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Economics of Insecticide Resistance Management in *Heliothis armigera* (Lepidoptera: Noctuidae) in Australia

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ABSTRACT An insecticide resistance management (IRM) strategy for *Heliothis armigera* (Hübner) has been used in Australia since 1983. An ex post evaluation is difficult because we are unsure what the outcome would have been had the IRM not been introduced. We compared the actual outcome with the projected outcome of various scenarios that captured the best available estimates concerning what would have happened without IRM or with alternative IRM strategies. We also compared two variants of the economic surplus method for evaluating the investment in IRM. Our analysis suggests that the economic benefits of the introduction of IRM have been substantial and that an IRM strategy should be designed to exploit insecticide susceptibility at an optimal rate. In Australia, the highest economic return was realized by the permitted use of three pyrethroid sprays per season. The low cost of implementing and maintaining the IRM in relation to its high rate of economic return indicated an excellent opportunity for increased investment in research into alternative IRM approaches. IRM is a social technology. The IRM in Australia is unusual because so many factors worked in its favor. The transfer of IRM technology to different socioeconomic situations might be more difficult.

KEY WORDS *Heliothis armigera*, resistance, management

USE OF CHEMICAL INSECTICIDES can increase crop yields by reducing the level of damage caused by insects. In many cases, insecticide use simultaneously selects for insects with resistance genes. The insect population becomes resistant to the insecticide, which will eventually no longer be used by growers because it does not work. Genotypes that are susceptible constitute a critical national resource (Moberg 1990); preservation of susceptibility is recognized as an important global issue (Riley 1990). Insecticide resistance is one of the constraints for the profitable production of food and fiber and maintenance of public health programs in the future (Dover & Croft 1984, National Research Council 1986). The way in which the development of resistance in insect populations can and should be managed is of current concern (Smale 1990).

The economic aspects of insecticide resistance management (IRM) must be understood if the introduction of a resistance management strategy is to be efficient. Knight & Norton (1989) provided an overview of the economics of agricultural pesticide resistance in arthropods, but we are not aware of any detailed economic evaluation of a successful IRM. As Sawicki (1989) indicated, all existing IRMs were established as emergency measures without any initial appraisal. A successful IRM for the management of insecticide resistance in *Heliothis armigera* (Hübner) in Australia has been in operation since 1983 (Forrester & Cahill 1987, Sawicki et al. 1989, Forrester 1990).

An IRM attempts to maintain genotypes for insecticide susceptibility by minimizing selection pressure in the target pest population. Minimizing selection pressure is usually achieved by restricting the use of particular pesticides to particular times or regions. Resource allocation decisions in market economies are usually made through the price mechanism. However, the price mechanism fails to value the stock of insecticide susceptibility correctly because it is not a traded commodity. This problem has been recognized by biological researchers such as Brattsten (1990), who stated, "A major problem in using chemicals is the mistaken notion that they can be used according to present-day economic marketing ideas; rather, toxic chemicals must obviously be used in accordance with biological and evolutionary processes, of which we have inadequate knowledge." An IRM tries to correct for this failure of the price mechanism. The susceptibility of insects to insecticides is a natural resource with unique features that are not found in other economic topics. One of them is nonrenewability; another is the problem of common property (Hartwick & Olewiler 1986).

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Renewability of Insecticide Susceptibility. The management of the stock of insecticide susceptibility has been considered by Hueth & Regev (1974), Regev et al. (1983), and Miranowski & Carlson (1986). In some situations, there is little doubt that susceptibility to a particular pesticide chemistry can renew itself. In others, this ability may decline with time or may be true for only a limited period. An IRM is considered successful if it can "buy time" (Hammock & Soderlund 1986, Sawicki & Denholm 1987); i.e., if it can delay an increase in the frequency of resistant genotypes.

The rate of regeneration of susceptibility to insecticides depends on the rate of use in a way such that, if we sought to maintain very high levels of susceptibility, the level of pesticide use might need to be so low that very few sprays would be applied at all. The economic benefit of the exercise would be small, but we are not usually interested in the maintenance of susceptibility to a particular type of chemical indefinitely because substitutes are already available or will be. Thus, this attitude is not simply naive technological optimism.

An IRM might seek to maintain the susceptibility of an insect population to a particular type of chemical because (1) substitutes are more expensive, (2) they are less efficacious, (3) they are less suitable (e.g., their ingestion mode of action is more restrictive or they control a narrower spectrum of pests), (4) alternative chemicals have environmental problems, and (5) we do not know how many more substitutes exist.

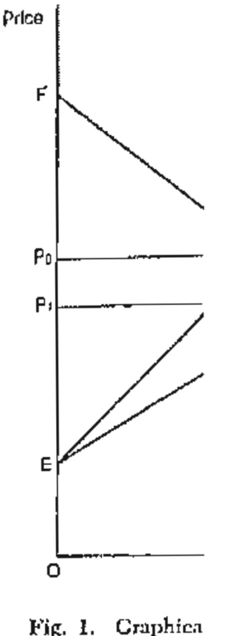
However, future benefits are valued less than present benefits because the income can be reinvested in other productive activities. Benefits received in different time periods can be compared by applying a discount rate to calculate their present value. In the analysis of IRM, we must reconcile the conservation criterion of keeping the stock of susceptible genotypes intact with the present value criterion of economic efficiency. 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 (Hartwick & Olewiler 1986). The notion that a responsible IRM uses up susceptibility is important.

Insecticide Susceptibility as a Common Property Resource. The management of pests as a common property resource is discussed by Regev et al. (1976) and by Lazarus & Dixon (1984). The development of resistance to a particular chemical in a pest population is an external effect associated with pesticide use. The externality arises because the costs of resistance are not borne by individual decision-makers; insects (including resistant ones) are mobile. Thus, use of the stock of susceptibility by one producer also reduces the stock for another producer, increasing his chance of experiencing a spray failure. The cost of consuming susceptibility is not directly related to the level of pesticide use on individual farms. Susceptibility is a common property resource which needs to be managed if the total benefit to all growers, and to the wider community, is to be maximized.

Other kinds of externality are associated with pesticide use that also pertain to this problem. The introduction of synthetic pesticides into the environment is a kind of environmental pollution which can affect anyone. The cost of pollution is also an externality but differs from that associated with reductions in the stock of susceptible genotypes because it is external to the industry, not just to individual producers. Expansion of the cotton industry in response to the successful management of insecticide susceptibility can lead to greater total pesticide use and to more pesticide in the environment. This effect occurs even though the chemical protected by an IRM may be safer than its substitute, and fewer pesticide applications per hectare are used. We do not yet know how to value the environmental costs which result. In this report, we assume that they are negligible.

The introduction of an IRM will usually depend on the incidence of the first kind of externality; i.e., where the benefits can be appropriated by the industry. However, the effects of pollution can support or detract from the benefits of introducing an IRM depending on whether the type of chemical protected by the IRM poses more or less of an environmental danger than substitutes. In Australia, the protected chemicals (particularly pyrethroids and, to a lesser extent, endosulfan) were more environmentally acceptable than possible alternatives such as the organophosphates.

A third kind of externality involves information. Extraction from the stock of susceptibility at a rate greater than the rate of regeneration yields declining annual benefits as the stock is depleted, plus information about the stock (its level, and the rate of depletion). Even if the protected chemical and the substitute technology were equivalent (in terms of price, efficacy, and environmental toxicity), it would pay to use up first the stock of susceptibility whose rate of regeneration was unknown because the process of extraction reveals information about its size and response characteristics (Hartwick & Olewiler 1986). Pest kill and information are joint products. However, the information component is an externality (in this case, a positive externality or benefit) because it will not be appropriated by individual growers but is readily available throughout the industry. This information can be important in justifying an investment in IRM (e.g., to support the argument, "We shall only know we can do it if we try.") and in maintaining it (e.g., "We are losing a valuable chemical: we must try harder to keep it.").



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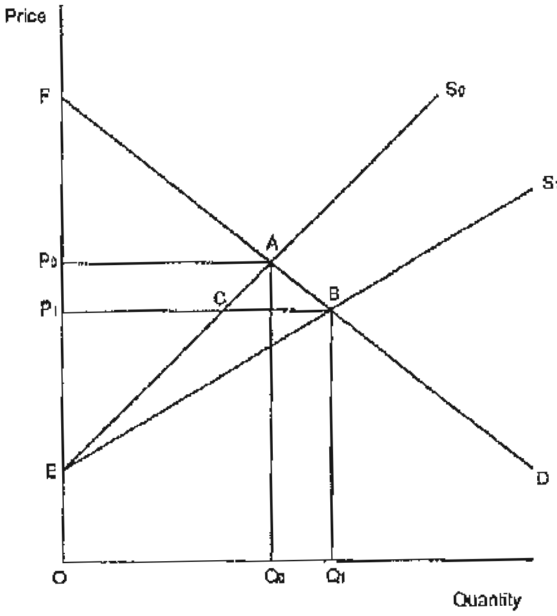


Fig. 1. Graphical illustration of changes in consumer and producer surplus in response to research which shifts the industry supply curve for a commodity from S_0 to S_1.

Analysis of Costs and Benefits of Resistance Management. Knight & Norton (1989) describe the economics of resistance management in terms of economic surplus. Several writers have used economic surplus for the analysis of alternative pest management practices (e.g., Taylor & Frohberg 1977, Taylor & Lacewell 1977, Taylor 1980).

As shown in Fig. 1, IRM is introduced to restrict the movement of the supply curve for the crop from S_1 to S_0 (so more is supplied at a given price in each time period; i.e., S_1, baseline; S_0, with resistance), a movement which would occur if resistance to pesticides developed in the insect population. The quantity term (shown on the x axis in Fig. 1) refers to total crop production in a given time period rather than to the agronomic concept of crop yield. The equilibrium price (where the supply curve intersects the demand curve for the crop) is less after the introduction of IRM because the demand curve is downward sloping. Thus, if the IRM maintains the supply schedule at S_1, consumers receive a surplus equal to the quadrilateral P_0ABP_1, the change in area above the price line and below the demand curve. Producers receive a surplus equal to the difference in the areas below the price line and above the supply curve; i.e., CBE − P_0ACP_1. This quantity is usually known as producer surplus. The economic surplus is the sum of the consumer surplus and producer surplus (ABE).

This framework for the analysis of the costs and benefits of agricultural research was first described by Griliches (1958). Edwards & Freebairn (1981) used this framework in Australia to measure the gains from rural research. The Australian Centre for International Agricultural Research (Ryan & Davis 1990) is currently using a similar framework to assist in setting of priorities for agricultural research.

IRM in Australia

In Australia, an IRM strategy was introduced in response to field failures of pyrethroids against *H. armigera* at Emerald in early 1983 (Gunning et al. 1984). The IRM concerns insect control in all summer crops in eastern Australia and was implemented to contain pyrethroid resistance, to prevent reselection of historical endosulfan resistance (i.e., curative IRM), and to avoid any future problems with organophosphate or carbamate resistance (preventive IRM). This voluntary strategy represents the world's first attempt at nationwide curative IRM, and compliance has been exceptional from its inception. An alternation strategy (with three stages) was adopted. This strategy was based on the rotation of unrelated chemical groups on a per-generation basis, along with a strong recommendation for the use of ovicidal mixtures. The middle (Stage 2) period defined a time when pyrethroids could be used. These chemical countermeasures were integrated with other nonchemical control methods (biological, agronomic, and cultural) into a workable Integrated Pest Management (IPM) program. Because of the mobility of the pest, the restrictions were applied to all crops (including cereals, oilseeds, grain legumes, tomatoes, tobacco, and cotton) susceptible to *H. armigera* and even to other coincident pest species (Forrester 1990).

Pyrethroids were introduced commercially into Australia in the late 1970s when summer crop industries were experiencing major problems with the resistance-prone and environmentally liable organochlorine, cyclodiene, and organophosphate insecticides. The pyrethroids had many benefits compared with insecticides that were then available. These chemicals were regarded as the almost perfect insecticide (Leahey 1985) because they were very cost-effective at extraordinarily low rates and had no residue problems, little adverse effect on the environment, and low mammalian toxicity (Elliott 1989). Their use was particularly favored in cotton because of their rapid contact mode of action and good efficacy against previously resistant pests. Before the IRM, pyrethroids would have accounted for at least two-thirds of the total insecticides applied on cotton. The development of pyrethroid resistance at Emerald was clearly of

Table 1. Insecticides used for control of *Heliothis* spp. larvae in Australian cotton

Chemical group	Active constituent	Most commonly used field rate, g [AI]/ha	Manufacturers–formulators
Organochlorine	Endosulfan	720	ICI, Rhone Poulenc, Nufarm, Hoechst, Incitec, Farm Oz
Pyrethroids	Deltamethrin	15	Hoechst
	Lambdacyhalothrin	18	ICI
	Esfenvalerate	25	Shell
	Cyfluthrin	40	Bayer
	Alphacypermethrin	40	FMC, Shell
	Fluvalinate	105	Sandoz
Organophosphates	Profenofos	750	Ciba Geigy, Incitec
	Chlorpyrifos	750	Dow, Rhone Poulenc
	Sulprofos	1,008	Bayer
	Monocrotophos	1,200	Ciba Geigy, Shell, Incitec
	Parathion	1,250	Bayer, Incitec, Rhone Poulenc
Carbamates	Methomyl	450	Hoechst, Shell, Incitec
	Thiodicarb	525	Rhone Poulenc
Benzoylphenylurea chitin inhibitors	Chlorfluazuron	100	ICI
Biologicals	*Bacillus thuringiensis*	n/a	Abbott

major concern to the Australian cotton and other summer crop industries.

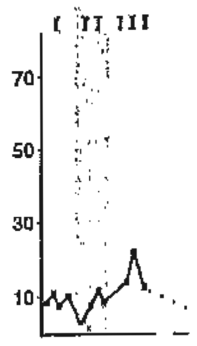
The other key product for *Heliothis* spp. control in summer crops is endosulfan. Endosulfan was discovered in the 1950s and has been used in Australia on cotton since the late 1960s. Its use has fluctuated according to its own resistance status and that of its contemporary alternatives. For example, endosulfan use increased after the development of DDT resistance in 1972, then reached a plateau because of the development of resistance to endosulfan itself. Endosulfan use decreased after the introduction of pyrethroids in the late 1970s. However, its use then escalated dramatically after the development of pyrethroid resistance in 1983 because of restrictions on pyrethroid use imposed by the IRM strategy. This transition was facilitated by the introduction of an ultralow volume formulation of endosulfan with improved efficacy in the early 1980s. Endosulfan now accounts for over half of all insecticide use against *Heliothis* in cotton (Table 1) and for an even greater proportion in the other summer crops. Like the pyrethroids, endosulfan has no residue problems but is slightly less environmentally desirable because of its acute fish toxicity. The major advantage of endosulfan is that it has little effect on beneficial insects and can be used early in the season to preserve the maximum benefit from parasites and predators without causing outbreaks of secondary pests such as mites, aphids, and whiteflies. Thus, endosulfan has a key early-season role in the Australian IRM strategy. Early-season (Stage I) endosulfan use is followed mid-season (Stage II) by the highly efficacious pyrethroids targeted to protect peak flowering and early boll set (a vulnerable period of the cotton growth cycle). Use of neither endosulfan nor pyrethroids is allowed by the IRM late in the season (Stage III).

As well as their key roles in the Australian IRM strategy, pyrethroids and endosulfan are also the least costly of the insecticides used for control of *Heliothis* species. Insect control (scouting, chemical cost, and application) accounts for about one-third of the total variable costs of Australian cotton growers (Bryant 1986, Volck & Turner 1986). These two cost-effective insecticides are the most widely used insecticides in cotton production (and other summer field crops); together, they also account for >80% of insecticide use against *Heliothis* species. Their loss to resistance would have had a major economic effect, particularly in the cotton industry.

We estimated the level of pyrethroid resistance weekly during the cotton season from the start of the IRM (Fig. 2). The percentage of *H armigera* larvae surviving the test with the discriminating dose of fenvalerate at the start of each cotton season increased from a total Stage I average of <10% in 1983–1984 to ≈25% in 1989–1990. The average Stage III percentage at the end of each season increased from 15% in 1983/84 to >60% in 1989/90 (N.W.F., unpublished data). The stock of susceptibility to pyrethroid insecticides was being gradually exhausted.

The Model

Two models of the economic benefit from investment in IRM in Australia were used. Model 1 is an economic surplus model. Model 2, an input-saving model, is a variant of the economic surplus model. Both models use a net present value (NPV) criterion. According to the NPV investment criterion, a project should be implemented if its NPV is positive in the absence of any budget constraint (Sugden & Williams 1978). The cost of establishing the IRM, and of moni-



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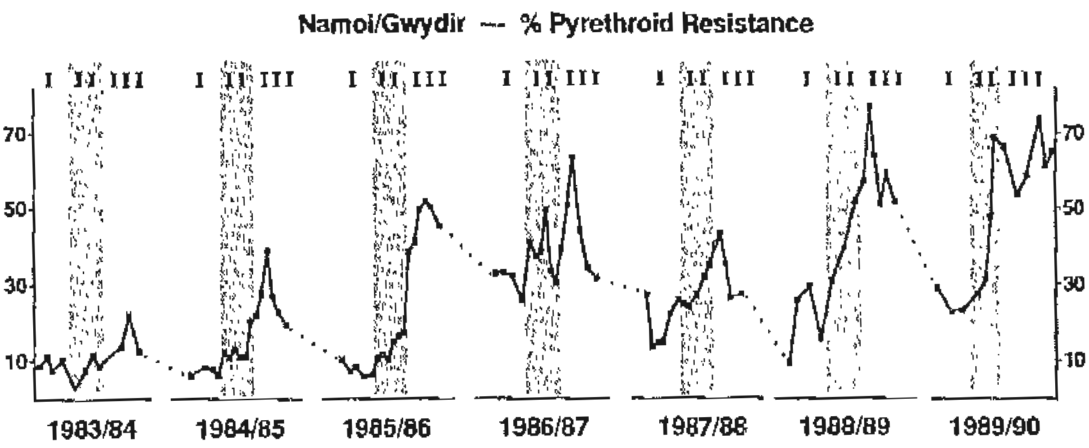

Fig. 2. Weekly pyrethroid resistance in *H. armigera* from the Namoi and Gwydir river valleys of northern New South Wales, Australia, for the seven seasons since the introduction of a curative IRM strategy (for Stages I, II, and III). Results expressed as the percentage of larvae (reared from field-collected eggs) surviving the fenvalerate discriminating dose (0.2 μg/30–40 mg larvae). *, 1989–1990 stage II pyrethroid window, 35 d duration; all others, 42 d (N.W.F., unpublished data).

toring and maintaining it, are costs borne at the industry level. We applied the models to several scenarios which related to differences in what might have happened had no IRM been introduced, and the way in which the IRM might have been implemented.

Our analysis is restricted to the effect of access to pyrethroids on cotton production. If no IRM had been introduced, we assume that the stock of susceptibility of *H. armigera* to pyrethroids would have been substantially depleted by the end of 1983–1984 (the season after the first experience of field failures following pyrethroid applications). Efficacy would most likely have been quickly attenuated to the point where pyrethroids would no longer have been regarded as a reliable control measure.

In both models, the costs and benefits are expressed in real terms (1990–1991 Australian dollars). We used a discount rate of 10% per annum for NPV calculations. Insecticide costs were assumed to be constant at 1990–1991 prices. Fine adjustment of historical price data for differences in the rate of inflation, or differences in pesticide pricing policy, in different years do not substantially affect our analysis.

The annual cost of monitoring and maintaining the IRM was about $300,000 Australian. This represents the input from both government and private sectors. It includes the cost of an entomologist, technical support staff, and laboratory facilities as well as travel necessary to monitor resistance levels and attend grower meetings. There were no initial research costs; e.g., to evaluate the efficacy of the IRM using a small-scale pilot project. The IRM has always been seen as an industry-wide attempt to manage resistance; it was all or nothing. The cost represents the direct annual cost of monitoring and maintaining the IRM. Other research programs in Australia provide information to support the strategy. The annual total of this public- and industry-funded investment in broadly resistance-related IRM research is generously estimated to be $1 million Australian. This figure is used for the sensitivity analyses.

Model 1. In the case of cotton in Australia, the economic surplus framework can be simplified considerably (Fig. 3). Cotton is traded internationally, most of the Australian cotton production is exported, and Australia is not a major producer in world terms. The level of Australian produc-

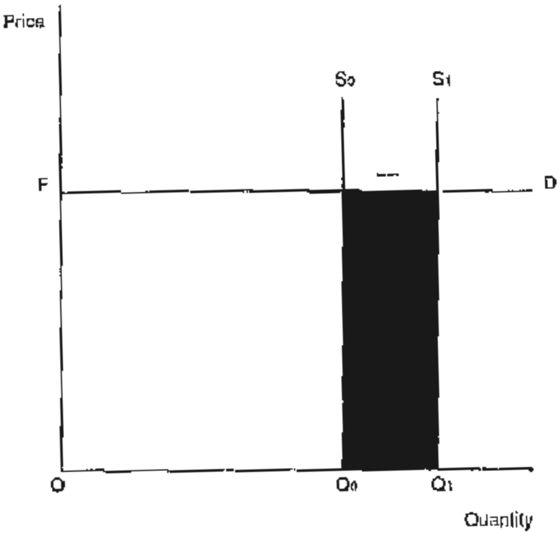

Fig. 3. Producer surplus for a traded good with elastic demand (the area between the two supply curves, the demand curve, and the axis).

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Table 2. Algebraic formulation of model 1

$$NPV = \sum_{n=1}^{n=H} \frac{1}{(1+r)^n}((Q_{with} - Q_{without})_n P_n - M_n),$$

where NPV is net present value,
n is year,
H is planning horizon (years),
r is discount rate,
Q_{with} is quantity supplied with IRM (bales),
$Q_{without}$ is quantity supplied without IRM (bales),
P is price of crop (A$/bale), and
M is establishment, monitoring, and maintenance costs (A$)

tion does not affect the world price of cotton to any appreciable extent. The annual price is determined exogenously and the demand curve is horizontal. Because there is no additional consumer surplus, we are not concerned with the distribution of the benefits of new technology between producers and consumers. The introduction of an IRM is effectively a costless transition at farm level, requiring only a change in the sequence of different types of chemicals within the overall spray regimen. The economic surplus can be estimated directly from the shift in the (annual) supply curve. This is represented by the shaded area in Fig. 3. The model is expressed in algebraic form in Table 2. The Net Present Value of the investment in IRM is the sum of the discounted annual net benefits (value of production attributable to the technology, less agency costs) over the life of the project.

We are certain that, if there had been no IRM, the Australian cotton industry would not have expanded as rapidly as it did. Indeed, it might have collapsed in the same way as the industry in the Ord River valley of northwestern Australia in the 1970s (Hearn 1975). The collapse of the cotton industry in the Ord was associated with high (and rapidly increasing) levels of resistance to DDT in the absence of a management strategy Forrester (1992), using Hearn's data, has demonstrated the economic effect of DDT resistance in *H. armigera* on cotton production in the Ord in the five seasons preceding the abandonment of cotton growing in the area. The total sprays per season increased from 15.9 in 1969 to 33.7 in 1973. The cost of insect control increased from $63 Australian/ha to $214 Australian/ha. The average yield decreased to 4.1 bales/ha, the same value as in 1969 but after reaching 4.79 bales/ha in 1971. Consequently, the breakeven price of cotton increased from $157 Australian per bale to $208 Australian per bale. Cotton production was no longer economically viable. When resistance to pyrethroids first became a problem in eastern Australia in the early 1980s, the specter of the Ord catastrophe was one of the factors which predisposed the cotton industry toward acceptance of IRM.

A similar scenario has been reported from southwestern Texas, northeastern Mexico, and Central and South America by Bottrell & Adkisson (1977). The comparison with the situation in Thailand is particularly similar. In 1983, the size of the Thai cotton industry was similar to that of Australia (Fig. 4). Problems with the development of resistance to pyrethroids appeared at about the same time in the two countries. The Thai Department of Agriculture produced a strategy of recommended alternations of pesticide chemistries to reduce the selection pressure, but the alternation was haphazard and uncoordinated (Collins 1986). Without an effective IRM, the Thai industry collapsed (Collins 1986, Sawicki & Denholm 1989). The heavy insect pressure and the very strong resistance to pyrethroids forced growers to abandon growing cotton. This decline in the Thai cotton acreage occurred despite a strong local demand for raw cotton for the booming textile industry (Wangboonkong et al. 1989; Fig. 4). With an IRM, the Australian cotton industry thrived and expanded to become a rural success story. Ironically, a portion of Australia's increased production is exported to help satisfy the supply shortfall in Thailand. Although other factors undoubtedly contributed to this difference between experiences in Thailand and Australia (such as the relatively high capitalization of the Australian industry and the ease of switching to an alternative crop in Thailand), the comparison is suggestive of the importance of managing insecticide resistance.

If the Australian cotton industry had collapsed in the same way as that in Thailand or in the Ord River Valley, the downstream costs would have been large both in terms of the accelerated depreciation of capital assets (e.g., abandoned gins, oil mills, specialized cotton machinery such as pickers and module makers) and reduced rural employment (e.g., agrochemical and equipment suppliers; crop and financial advisers; farm, gin, and mill workers) leading to massive social restructuring in the affected areas. We have not tried to account for these social costs separately in our analysis.

Furthermore, we do not know how much the growth of the cotton industry in Australia would have progressed if insecticide resistance had been managed by some other method. Other mechanisms would probably have come into play (e.g., the adoption of expensive alternative chemicals, the use of which was constrained by the pricing policy of the chemical companies [Miranowski & Carlson 1986]). These would have helped to maintain the economic benefits of resistance management, but the distribution of the benefits would have been different; a larger proportion would have been transferred to the chemical companies.

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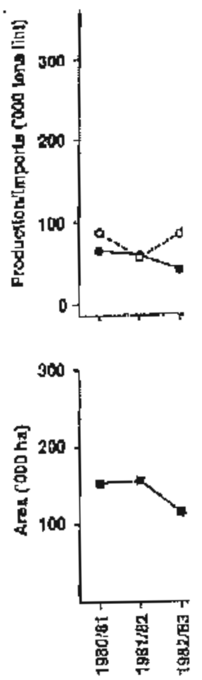

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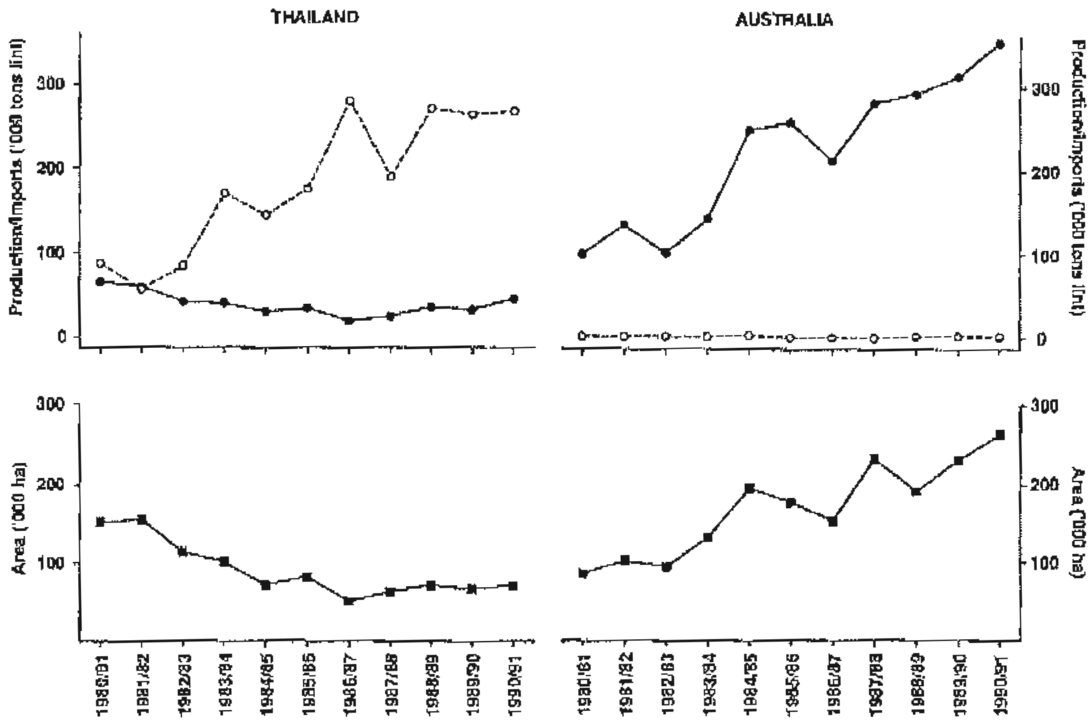

Fig. 4. Growth of Australian and Thai cotton production, area of cotton cultivation, and imports from 1980–1981 to 1990–1991 (after International Cotton Advisory Committee, personal communication; data for 1990–1991 are estimates). ■, area of cotton production ('000 ha); ○, cotton imports ('000 tons lint); ●, cotton production ('000 tons lint).

agement, we are obliged to use the best estimates provided by technical specialists. Such estimates are inevitably subjective. We considered three scenarios for the situation if no IRM had been introduced in 1983. These scenarios were that annual output of the cotton industry would have stayed at its 1983 level, the annual production would have halved from its 1983 level and remained there, and the actual annual production would have been cut by half. All three scenarios are realistic assessments of the probable course of events. They reflect both the subjective assessment at the time the IRM was formulated and the historical experience elsewhere. They differ only in our subjective evaluation of the ability of the Australian cotton industry to survive using alternative chemistries. We assumed a project life of 10 yr Data on cotton area and production were taken from ABARE (1991).

Model 2. The inputs-saved approach of Schultz (1953) can also be used for the analysis of the value of IRM in Australian cotton production. The total number of *Heliothis* spp. sprays used currently is about 8 per season (range, 6–16). Of these, 2.5 are pyrethroids, 4.5 endosulfan, and 1.0 are others (0.5 organophosphates plus 0.5 thiodicarb). If pyrethroids were lost (no IRM), the total number of sprays would increase from 8 to 12 because some of the alternative chemicals (organophosphates) have a shorter residual effect and others (thiodicarb, benzoylphenylurea chitin inhibitors) have a different mode of action (they are stomach poisons which require more frequent application than contact pesticides on rapidly growing crops). Of these 12 sprays, 4.5 would be endosulfan (there would be no opportunity to increase endosulfan use because of resistance problems with that chemical), 4 would be organophosphates, and 3.5 would be thiodicarb. Pyrethroids cost \$17 Australian/ha, organophosphates \$39 Australian/ha, and thiodicarb \$41 Australian/ha (1990–1991 prices). Aerial application costs about \$7 Australian/ha. The saving per season if the low-cost pyrethroid technology is preserved is thus \$245 Australian/ha (chemical plus application costs). Assuming linear interpolation, the cost saving per pyrethroid spray is ≈\$100 Australian/ha.

This estimate of the benefit of IRM is represented by the shaded area in Fig. 5. According to this model, the same quantity of cotton is produced both with and without IRM, but the benefit is a reduction in the cost of producing that quantity. Without IRM, the marginal cost of cotton production will increase. An algebraic formulation of model 2 is given in Table 3. The NPV of the investment in IRM is the sum of the discounted annual net benefits (area of crop grown

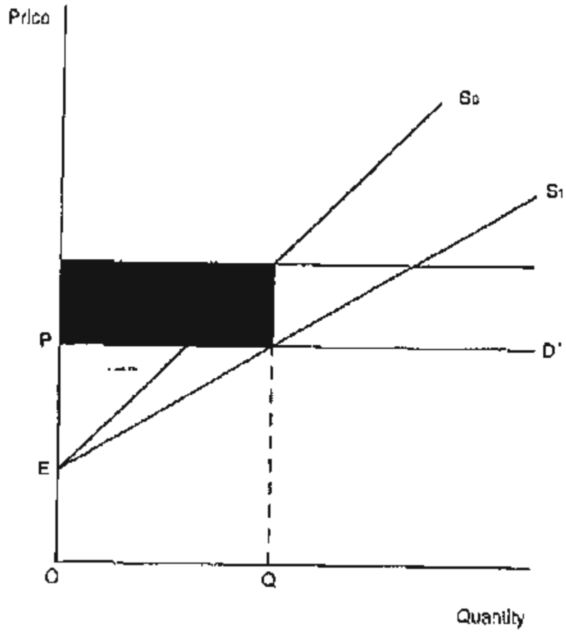

Fig. 5. Economic benefit estimated using the input-saving approach (represented by shaded area).

times number of applications of the protected chemistry per hectare times the cost saving associated with access to a protected chemistry, less agency costs) over the life of the project.

Using model 2, we considered only the value of protecting access to pyrethroids. Simultaneous loss of access to both endosulfan and pyrethroids would alter the pattern of pesticide use to such an extent that we could not predict the result. We assumed that the life of the project in years (H) was directly proportional to the number of pyrethroid sprays (Py) allowed by the IRM strategy, by the equation $H = 25 - 5Py$. The justification for this assumption rests on the subjective belief of technical specialists that, if the number of pyrethroids allowed by the IRM had been set at four, this chemical would have been abandoned within 5 yr. With three pyrethroids allowed under the IRM, it has lasted 8 yr, but distinct signs of collapse are already evident (Fig. 2). If use of only one pyrethroid had been allowed by the IRM, susceptibility could have been maintained for an indefinite period. With a discount rate of 10%, any benefits occurring >20 yr in the future can be ignored. We considered four cases corresponding with the use of one, two, three or four pyrethroid applications in the IRM pyrethroid window. The costs of establishing and maintaining the IRM are considered to be independent of the severity of the strategy and are the same as those used in model 1.

Table 3. Algebraic formulation of model 2

$$NPV = \sum_{n=1}^{n=H} \frac{1}{(1+r)^n}((C_{without} - C_{with})_n A_n - M_n)$$

where NPV is net present value,
- n is year,
- H is project life (years),
- r is discount rate,
- C_{with} is production cost with IRM ($ Australian per ha),
- $C_{without}$ is production cost without IRM ($ Australian per ha),
- A is area affected by IRM (ha), and
- M is establishment and monitoring costs ($ Australian).

Results

Model 1. Our analysis of economic surplus suggests that value of the investment in IRM has been substantial. If 1983 production had been maintained without an IRM, the NPV was $1,405 million Australian. If production had stayed at half the 1983 level without an IRM, the NPV was $3,398 million Australian. If production would have been reduced by 50% without an IRM, the NPV was $2,695 million Australian. Thus, depending on the scenario, the NPV of the investment in IRM is between $1,400 million Australian and $3,400 million Australian (mean, $2,500 million Australian). These NPVs should be seen as upper-bound estimates. Undoubtedly, such a profound change in the Australian cotton industry would have released resources for use in other production processes, although we are unsure how.

Model 2. The results of the NPV calculation suggest that a resistance management strategy based on restriction of the number of pyrethroids to between one and four all give a positive NPV. The size of the NPV depends on the number of pyrethroid applications allowed. With 1 spray, the NPV was $181 million Australian; with 2 sprays, $314 million Australian; with 3, $350 million Australian; and with 4, $240 million Australian. Thus, restriction of the number of permitted pyrethroid sprays to three gives the highest NPV (≈$350 million Australian).

Benefits estimated with the economic surplus approach are substantially higher than those estimated using the input-saving approach, partly because the direct cost savings on a fixed-spray regimen for a single chemical do not capture the full value of the technology. The IRM manages resistance to chemicals other than pyrethroids, both directly (e.g., endosulfan) and indirectly (by restricting the use of expensive pesticides because it maintains continued access to cheaper chemicals). Cox et al. (1990) estimated that loss of access to endosulfan (whether through the development of resistance or because of legislation) would cost the Australian cotton industry ≈$200 million Australian.

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The value of the investment in IRM in Australia is probably between $350 and $2,500 million Australian. This value is the NPV of the investment undertaken in 1983 expressed in 1990–1991 Australian dollars. These estimates are admittedly very crude, but whichever estimate is used, the value of the economic return has been substantial. Restriction of the number of pyrethroid sprays to three gives the highest economic return consistent with our assumptions. Three is the actual number permitted under the IRM. Necessarily, the number was determined before any economic assessment was made.

If the agency cost of the IRM is represented instead by the cost of all resistance-related research supported by the Australian cotton industry ($1 million Australian per annum), the NPV would be reduced by only ≈1%. The rate of return on research investment would still have been substantial.

Discussion

In the Australian IRM, the duration of the period when the protected chemical could be used was determined largely on biological grounds. The use of pyrethroids was confined to a single generation of the pest, thus reducing the overall selection pressure and allowing time for susceptibility to partially regenerate before the following season. In addition, the maximum number of protected sprays was specified at three at the inception of the IRM. The choice of three pyrethroid sprays (rather than two) appears rational for several reasons. First, the IRM had a better chance of being accepted if it was less severe and gave more immediate economic returns to growers; the effect was uncertain, so better to try for the greater gain. Second, the progressive increase in spray failures associated with a more liberal IRM helped to reinforce the perceived benefit of maintaining the strategy. Finally, much information was gained about the behavior of the biological processes that would have been lost if the final spray had not been marginal.

An IRM of the type used in Australia will generally be of limited duration because the optimal rate at which susceptible genotypes are used up is positive. The extraction rate will converge with the rate of regeneration as time progresses because of the increasing risk of a spray failure as the stock of susceptibility is used up. The extraction of susceptibility was achieved in Australia by targeting a single *H. armigera* generation per season. The number of applications required to do this also represents the level which maximized the economic benefits of the investment in IRM. This coincidence was not entirely fortuitous. However, as the stock of susceptibility is used up, it will lead to increasing pressure to shorten the period when the particular chemistry can be used and hence reduce the value of the net annual benefit from the IRM. This happened in Australia. For 6 yr, the period for pyrethroid use was held at 42 d; from the 1989–1990 season, the window was shortened to 35 d. The number of pyrethroid applications permitted under the IRM remained at three. Whereas 2.5–3 pyrethroids were used originally, the number used now is closer to 1.5–2.0 per season (because of the increasing incidence of spray failures rather than the shortening of the pyrethroid window). In practice, the specification of an optimal extraction rate is largely beside the point; an IRM is a holding action to preserve the use of pesticides which are cheap, effective, and environmentally sound.

Miranowski & Carlson (1986) discussed the conditions favoring voluntary multifarm resistance management. These are that pests are mobile, that the coordination costs are low, that the benefits and cost are proportional to the level of participation, and that minor benefits accrue to those who do not abide by the strategy. All of these conditions apply to the successful IRM in Australia. *Heliothis* spp. are very mobile pests (Fitt 1989). The effect of dilution from a susceptible refugia is one of the mechanisms by which susceptibility is regenerated. The coordination costs have been low. Because sprays are applied predominantly by independent aerial operators (often on the advice of third-party crop consultants), adherence to the IRM is maintained by peer pressure within the industry. The IRM guidelines are not easily violated without anyone knowing about it, and breaking the guidelines is unacceptable behavior. Few violate the guidelines. Some growers of crops other than cotton have had difficulties; e.g., the need to use pyrethroids against armyworm on wheat outside the pyrethroid window or the need to accommodate sorghum growers' access to pyrethroids for midge control. However, these difficulties are not a major threat to the IRM because the problems faced by these growers were widely recognized and every effort was made to meet their needs.

In addition, there was little opportunity for a single chemical company to manage resistance successfully because both pyrethroids and endosulfan are manufactured and marketed by several different companies, each with limited ability to increase prices (Table 1). However, compliance of the chemical companies as a group was achieved because the IRM extends the product life cycle of the generic product. Suppliers of substitute technologies also cooperated with the strategy; the higher prices which they obtain is a justification for maintenance of the IRM.

Parvin (1988) indicated two troublesome aspects of the IRM concept; i.e., that it gives chemical companies the wrong impression and actually delays the arrival of the next technological

Table 4. Characteristics of the Australian cotton industry that contributed to the success of IRM

Biological	Historical	Economic	Social
Dilution of resistant pest populations from a susceptible refugia	Experience of pesticide treadmill within industry	High capitalization of Australian cotton industry	Crop consultants widely used
Simple, effective, and sensitive method for monitoring resistance	Rapid growth of industry, with many new growers	Target chemistries low cost, efficacious, and environmentally sound compared with substitute technologies	Pesticides commonly applied by third party
IPM is standard practice in Australian cotton production		Benefits of IRM can be fully appropriated by producers	Modern progressive innovative industry open to new ideas
			Integration of industry; e.g., through ginning and marketing companies, research conferences
			Concept of stewardship
			Public concern about environmental pollution associated with pest control
			Willingness of participants to accept outside direction from credible sources

breakthrough in chemical insect control, and that the success of an IRM depends on the perception of the suppliers. If a chemical supplier perceives that IRM will fail, it will cut prices to maintain market share and revenue. If pyrethroid prices fall low enough, Parvin maintains that the IRM cannot be successful. However, neither of these considerations applies to the IRM in Australia.

First, the Australian cotton industry is comparatively small by world standards, and all the chemical manufacturers are based overseas. Any action in Australia to prolong the life of nearly obsolete chemical technologies is unlikely to influence the rate of innovation by pesticide manufacturers in Europe and North America. However, the loss of these pesticides would be a very serious matter for the Australian cotton industry. The IRM was instrumental in eliminating the assumption that novel pesticides would always be available if the current ones failed.

Second, the protected chemicals (pyrethroids and endosulfan) are already inexpensive compared with substitutes (such as organophosphates); this is an important part of the argument that maintains the IRM. Further price reductions of the protected pesticides would enhance the perceived need for an IRM and augment the cost-saving to growers. The possibility of collapse in the IRM because of a price war between suppliers of the protected chemistries emphasizes the importance of ensuring the participation of the chemical suppliers in the design and management of the IRM. IRM should not be perceived by either growers or by their suppliers as a technology which is imposed on them by higher authority, a point emphasized previously by Forrester (1990). In practice, pyrethroid use is limited more by decreasing efficacy over time. To a large extent, changes in efficacy override changes in price; if the sprays do not work, they will not be used whatever the price.

Conversely, the suppliers of the key chemicals also supply substitutes. If the supply of new pesticides is limited, the introduction of IRM will help to maintain their cash flow and profit margin through the pricing of the substitute technologies; the higher the price of the substitute, the greater the benefit to the pesticide industry of maintaining the IRM. Reduced use of the substitute technology will also help to prolong its life and the income associated with it. Thus, far from expecting a collapse of the IRM because of the pricing policy of the chemical manufacturers, we expect manufacturers to be interested in ensuring its success. Because the chemical suppliers valued the orderly marketing and predictable volumes associated with the IRM, Parvin's (1988) fears are largely groundless in the Australian context.

The Australian IRM was fortunate because its major beneficiary was the cotton industry. Many factors contributed to its success (Table 4). The realization of the benefits of IRM depended on a combination of historical, economic, and sociocultural experiences, not just the technical considerations concerning the behavior of pest populations and pesticide chemistries. For example, it is unclear what would have happened if cotton growers had been isolated and made their own decisions without the help of crop consultants, chemical resellers, and aerial operators.

The high rate of economic return generated by the introduction of IRM in Australia is consistent with the argument that agricultural research is underfunded. Additional research investment could be used to finance the development of alternative pest management technologies. Such technologies will be needed once the current

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In Australia, novel chemicals for use in summer crops will probably not be widely available until the mid-1990s, and they will be expensive. The present IRM will have only just managed to support the growth of the Australian cotton industry until the current group of pesticide chemistries can be safely discarded (≈10 yr). We have described the economics of curative IRM in response to the development of field resistance to pyrethroids. An analysis of the economics of preventive IRM is slightly different because of the uncertain temporal displacement of the benefits. An answer to this uncertainty will soon be required by the Australian cotton and summer crop industries. We must develop innovative approaches within IRM to cope with the changed situation; e.g., the use of simulation models to design and evaluate alternative strategies (Cox et al. 1991), or the marketing of product-use periods in the strategy to pesticide companies to help finance the research into IRM.

The design of any future IRM, whether in a developing or a developed agricultural system, must include recognition of the importance of commercial and regional linkages and the participation of many different actors in the design of the technology. This approach to agricultural research has been institutionalized in recent years through the development of farming systems research (Remenyi 1985). Fox et al. (1990) suggest the importance of expanding the policy dimension of farming systems research through consideration of social and macroeconomic issues. IRM is an example of a social technology. The problem facing IRM is the development of sustainable institutions (Brinkerhoff & Goldsmith 1990) to manage susceptibility to valuable pesticide chemistries.

Conclusion

Although the experience with the management of insecticide resistance in *Heliothis* spp. in Australia shows that the economic returns associated with IRM can be substantial, IRM is a social technology. The design and management of institutional sustainability is a new experience for researchers trained in the natural sciences. The appraisal of any IRM project in other countries, where the socio-cultural context and historical experience are different, must consider all of these factors. Insecticide resistance management cannot be based simply on the perceived necessity to preserve a particular pesticide without reference to economic and social forces.

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