after application	Score
Bt (Bacillus thuringiensis) NPV (Nuclear polyhedra virus) Aldicarb (carbamate)	very low	<10%	1
Dicofol (organochlorine) Pirimicarb (carbamate) Propargite (sulfite ester) Spinosad (spinosyn)	low	10-25%	2
Diafenthurion (thiourea)	low-moderate	20%	3
Amitraz (formamidine) Chlorfenapyr (pyroll) Endosulfan (organochlorine) Fipronil (phenyl pyrazol) Imadacloprid (chloronicotinyl)	moderate	20-40%	4
	moderate-high	40%	5
Methomyl (carbamate) Organophosphates Thiodicarb (carbamate)	high	40-60%	6
Pyrethroids	very high	>60%	7

Notes: Some additives to insecticide applications were given a score of zero as they are assumed to have no effect on beneficial insects. These included synergists and UV protectants. Applications of sugar and protein supplements like Predfood and Envirofeast were given a score of -1 because they specifically benefit predatory insects.

Table 4
Classification of case study farms by crop type and chemical option

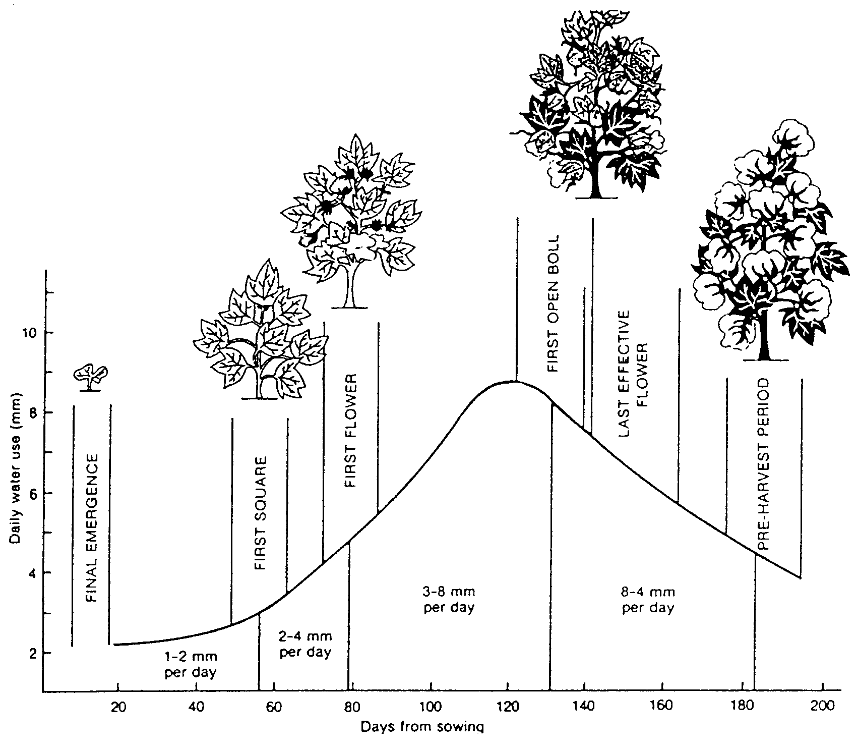
Cotton crop type	Chemical option	Number of fields	Rank (a) range	Average rank
	Soft	18	44-100	85
Conventional	Intermediate	18	110-125	119
	Hard	18	125-192	151
INGARD	Soft	20	36-76	58
	Hard	19	79-150	109

(a) The ranking for each cotton field is found by multiplying each insecticide chemical score by the number of applications of that chemical.

Table 5
Yield, costs and gross margin by chemical option groups

Cotton crop type	Chemical option	Average cotton yield	Average Nitrogen rate	Average spray costs	Average gross margin
		bales/ha	kg/ha	$/ha	$/ha
Conventional	Soft	7.44	184	765	1844
	Intermdte.	7.34	185	758	1792
	Hard	7.65	181	967	1765
INGARD	Soft	8.13	178	516	2251
	Hard	7.58	181	656	1795

Figure 1. Cotton Seasonal Calender
(Water Use Chart courtesy NSW Department of Agriculture)



| OCT | NOV | DEC | JAN | FEB | MAR | APR |

Planning - consultant, contract harvest, paddock selection

Land Preparation - fertiliser, herbicide

Planting

Emergence - 7 to 14 days

Squaring - 42 days after sowing

Flowering - 65 days after sowing

Boll Opening - 63 days after flowering >

Crop Conditioning >

Harvest >

Soil insects

Seedling insects - thrip, jassid, mirid

Tipworms, heliothis

Heliothis

Rough & Pink Spotted Bollworm

Figure 2: *Helicoverpa armigera* abundance in the Macquarie Valley

Figure 3: *Helicoverpa* resistance levels in the Macquarie Valley - carbamates

Figure 4: *Helicoverpa* resistance levels in the Macquarie Valley - endosulfan

Figure 5: *Helicoverpa* resistance levels in the Macquarie Valley - organophosphates

Figure 6: ***Helicoverpa*** **resistance levels in the Macquarie Valley - fenvalerate**

Figure 7: ***Helicoverpa*** **resistance levels in the Macquarie Valley - bifenthrin**

Figure 8: Average eggs per check over the whole season