Silver Anniversary of Resistance Management in the Australian Cotton Industry
An overview and the current situation for *Helicoverpa armigera*

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The Australian Cotton Industry has been actively practising insecticide resistance management for 25 years, with the introduction of the Insecticide Resistance Management Strategy (IRMS) in 1983. Initial focus was on *Helicoverpa armigera*, and managed resistance primarily to the pyrethroids and endosulfan. The IRMS has since evolved to include aphids, mites, and whiteflies with guidance provided also for mirids. There are now more than 18 chemical groups managed for these 5 cotton pests.

In January 1983 resistance to the pyrethroids was found to be the cause of unsatisfactory control of *Helicoverpa armigera* in central Queensland resulting in yield losses of up to 20 % in late crops. Monitoring further confirmed resistance was present in most other cotton growing regions of NSW and Queensland (Gunning *et al*., 1984). Within 6 months an IRMS had been formulated through consultation with various industry representatives and State government and CSIRO researchers (Forrester *et al*., 1993). The basis of this strategy is still being used in resistance management today.

The strategy taken to manage pyrethroid resistance was based on restricting their use to a specific period in the season, the length of which corresponded to the minimum time required to complete one generation of *H. armigera* in the field, 42 days (Room, 1983) (Figure 1). The principle was based on restricting selection to only 1 generation with other chemicals used to control earlier and subsequent generations. The cotton season was divided into stages, and as pyrethroid resistance was of greatest concern there was only one period of use for these in the middle of the season (Stage II), with a restriction of three applications. This position for the pyrethroids was chosen as it coincided with the important peak flowering/early boll set stage in cotton, and also corresponded to the peak sorghum flowering period where pyrethroids were used for sorghum midge control (Forrester *et al.*, 1993). Endosulfan was available in Stages 1 and 2, with end of season control on cotton relying on the other chemistries such as the organophosphates and carbamates. Endosulfan resistance was known to be present in populations, although not to the extent of pyrethroid resistance. This strategy involved chemical use on all crops grown within a mixed farming system incorporating cotton as it was recognised that such an approach was necessary for effective management. While pyrethroid and endosulfan resistance management were the major focus of the strategy, the overall aim was to also manage resistance to all the chemistries used against Helicoverpa (Forrester *et al*., 1993).

A number of guidelines were provided with the strategy including adding an ovicide to pyrethroids/endosulfan under high egg pressure, not following a suspected pyrethroid spray failure with another pyrethroid, and using at least 3 of the 5 available chemical groups in multiple spray crops. A number of non chemical measures were also incorporated and outlined with the strategy as part of fitting with an IPM system. Guidelines were provided regarding planting crops earlier to avoid later season *H. armigera* dominant populations. Thorough crop checking was also highlighted, as was spraying on thresholds to reduce applications by optimising their timing. Pupae sampling under cotton stubble was also recommended following by cultivation if they were found to exceed suggested thresholds.

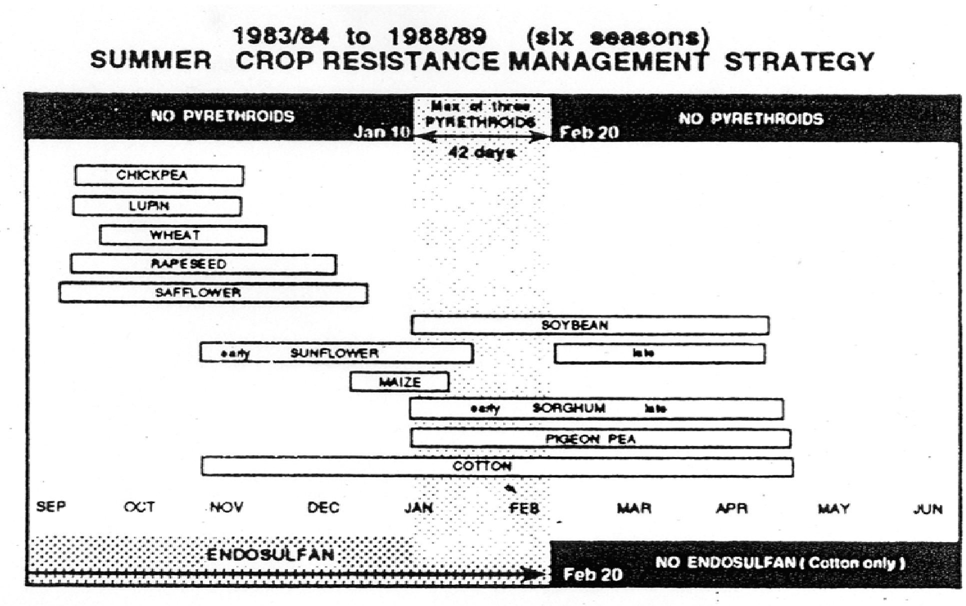

Figure 1. First IRMS developed following detection of pyrethroid resistance (source: Forrester *et al*., 1993)

This voluntary strategy was well received, with almost complete compliance by the industry faced with the very real threat of losing the important pyrethroids in a range of crops. The frequency of pyrethroid resistance was observed to stabilise at least in Stages 1 and 2 of each season, with Stage 3 resistance generally being a lot higher after pyrethroid use in Stage 2 (Figure 2). The strategy remained unchanged until in 1988/89 pyrethroid resistance was observed valley wide to have increased to end of season levels higher than previously observed (Figure 2). In addition the level of resistance in refugia, primarily unsprayed dryland crops, had also increased to levels where the annual spring dilution that resulted in decreases in resistance at the start of each season from the end of the previous one was threatened. In response the strategy was modified by reducing the pyrethroid window to 35 days (Forrester, 1990). This overcame selection across consecutive generations that had been occurring as a result of a late Stage 2 spray and the residual nature of pyrethroids (Forrester *et al.*, 1993). It also helped to reduce selection in both moths and larvae which had also been occurring. Stricter guidelines regarding pyrethroid use were also added including targeting smaller larvae which could still be killed by pyrethroids.

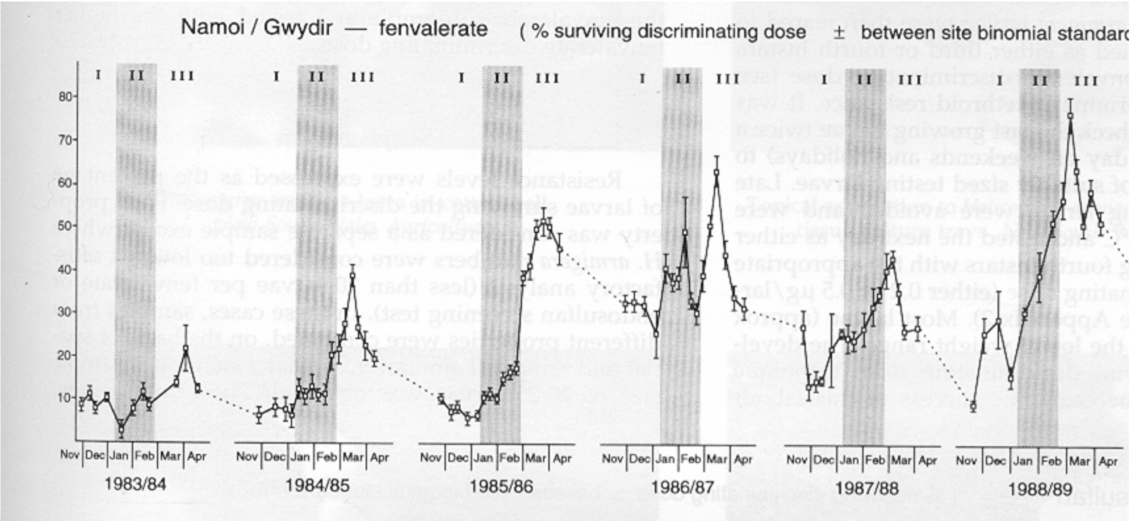

Figure 2: Pyrethroid resistance frequencies in *H. armigera*, Namoi/Gwydir Valleys, 1983-1989 (source: Forrester *et al*., 1993)

In 1990/91 the strategy was again modified slightly to incorporate the synergist piperonyl butoxide (Forrester & Bird, 1996) Resistance mechanism research had shown that the primary mechanism thought to confer pyrethroid resistance in 1983/84 of nerve insensitivity had been replaced by an enzyme mediated resistance mechanism (Gunning *et al.*, 1996). Piperonyl butoxide was shown to synergise this resistance mechanism and it was rapidly taken up by the industry, applied alternatively with foliar Bt in mixtures with pyrethroids to restore susceptibility. While this achieved the desired outcome, resistance monitoring indicated that pyrethroid resistance continued to increase. The 1990/91 strategy remained unchanged for three seasons.

The 1993/94 season saw the introduction of the LepTon® Test Kit that enabled relatively rapid identification of *H. armigera* and *H. punctigera*. This resulted in the underlying logic behind the strategy being modified from concentrating on limiting selection to just one generation to actually being able to avoid pyrethroid and endosulfan use on resistant *H. armigera* populations and using them only on susceptible *H. punctigera* populations. Pyrethroid restrictions in terms of availability as well as maximum number allowed were relaxed as early season susceptible *H. punctigera* pressure could be confidently targeted with the cost effective pyrethroids or endosulfan on their own, and the onset of *H. armigera* dominance could be detected and chemical use changed accordingly. The pyrethroid restrictions on other crops were also removed for both Helicoverpa control as well as control of other insects. As well as the obvious benefits of insect control, the relaxation of pyrethroid use and their availability earlier in the season was recognised as possibly having the adverse effect of flaring mites, aphids and whitefly by beneficial disruption. Additional guidelines were therefore incorporated that suggested avoiding early season broad spectrum sprays and if mites were present at a certain pressure to use pyrethroids that also had mite action, or alternative softer chemistries such as endosulfan or foliar Bt. This was also the first season where guidelines included information on restricting propargite use on mites because of resistance risks.

The following year, 1994/95, mite control and acaricide resistance management was incorporated into the main body of the strategy (Figure 3). This was an important first step in incorporating resistance management for other pests as it involved accounting for insecticides that had both mite and Helicoverpa action, and positioning them for use in the strategy for one pest in a way that didn't adversely affect resistance management for other pests. Acaricide resistance management did not involve restrictions over time, but focussed on non-consecutive use of these chemicals due to the shorter life cycle of mites. Controlling weeds on farms to reduce alternative mite hosts particularly for overwintering populations was also added to the guidelines.

In 1995/96 while there were minor changes to the strategy, including voluntary removal by the industry of chlorfluazuron because of contamination issues in beef, a major change related to the use of pre-flowering thresholds. In order to decrease selection pressure early season thresholds were increased from 1 to 2 larvae per metre following research that indicated plants pre-flowering could tolerate more damage without yield losses later on. Despite reservations that the threshold was too high and would lead to problems controlling larger larvae later, this recommendation was taken up by the industry driven by the worsening resistance situation. 1996 also saw the formation of a formal committee to oversee the strategy, supported by the ACGRA and composed of representatives from all aspects of the industry. This committee, the Transgenic and Insect Management Strategy Committee (TIMS), deals with both insecticide and transgenic resistance management and is composed of further subcommittees that provide technical advice and support to the main committee.

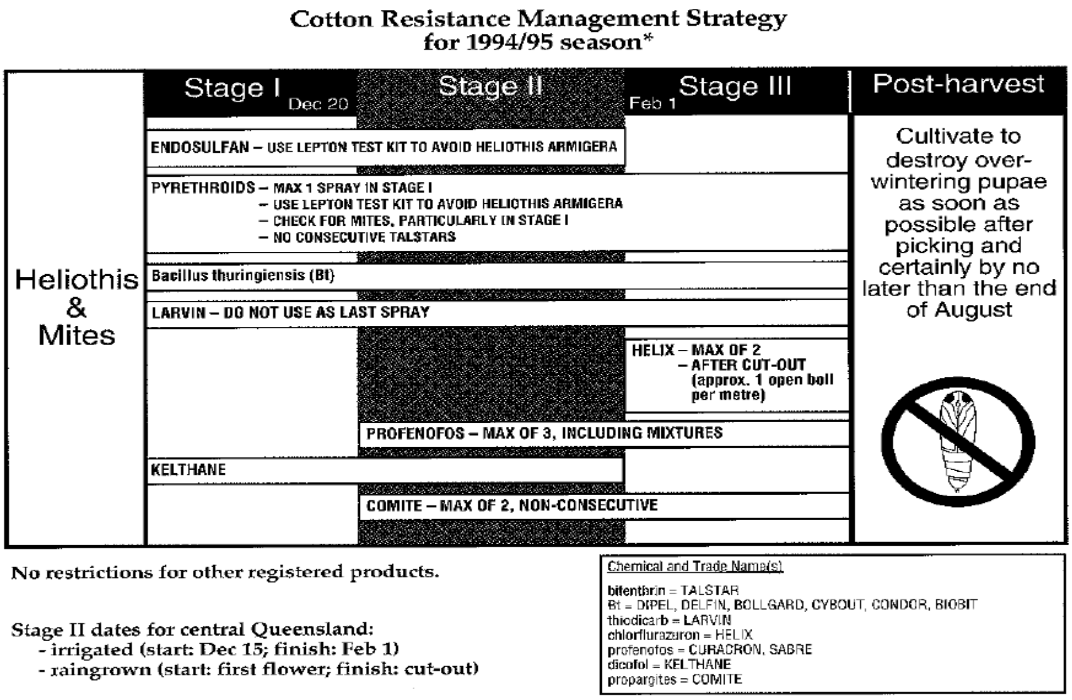

Figure 3. 1994/95 IRMS incorporating mites into the Heliothis strategy.

Despite the threshold changes and restrictions on chemical use, resistance to endosulfan and the pyrethroids continued to increase and carbamate resistance also emerged as an increasing problem. Over the next two seasons further restrictions were applied to these chemistries in relation to period of use and number of maximum applications permissible. There were also restrictions imposed on the soft foliar Bt option due to the introduction of the transgenic Ingard® cotton, making foliar Bt not available for use on Ingard® or Ingard® refuge crops which were commonly sprayed cotton (Forrester, 1998). This resulted in increasing pressure on the alternative chemistries.

With an increasing focus on using non chemical tools for insect control and the taking of a more IPM approach that utilised all control options, the 1998/99 season saw the introduction of the first of several truly soft chemical options with the registration of the active spinosad (Tracer™). This was made available across the whole season to allow for its best period of use to be determined, an approach which is generally still taken for new chemistries unless there is an already identified risk with a particular chemical. This season also saw the complete removal of pyrethroids early season in Stage 1 to account for IPM and beneficial preservation, made possible by the introduction of spinosad. There was also a restriction placed on Helicoverpa sprays of 2 maximum consecutive sprays of the one chemistry, to reduce selection pressure and encourage rotation. Foliar Bt was also reintroduced for use on Ingard® crops and refuges in Stage 1 only as a soft option particularly in environmentally sensitive areas, such as where endosulfan was not an alternative due to proximity to beef cattle.

Aphid resistance management was incorporated into the strategy in 1999/2000 following increasing concerns regarding resistance (Figure 4). Again like mites, management focussed on rotation of chemistries because of the short life cycle. Additional soft chemical options for Helicoverpa were introduced over 1999-2001, including the viral formulation Gemstar®. These soft options provided an alternative for spinosad in an industry increasingly taking up an IPM approach through preservation of beneficial predators and parasitoids. Despite these alternatives there was more experience with spinosad which was a popular chemical choice and in 2000/2001 its use was restricted in an attempt to curb increasing resistance frequencies that were causing control problems in the field (R. Gunning, unpublished).

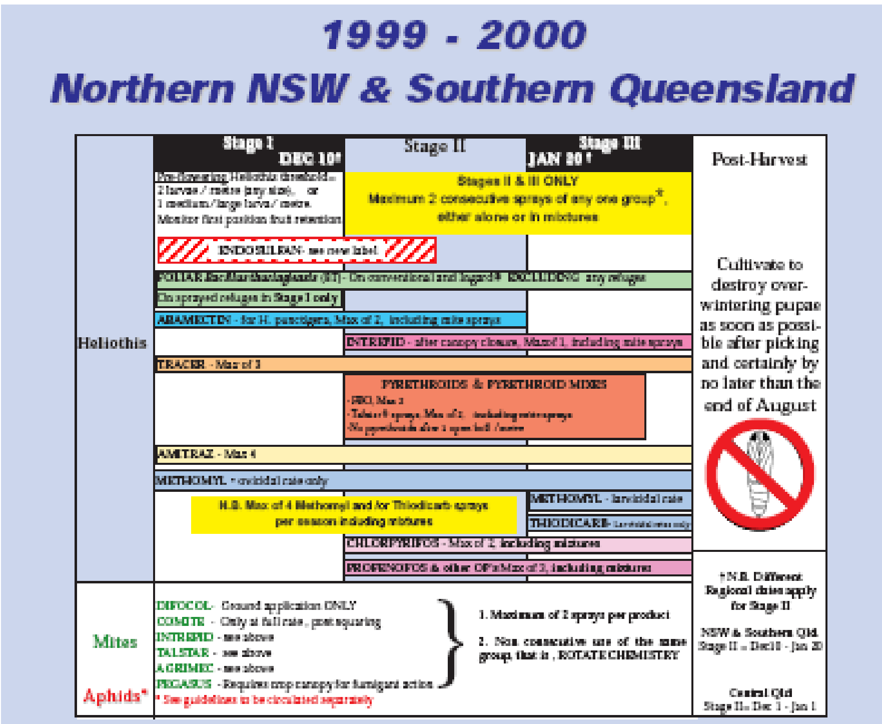

Figure 4. 1999-2000 IRMS showing incorporation of aphids into strategy.

The following seasons saw more soft options introduced for control of both Helicoverpa and aphids and mites, and the older harder chemistries were pushed for use further into the season. The LepTon® test kit for identifying Helicoverpa species was also removed from the market, removing the ability to rapidly determine which species dominated insect pressure. This removal was primarily because it wasn't commercially viable, however with the removal of pyrethroids from early season use and the availability of multiple soft options that had equal efficacy on both species, this removal did not cause the problems that it might have back when pyrethroids and endosulfan were the mainstay chemicals for use against Helicoverpa.

The introduction of Bollgard II® transgenic cotton in 2003 and its subsequent widespread uptake in following seasons has resulted in a significant reduction in insecticide use for Helicoverpa control. While the windowing of chemicals for Helicoverpa control has remained, the practicalities of cotton production and the increased chemical options available (plus Bollgard II®), has resulted in a lengthening of most of these windows corresponding to within approximately two generations. With sprayed conventional cotton currently representing a small proportion of total cotton production, guidelines regarding pupae busting have also been amended to pupae bust only those crops that haven't been harvested by March 9th, based on the QLD DPI&F developed Helicoverpa Diapause Induction and Emergence Tool (http://tools.cottoncrc.org.au/cl2/diapause/index.aspx).

Underlying all amendments to the IRMS are the results of the insecticide resistance monitoring program conducted annually by NSW Dept. of Primary Industries. This program provides information on resistance frequencies for all insecticide groups used against Helicoverpa, and provides a measure of the success of the IRMS. Resistance frequencies for *H. armigera* have decreased in the last 5 years for a number of insecticides (Figure 5). The results of the 2007/08 resistance monitoring program indicated that resistance frequencies to the key IPM compatible insecticides of spinosad (Tracer™), indoxacarb (Steward®) and emamectin benzoate (Affirm®) are very low, which for spinosad particularly represents a significant turnaround. Likewise resistance frequencies to the synthetic pyrethroid bifenthrin (Talstar®) have decreased significantly, with no resistant individuals found this last season. This finding however cannot be extended to all synthetic pyrethroids as testing with fenvalerate, used as a general pyrethroid indicator, returned a high frequency of resistance. In addition, bifenthrin resistant individuals did not exhibit cross resistance to fenvalerate.

Monitoring for other insecticides (endosulfan, carbamates, organophosphates) likewise suggests lower resistance frequencies than observed in 2006/07. *H. punctigera* remains insecticide susceptible.

The 2008/09 IRMS has been formally approved by the TIMS committee, with minor changes from the 2007/08 IRMS. These include an extension of the abamectin window by 15 days in Central, Southern and Northern Regions (for use on mites later season) and the addition of Altacor®, a new Helicoverpa insecticide that will be registered for use in 2008/09.

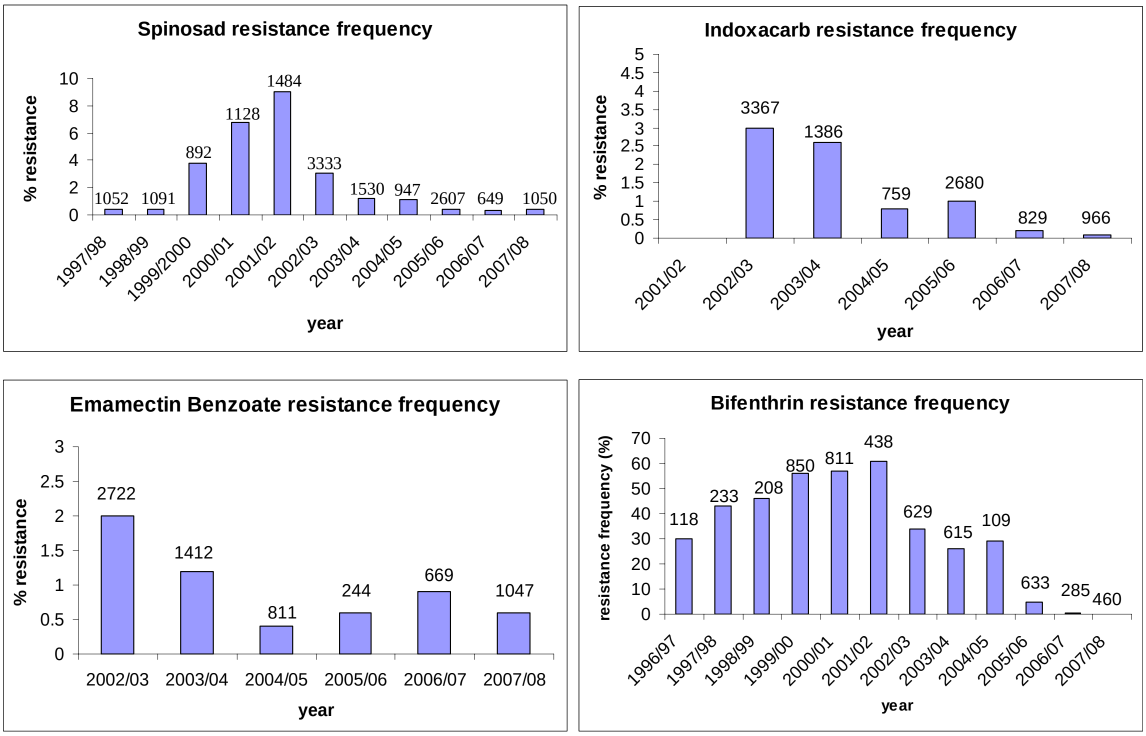

Figure 5: *H. armigera* insecticide resistance frequency trends over time (numbers above bars indicate no. of larvae tested).

Despite the widespread uptake of Bollgard II®, reduced insecticide use and the current situation of low/decreased insecticide resistance frequencies, it is imperative that insecticides continue to be managed to remain efficacious and available for use. Likewise, continued insecticide resistance monitoring is vital to provide the necessary information as to the success of resistance management tactics and insecticide efficacy. The industry has made enormous achievements in the area of both pest and resistance management, with the result that the newer chemistries that have become integral in Helicoverpa control have not succumbed to resistance. Conventional cotton may only currently comprise a small area relative to total cotton production, but it is an important component and relies on insecticides to protect it from Helicoverpa. Insecticides have likewise been applied on occasion to Bollgard II® crops over the last 5 years and users must be confident the products will provide control. Like insecticides, resistance is an ever present threat for transgenic cotton, and if the technology were to be threatened by a high frequency of resistance to either one of or both toxins in Bollgard II®, increased use of insecticides for Helicoverpa control could be required. Finally insecticide use for Helicoverpa control is not limited to cotton, and the cotton industry must ensure their insecticide use does not adversely affect efficacy for other industries, and vice versa. Both Tracer and Steward are two of the IPM compatible insecticides that are now registered in a range of pulse and/or grain crops, and there is the potential for selection to occur over several generations from spring through to autumn. It is important therefore lessons are learned from the past and principals of good resistance management are adhered to when applying insecticides targeting Helicoverpa. There are so many variables and unknowns to be accounted for as there always has been that the industry must continue to be proactive in the way it manages resistance.

References:

Forrester NW (1990). Strategy change for the 1989-90 insecticide resistance management strategy for Heliothis. NSW Dept. of Agriculture Advisory Note

Forrester NW, Cahill M, Bird LJ, and Layland JK (1993). Management of pyrethroid and endosulfan resistance in *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Australia. *Bulletin of Entomological Research, Supplement 1.*

Forrester NW and Bird LJ (1996). Conventional insecticide and Bt transgenic resistance management in Australian cotton. *Proceedings, Eighth Australian Cotton Conference*, 14th-16th August 1996, pages 159-172

Forrester NW (for ACGRA TIMS committee) (1998). Changes to the resistance management strategies for conventional insecticides and Bt transgenic cotton (1997/98 – 1998/99). *Proceedings, The Ninth Australian Cotton Conference*, 12th-14th August 1998, pages 247-262.

Gunning RV, Easton CS, Greenup LR and Edge VE (1984). Pyrethroid resistance in *Heliothis armiger* (Hubner) (Lepidoptera: Noctuidae) in Australia. *J. Econ Entomol* **77**: 1283-1287

Gunning, RV, Moores, GD & Devonshire, AL. (1996). Esterases and fenvalerate resistance in Australian *Helicoverpa armigera* (Hubner) Lepidoptera: Noctuidae. *Pestic. Biochem. Physiol*. 54: 12-23.

Room, PM (1983). Calculations of temperature driven development by *Heliothis* spp. (Lepidoptera: Noctuidae) in the Namoi valley, New South Wales. J. Aust. Ent. Soc. 22: 211-215.

Acknowledgements

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IRM Strategies from 1990/91-present are available on the Cotton CRC website - www.cottoncrc.org.au