Implementing IPM in Australian cotton

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ABSTRACT

*The Australian cotton industry continues to face a number of challenges in pest management. These include insecticide resistance in the primary pest (*Helicoverpa armigera*) and secondary pests (mites and aphids), escalating costs of production, and environmental concerns. To help address these issues a major research effort has focused on reducing dependence on insecticides through the development and implementation of IPM systems. The IPM approach taken integrates all farm management activities, both through the cotton season and the 'off' season, so that they contribute toward the goal of reduced insecticide use. Conservation and utilization of beneficial insects is emphasized. The development and implementation of this approach involved extensive interaction between cotton growers, pest management consultants and government researchers. This ensured it was practical, included current research outcomes and encouraged a farming-systems and participatory philosophy thereby reducing the tendency to become 'entomology-centric'. Profitability and sustainability are emphasized so both input costs and yield are considered, rather than the traditional emphases on maximizing yield. Key elements through the growing season include use of early season trap-crops to reduce *H. armigera* abundance, optimal planting time, regular crop checking for pests, plant damage and beneficial insects, integration of predators into decisions using a predator/pest ratio, use of beneficial refuges and attractant food sprays to enhance predator numbers, use of combined pest and damage thresholds, strategic use of plant growth regulators, optimal water management to avoid extended late season growth, preferential use of more selective insecticides, use of genetically engineered Ingard® cottons expressing the delta-endotoxin genes from *Bacillus thuringiensis* subsp. *kurstaki* (Bt), and an effective resistance management strategy. Key elements in the 'off season' include destruction of diapausing pupae of *H. armigera* which may be a reservoir of resistance genes into the next season, selection of rotation crops to reduce pest carry-over, management of weeds and cotton regrowth that are over-wintering pest hosts, optimization of fertilizer strategies to avoid excessive plant growth, matching of cotton varieties to regions and pest complexes, a spray drift management plan and the selection of appropriate insecticide seed treatments. Adoption of an IPM approach, incorporating many of the elements above, has had a dramatic uptake over the past four years. This has been fostered by the development of regional IPM groups, where groups of growers agree on core goals and communicate throughout the season to achieve them, for instance delaying use of disruptive pyrethroids. Further support has come from a focused extension effort, information tools such as the Australian IPM Guidelines (http://www.cotton.crc.org.au), DSS and favorable economic analyses of IPM versus traditional approaches. The development of transgenic cotton with two Bt genes (Bollgard II®) and increased commitment to IPM bodes well for the future sustainability of Australian cotton. However, as the system changes, the pest complex also changes and sucking pests, formerly suppressed by sprays targeted against *Helicoverpa* are emerging as new challenges, threatening IPM. The fundamental role of IPM in reducing pest pressure and insecticide use means that its continued evolution and use is critical to the future viability of both transgenic and conventional cotton production*

Introduction

The Australian cotton industry continues to face a number of challenges in pest management. These include damage due to a number of pests from including *Helicoverpa armigera* and *H. punctigera*, spider mites (*Tetranychus urticae*), aphids (*Aphis gossypii*), thrips (*Thrips tabaci*, *Frankliniella schultzei* and *F. occidentalis*), and mirids (*Creontiades dilutus*), insecticide resistance in the primary pest (*Helicoverpa armigera*) and secondary pests (mites and aphids), escalating costs of production, and environmental concerns over off-farm movement of insecticides. To help address these issues a major research effort has focused on reducing dependence on insecticides through the development and implementation of integrated pest management (IPM) systems. Common to IPM systems in other cotton producing countries and in other crops, the Australian cotton IPM system emphasizes the use of a range of tools to help manage pest populations, with insecticides seen as a last resort. What is unique about the approach taken in Australia is the heavy involvement of cotton growers and consultants in the development of the system, the emphasis on incorporating IPM as a component of the overall farming system and the development of IPM groups (groups of growers who agree on a common set of aims related to IPM and who communicate and support each other to achieve them). This participatory action research approach provides a framework for engaging research with industry (Dent, 1995).

During the 1980's and early 1990's the SIRATAC computerized decision support system fostered the shift from prescriptive insecticide use to more IPM-based systems including rigorous pest sampling, incorporation of plant compensation, the use of pest thresholds and the selection of the control option with the least disruption to beneficial populations (Hearn and Bange, 2002). During the early to mid-1990's a range of different IPM components were gradually developed and extended to the cotton industry, including tolerance of early season damage (Sadras and Wilson, 1998), avoidance of broad-spectrum insecticides early in the production cycle (Wilson *et al*., 1998), use of beneficial arthropod nurseries (Mensah, 1999), use of food sprays to attract beneficials (Mensah, 1997), cultivation of cotton post-harvest to kill diapause pupae of *Helicoverpa armigera* in the soil which may carry resistance genes from one season to the next (Fitt and Daly, 1990). However, the lack of an explicitly elucidated IPM system meant that growers were left to incorporate these concepts piecemeal into their farming practices. The concept of IPM, though referred to in extension publications repeatedly remained undefined and there was no clearly and consistently elucidated system that could be explained to industry. This paper briefly outlines the efforts to develop a workable IPM system for cotton in Australia, the approach taken, the delivery of that approach to industry and the uptake and success of this approach.

Developing the IPM framework

To address the pest management challenges confronting the cotton industry the IPM system needed to (i) reduce insecticide use (ii) maintain crop yield and earliness of maturity (iii) maintain the susceptibility of pests to new selective insecticides (iv) be practical and workable and (v) be effective both for conventional cotton and transgenics. It is worth noting that earliness of crop maturity is a controversial topic. In addressing these goals the approach developed promotes four key principles, firstly the conservation and utilization of beneficial insects, secondly, the preferential use of selective insecticides, thirdly, profitability and sustainability are emphasized ensuring that both input costs and yield are considered, rather than the traditional emphasis on maximizing yield and finally integration of all farm management activities, through both the cotton season and the 'off' season, so that they contribute toward the goal of reduced insecticide use. This approach has been captured in the 'Guidelines for Integrated Pest Management in Australian Cotton' (Mensah and Wilson, 1999).

The development and implementation of the IPM framework flowed from a meeting of a core group of growers, consultants, extension officers and researchers committed to IPM, called in response to the difficult 1998/99 season. The extensive interaction between cotton growers, pest management consultants and government researchers ensured that the final result was practical, included current research outcomes and encouraged a farming systems philosophy. From this meeting a draft document was developed and circulated widely amongst all sectors of industry, including growers, consultants, extension and research staff and the agrochemical industry for feedback and revision before the final document was published and disseminated throughout the industry via mail-outs and being placed on the Australian Cotton CRC Website. This process has provided a clear foundation on which both industry and research can (i) engage in discussion and communication about issues relating to IPM and influence research direction and (ii) provides a clear mechanism in which to apply new technologies relating to IPM or other parts of the farming system that can influence IPM.

The system developed, partitions the cotton season into five key periods; planting to first flower, first flower to first open boll, first open boll to harvest, post harvest, pre-planting. The three first periods deal with the growth cycle of the crop. The final two deal with the off-season or 'winter' period. The inclusion of the winter period was regarded as essential as many actions taken through this period have important implication for the success of IPM endeavors during the following growing season. A critical feature is the incorporation of a range of agronomic, varietal and physiological issues that arise as part of the farming system and which are not normally thought of as IPM tools but which influence the likely success of the IPM system.

For simplicity, the key tools and the rationale are briefly explained below for the growing season as a whole, and for the winter as a whole. More detail can be found in Mensah and Wilson (1999). It is important to note that the guidelines produced provide a structure to identifying issues that are relevant to that particular time-period or that need to be taken in order to have a tool ready for a later period.

IPM Strategies through the Growing Season

Key elements through the growing season include:

1. **Use of early season chickpea trap-crops to capture eggs from *H. armigera* moths that emerging from their over-wintering diapause** (Ferguson *et al*., 2000). These moths are the carriers of resistance from one season to the next.
2. **Planting at the optimal planting time, which for most Australian regions is early October.** Planting outside this window generally adversely affect yield potential and is counter-productive to the IPM system due to risks of reduced yield or delayed maturity.
3. **Regular crop checking for pests, plant damage and beneficial insects (Deutscher and Wilson, 1999).** Regular sampling of all fields, at least once every three days is emphasized to keep track of pest

and beneficial populations. This short interval means that decisions to delay implementation of control can be monitored and action taken if the situation changes while the pest population is still small enough that it can be effectively controlled with selective insecticides. Sampling plant damage provides a measure of how the plant is responding to the environment as well as pest damage. Extensive research has developed damage thresholds for reduced leaf area (thrips damage) or tip damage (*Helicoverpa* spp.) (Gibb, 1999; Wilson *et al*., 2003).

4. **Integration of predators into decisions using a predator/pest ratio.** This is based on extensive field research and ensures that the value of beneficial insects is used pro-actively when deciding if a pest population requires control (Mensah, 2002a).
5. **Use of beneficial refuges and attractant food sprays to enhance predator numbers.** Provision of perennial lucerne on-farm beneficial arthropod nurseries provides some buffer against the vagaries of natural beneficial populations. Positioning them adjacent to, or as strips within, cotton crops means an increased likelihood of beneficials foraging and establishing in cotton crops (Mensah, 2002b).
6. **Use of combined pest and damage thresholds.** This allows for the situation that the pest is over-threshold but the plants growth indicates it will recover without loss, thereby avoiding use of an insecticide to prevent non-economic damage. Thresholds based only on pest numbers alone assume that all cotton crops will respond in a similar way to a given pest density.
7. **Strategic use of plant growth regulators.** Appropriate use of growth regulators can help to reduce the risk of rank crops that are attractive to pests and mature late, increasing the risk of needing to control pests for a longer period and thereby undermining the IPM system.
8. **Optimal water management to avoid extended late season growth.** Irrigation decisions should be based on crop need and the recognized soil water deficit for that particular soil. A critical decision is the timing of the final irrigation. If this is applied to a crop that doesn't require it, then there will be no gain in yield but a cost due to extra growth being produced that is attractive to pests, which may require control for a longer period, undermining the IPM system and potentially exacerbating insecticide resistance problems.
9. **Preferential use of more selective insecticides.** Selective insecticides are powerful tools in helping to control pests with less risk to beneficial populations and greater chances of maintaining an effective IPM system. They provide a greater flexibility and a safety net for growers as they develop confidence in IPM.
10. **'Site-specific' pest management.** Treating only those fields that are over-threshold and using selective chemistry, means that fields that are not sprayed can serve as a refuge for beneficials to recolonize sprayed fields. Recent research on this issue with Colorado potato beetle showed that site-specific management significantly also decreased resistance selection and increased beneficial numbers (Midgarden *et al*., 1997).
11. **Use of genetically engineered Ingard® cottons expressing the delta-endotoxin genes from *Bacillus thuringiensis* subsp. *kurstaki* (Bt). (Fitt and Wilson,** 2000) suggested that insecticide resistant transgenic plants, such as Ingard®, can form a good base for IPM by reducing the need to control Helicoverpa spp., the primary pest of cotton, thereby reducing the risk of disruption to beneficials.
12. **An effective resistance management strategy.** This is crucial to the preservation of newer selective insecticides as well as older chemistry. Our current strategy is based around rotation, use of 'windows' of use and non-use of particular chemicals and limitations in the number of applications of those chemicals. Increasingly the positioning of insecticides within this strategy is being influenced by our IPM system (Gunning *et al.*, 2002). This ensures that growers have access to some effective selective insecticides for control of key pests at all times of the season. Similarly, a proactive strategy as been developed to manage resistance to the Cry1Ac protein in Ingard® cotton (Fitt and Wilson, 2000).

Winter

Key elements in the winter or "off season" include:

1. **Destruction of diapausing pupae of *H. armigera* that are a reservoir of resistance genes into the next season (Fitt and Daly, 1990).** Growers are advised to sample cotton stubble for pupae, using published guidelines, to determine which fields require control, and to prioritize amongst those that do.
2. **Selection of rotation crops to reduce pest carry-over.** Some rotation crops provide over-wintering hosts for pests, such as faba beans (mites, aphids), safflower (mites, mirids), chickpeas (*H. armigera*) or cereals (*H. armigera* and thrips).
3. **Management of weeds and cotton regrowth that are hosts for over-wintering pest.** Weeds and cotton regrowth following harvest can provide over-wintering hosts for a number of pests including *Helicoverpa*, mites (Wilson, 1994), mirids, aphids, tipworm, cutworm, armyworm and whitefly.
4. **Optimization of fertilizer strategies to avoid excessive plant growth.** Excessive nitrogen often creates excessive growth of cotton toward the end of the season. This makes the crop more attractive to *Helicoverpa*, requiring additional inputs of expensive late season insecticides (and mixes) for control, and can also delay crop maturity by 1–2 weeks and make crops harder to defoliate (Rochester *et al.,* 2001). Growers are advised to manage nitrogen on a field-by-field basis and to do soil tests to determine the background level of nitrogen in each

field so that the amount required can be accurately determined (Constable and Rochester, 1988).

5. **Matching of cotton variety to region and pest complex.** The variety should be matched to the region and likely pests and diseases (see seed company variety guides). Planting a variety with a long growing period and a high yield potential in a cooler, shorter season region is likely to create problems with late maturity, prolonged protection and difficulty with defoliation. Okra-leaf varieties have a degree of resistance to both *Helicoverpa* spp. and spider mites potentially reducing sprays for each pest by about one per season (Thomson, 1994).
6. **Development of a spray drift management plan.** Mutual agreement on the IPM approach between the growers and their pest managers or consultants is essential for success. The grower should also discuss IPM strategy and significance of drift management with the insecticide applicator as well as neighbors.
7. **Seed bed preparation.** A good seed-bed, typified by friable, non-cloddy soil and firm, high, well shaped beds helps to achieve earliness by providing the seedling plants the best chance to grow and not be held back.
8. **Selection of appropriate seed insecticide treatments.** The decision to use any of these products must be made before there is a pest problem, which means their use is 'prophylactic'. Their use should be considered carefully and they should only be used where there is a reasonable expectation that their use will provide an economic benefit. They are likely to have less impact on beneficials than a foliar application of an insecticide that targets thrips or mirids.

Extension and implementation

Defining and formalizing our IPM system by publishing guidelines for industry has been critical in allowing a consistent and coherent model of IPM to be delivered throughout the cotton industry. They also served as a critical resource for a focused extension effort by the National Cotton Extension Team. This team has been progressively expanded over the last ten years with 'Industry Development Officers' (IDO's) now present in all main cotton regions, with funding coming largely from the Cotton Research and Development Corporation and the Australian Cotton Cooperative Research Centre. The latter institution in particular has been critical to success in delivery of IPM by bringing together researchers and extension personal for different federal, state and University departments to work together in the development and implementation of the system. This co-ordination ensured a high degree of consistency in the message being delivered and co-operation in providing information.

The extension team used a range of strategies to deliver the IPM system (Christiansen, 2002). This involved a range of field days in each region to discuss IPM issues relevant at the time or about to become important. The extension team also implemented a range of demonstration experiments for growers, including a range of experiments to investigate cotton recovery from early-season damage. These experiments were critical in giving growers confidence to tolerate some early pest damage, avoid spraying and allow establishment and development of beneficial populations. The extension staff in each region also produces a local extension update, known as 'Cotton Tales' on a regular (weekly or fortnightly basis). This goes to all growers and consultants in the region by fax or email and usually draw on components of the IPM guidelines that are relevant at the time as well as serving as updates for research.

Further support has come from the provision of a range of information tools such as ENTOpak, which includes the IPM guidelines, a pest and beneficial identification guide, a range of supporting documents providing detailed information on pest thresholds, sampling, pupae control, selectivity of insecticides, crop damage monitoring and planning of last irrigation. These also provide links to other 'Paks' which provide support in implementing IPM, for instance MACHINEpak for information on the effectiveness of implements for pupae control, NUTRIpak for information to ensure optimal fertilizer rates are used, WEEDpak for information on management of weeds that are hosts for pests and DISEASEpak for information on accurate diagnosis of disease symptoms that may be confused with pest damage. Implementation is continually updated and effectively disseminated to industry through the Australian Cotton Cooperative Research Centre's Technology Resource Centre and website.

As part of a drive to improve the level of management of cotton farms at all levels, including environment issues, a process known as 'Best Management Practice' has been established. This provides a framework for growers to evaluate how they are performing against the best standards in the industry, for identifying areas of improvement and documenting this in an auditable fashion. The core principals of the IPM guidelines have been distilled and now form a module in the 'Best Management Practice Manual'. This provides growers with a means to assess how they are progressing in adopting IPM principles on their farm.

The effectiveness of the extension effort has been further fostered by the development of regional IPM groups, where groups of growers agree on core goals and communicate throughout the season to achieve them, for instance delaying use of disruptive pyrethroids. The initiation by growers and consultants of these groups has provided the peer support and communication necessary to give growers the confidence to set and achieve goals relating to IPM. The IDO's have played a crucial role in providing support for these groups in terms of organizing meetings, coordinating visits by researchers and chasing-up information. The IPM groups have allowed growers and consultants to address the pest problem more effectively than if each grower worked alone. Examples of IPM group aims include delaying the use of 'hard' chemistry to conserve beneficial populations, the co-ordinated planting of trap crops and sharing of information through regular meetings. The pioneering work of these IPM groups is a good example of this participatory research approach outlined by Dent (1995).

A key process that continues to be used by the Australian cotton industry to influence IPM implementation is the use of computerized decision support systems (DSS). The use of CottonLOGIC and more recently the CottonLOGIC for Palm OS has been important across the industry in supporting key elements of IPM and providing a benchmark against which decisions can be compared (Deutscher and Bange, 2003). The CottonLOGIC DSS provides a disciplined and objective sampling process, ensuring that the basis for making decisions is sound. CottonLOGIC also includes a *Helicoverpa* development model, which forecasts populations three days ahead based on current estimates of eggs and larval numbers of each size category (Hearn and Bange, 2002). A simple model is also used to forecast likely yield losses due to mites, based on rate of increase of populations and stage of the crop (Wilson, 1993). The DSS also supports the collection of predator numbers and estimation of the predator/pest ratio. Data collected can be entered in the office at a PC, or collected in the field using the revolutionary 'CottonLOGIC for the Palm' software, based on the Palm OS (Deutscher and Bange, 2003). This provides the power of CottonLOGIC and its models in the palm of the users hand, for use in the field, expediting data collection and entry via later synchronisation with an office PC. Users of CottonLOGIC can later access the data to analyze and compare the effectiveness of IPM strategies in terms of control and economics. Links with another package, NutriLOGIC, provide support for decisions regarding fertilizer requirements, important in meshing agronomic management and IPM (see above).

Another critical factor in gaining support for IPM systems has come from favorable economic analyses of IPM versus traditional approaches. One of the first of the IPM groups was established in a cotton-producing region on the border between the states of Queensland and New South Wales. This group, known as the 'Boggabilla IPM group" collected detailed records of pest abundance, insecticides used and crop yields. Hoque *et al*. (2000) collated this data for analysis. They used information available in Wilson *et al.* (2002) to rank each insecticide in terms of its impact on beneficial population with 1 being very selective insecticides with no effect and 7 being more broad-spectrum insecticides that caused a very high reduction (>60%) in beneficial populations. They called this the beneficial disruption index (BDI). They then derived a score for each field by summing the BDI for each spray across the season. They separated the data into fields with a high BDI score, termed hard, and those with a lower BDI score, termed soft. Economic analysis showed that the soft, IPM approach generally had equal or higher gross margins than the harder approach (Figure 1). The difference was attributed to higher beneficial populations in the field managed with more selective insecticides. This analysis was critical in providing 'economic' credibility for the IPM approaches. Such studies have now been extended to other regions with similar findings.

Has the extension effort been effective?

Adoption of an IPM approach, incorporating many of the elements above, has had a dramatic uptake over the past four years. Two recent surveys have found that "Integrated Pest Management (IPM) has become widely accepted by growers, consultants, researchers and extension officers in the Australian Cotton Industry" and that "(IPM or) Area wide management groups are highly valued for their role in enhancing communication and increasing confidence in IPM approaches" (Christiansen and Dalton, 2002). These finding suggest that grower attitudes and practices have been significantly altered over the past five years. Further support comes from the increased uptake and use of the CottonLOGIC DSS for its scientific values in IPM decision support as well as for accurate record keeping, with use across about 51% of the crop area (Deutscher and Bange, 2003).

Data on insecticide use is also encouraging. Since the publication of the IPM guidelines and the initiation of the extension effort to promote IPM there has been a trend toward a reduced number of insecticide spray applications in total, especially in Ingard® cotton (Figure 2), and an increasing toward more selective insecticides. Some of the insecticide sprays have been replaced with biological insecticides. Analysis of the overall amount of active ingredient (a.i.) per ha shows a marked drop since the emphasis on IPM began (Figure 3) due in part to reduced insecticide use in total, reduced use of older products which required high amounts of a.i. for efficacy (endosulfan, organophosphates and carbamates) and possibly due to lighter pest pressure. Care must be taken in interpretation of these results though, as insecticide use to some extent reflects the pest abundance of a particular season, and the seasons since 1998/99 have been regarded as lighter. How much of the lighter pressure is attributable to season differences and how much to IPM is almost impossible to unravel. It is significant though, that we expected that increased conservation of beneficials would lead to some reduction in pest populations. Consultants are noting that in fields managed selectively *Helicoverpa* egg numbers and survival of eggs and larvae remain low through the season, whereas field where more disruptive insecticides are used tend to have higher egg laying and higher survival of eggs and larvae.

Conclusions

The development of transgenic cotton with two Bt genes (Bollgard II®) and increased commitment to IPM, bodes well for the future sustainability of Australian cotton. However, as the system changes the pest complex also changes and sucking pests, formerly suppressed by *Helicoverpa* sprays, are emerging as new challenges, threatening IPM. The fundamental role of IPM in reducing pest pressure and insecticide use means that its continued evolution and use is critical to the future viability of both transgenic and conventional cotton production. The farming systems and participatory approach developed provides a framework that will help to ensure effective engagement between research, extension and industry to ensure the continued development and evolution of our IPM system.

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References

- Christiansen, I. (2002). Extension and Profitability – Implementation of Profitable and Sustainable Approaches. 11th Australian Cotton Conference.
- Christiansen, I. and Dalton, B. (2002). Understanding IPM - Industry attitudes, practices and education. 11th Australian Cotton Conference.
- Constable, G. and Rochester, I. (1988). Nitrogen application to cotton on clay soil: Timing and soil testing. *Agronomy Journal*, **80**: 498-502.
- Dent, D.A. (1995). "Integrated Pest Management," Chapman and Hall, London.
- Deutscher, S. and Bange, M. (2003). Advancement in computerized decision support systems for Australian cotton systems. Proceedings of the World Cotton Research Conference 3, Cape Town, South Africa, March, 2003. This volume.
- Deutscher, S. and Wilson, L. (1999). Insect and damage sampling for cotton. IPM Guidelines Supporting Document 1, Australian Cotton Cooperative Research Centre, Narrabri, NSW, Australia. pp 4.
- Ferguson, J., Miles, M., Murray, D., Dillon, M., Kauter, G., Lloyd, R. and Sequeira, R. (2000). Spring trap crop management, Cooperative Research Centre publication. pp 1-12.
- Fitt, G.P. and Daly, J. (1990). Abundance of overwintering pupae and the spring generation of *Helicoverpa* spp. (Lepidoptera: Noctuidae) in Northern New South Wales, Australia: implications for pest management. *Journal of Economic Entomology*, **83**: 1828-1836.
- Fitt, G.P. and Wilson, L.J. (2000). Genetic engineering in IPM: Bt cotton. *In* Emerging Technologies for Integrated Pest Management: Concepts, Research and Implementation (G.G. Kennedy and T.B. Sutton, eds.), pp. 108-125. APS Press.
- Gibb, D. (1999). Monitoring fruit retention. IPM Guidelines Supporting Document 10, Australian Cotton Cooperative Research Centre, Narrabri, NSW, Australia. pp 2.
- Gunning, R., Larsen, D., Pyke, B., Tucker, G. and Wilson, L. (2002). Insecticide resistance management strategy for conventional cotton 2002-03. Cotton Pest Management Guide 2002-2003 Agdex 151/680, NSW Agriculture, Narrabri, NSW, Australia.
- Hearn, A. and Bange, M. (2002). SIRATAC and CottonLOGIC: persevering with DSSs in the Australian cotton industry. *Agricultural Systems*, **74**: 27-56.
- Hoque, Z., Farquharson, B., Dillon, M. and Kauter, G. (2000). Soft options can reduce costs and increase cotton profits. *Australian Cottongrower,* **21**: 33-37.
- Mensah, R.K. (2002a). Development of an integrated pest management program for cotton. Part 1: Establishing and utilising natural enemies. *International Journal of Pest Management*, **48**: 87-94.
- Mensah, R.K. (2002b). Development of an integrated pest management program for cotton. Part 2: Integration of a lucerne/cotton interplant system, food supplement sprays with biological and synthetic insecticides. *International Journal of Pest Management*, **48**: 95-105.
- Mensah, R.K. (1997). Local density responses of predatory insects of *Helicoverpa* spp. to a newly developed food supplement 'Envirofeast' in commercial cotton in Australia. *International Journal of Pest Management*, **43**: 221-225.
- Mensah, R.K. (1999). Habitat diversity: implications for the conservation and use of predatory insects of *Helicoverpa* spp. in cotton systems in Australia. *International Journal of Pest Management,* **45**: 91-100.
- Mensah, R.K. and Wilson, L.J. (1999). Integrated pest management guidelines for Australian cotton. CRC ENTOpak. Australian Cotton Cooperative Research Centre, Narrabri, New South Wales.
- Midgarden, D., Fleischer, S., Weisz, R. and Smilowitz, Z. (1997). Site-specific integrated pest management impact on development of esfenvalerate resistance in Colorado Potato Beetle (Coleoptera: Chrysomelidae) and on densities of natural en-

emies. *Journal of Economic Entomology*, **90**: 855-867.

- Rochester, I., Peoples, M. and Constable, G. (2001). Estimation of the N fertilizer requirment of cotton grown after legume crops. *Field Crops Research*, **70**: 43-53.
- Sadras, V.O. and Wilson, L.J. (1998). Recovery of cotton crops after early season damage by thrips (Thysanoptera). *Crop Science*, **38**: 399 - 409.
- Thomson, N.J. (1994). Commercial utilisation of the okra leaf mutant of cotton - the Australian experience. In "World Cotton Conference I, Challenging the future" (G. A. Constable and N. W. Forrester, eds.), pp. 393-401. CSIRO Australia, Brisbane, Australia.
- Wilson, L.J. (1993). Spider mites (Acari: Tetranychidae) affect yield and fiber quality of cotton. *Journal of Economic Entomology*, **86**: 566-585.
- Wilson, L.J. (1994). Habitats of two-spotted spider mites (Acari: Tetranychidae) during winter and spring in a cotton-producing region of Australia. *Environmental Entomology*, **24**: 332-340.
- Wilson, L.J., Bauer, L.R. and Lally, D.A. (1998). Effect of early season insecticide use on predators and outbreaks of spider mites (Acari: Tetranychidae) in cotton. *Bulletin of Entomological Research*, **88**: 477-488.
- Wilson, L., Mensah, R., Dillon, M., Wade, M., Scholz, B., Murray, D., Heimoana, V. and Lloyd, R. (2002). Impact of insecticides and miticides on predators in cotton, December 2002 update. IPM Guidelines Supporting Document 1, Australian Cotton Cooperative Research Centre, Narrabri, NSW, Australia. pp 2.
- Wilson, L., Sadras, V., Heimoana, S. and Gibb, D. (2003). How to succeed by doing nothing: cotton compensation after simulated early season pest damage. *Crop Science* (in press).

Figure 1.
Gross margins of cotton field grown using more selective insecticide (soft) versus those using more broad-spectrum insecticides (hard).

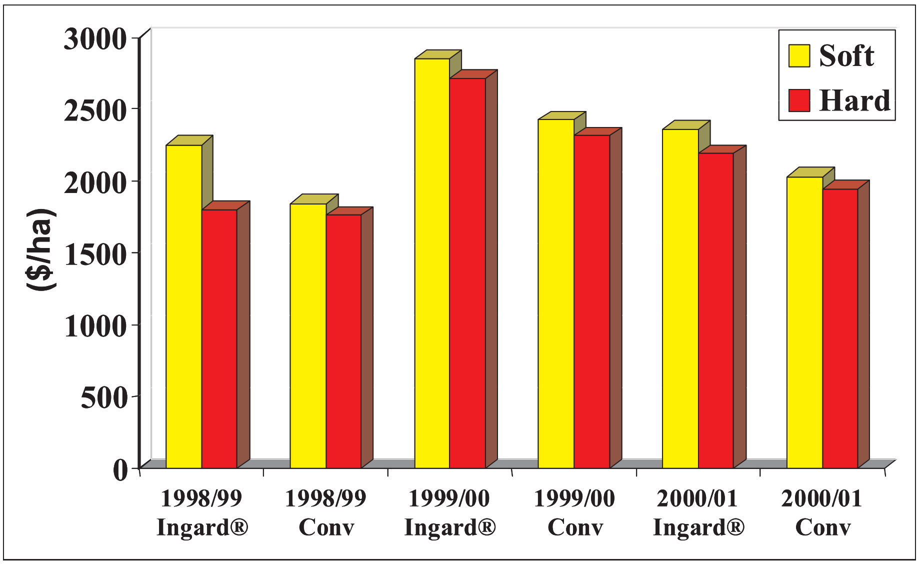

Figure 2.
Average number of insecticide applications to conventional and Ingard® cotton crops in Australia, 1996-2002.

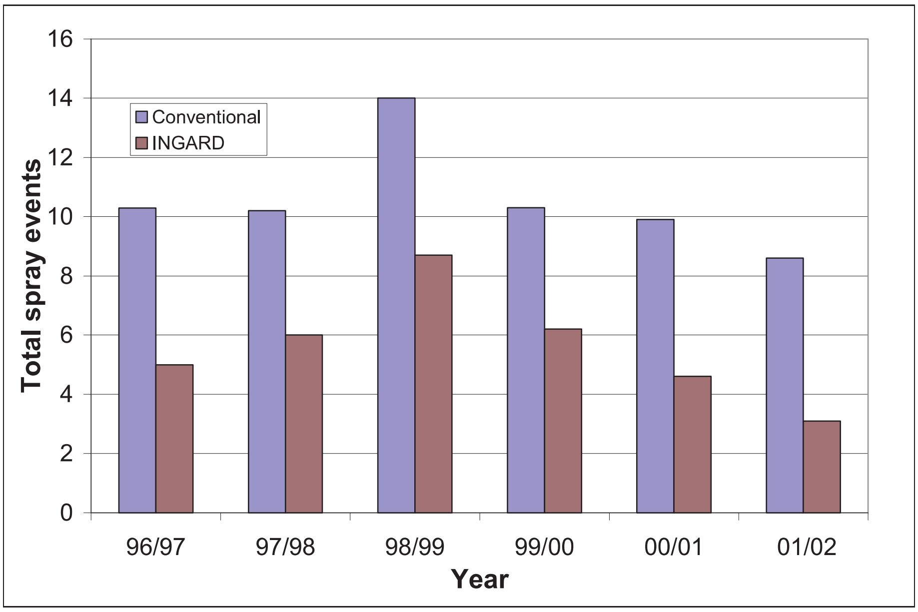

Figure 3.
Average amount of active ingredient (a.i.) of insecticide per hectare for conventional and Ingard® cotton crops in Australia, 1993 - 2002.