Assessing the feasibility for cotton in tropical Australia: Research for the development of sustainable pest management systems

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ABSTRACT

Previous attempts to establish commercial cotton production in tropical Australia have all ended in failure. The most successful was a 10-year industry located in the Ord River Irrigation Area in north-western Australia. The industry commenced on a small-scale in 1963 and expanded in area to about 4,500 ha. Acceptable yields and fiber quality were achieved but crop management under tropical wet season conditions was difficult and insect pest control, posed enormous challenges. After seven years of cotton production, the cotton budworm, Helicoverpa armigera, *had developed resistance to most insecticides and consequently the costs of pest control spiraled whilst yields declined. By 1974 production became uneconomic, due mainly to the 40 sprays per crop applied to control* H. armigera, *and the industry collapsed. Recent commercial availability of transgenic cotton varieties (INGARD®), with the capacity to control some lepidopteran pests through the expression of a gene from* Bacillus thuringiensis, *has led to renewed interest in the prospects for cotton production in tropical Australia. However, past experiences dictate that a cautious approach be taken to the possible establishment of an industry. Lessons from the past have shown that dependence on narrowly based pest management systems will lead to failure and modern industries must be based on sustainable production systems to gain acceptance from governments, investors and the general community. The Australian Cotton Cooperative Research Centre has fostered research into a multi-tactic approach to sustainable pest management systems. Key elements of research include pest avoidance, transgenic varieties, enhanced performance of beneficial insects, companion crops and pre-emptive strategies for transgene resistance management. In this paper we summarize research progress towards the development of a model for sustainable pest management in winter-growing regions of tropical Australia. Large-scale test farming of these novel systems may lead to the establishment of a cotton industry in northern Australia and serve as a model for other tropical areas with similar climatic and pest management challenges.*

Introduction

The cotton industry in Australia is a success story with high yields and quality ensuring that cotton exports are well regarded by the international market. Australia is the world's third largest exporter of lint in most years with about 95% of production being traded. Most cotton is grown in intensively managed irrigated farming systems, which are highly dependent on seasonal rainfall to maintain production levels. However, Australia is drought prone and thus annual production can fluctuate erratically in response to the availability of irrigation water and summer rain that enables rain-fed cropping when global prices are attractive.

Most of Australia's agricultural production, including cotton, is based in the temperate regions of the continent whilst the tropical areas (north of 20°S) have little intensive agriculture, apart from small horticultural production areas. The north is dominated by low productivity pastoral activities. However, northern Australia has abundant land and water resources, some of which could be directed to intensive agricultural production (Yeates, 2001). More than 50% of Australia's water run-off occurs in the north (Anonymous, 2001) and capturing a relative small proportion of this water would enable significant irrigated agricultural production. It is estimated that an additional 200,000 ha of cotton production in northern Australia would have an annual value of $750 million and lead to significant benefits to regional communities. It would also expand the Australian cotton production base by about 50% and enable the nation to become a year-round supplier.

Despite the obvious potential for industry development in the north, there is considerable skepticism about sustainability, and conflicting opinions concerning land use in the region. Some conservationists promote the idea that northern Australia should be left as a pristine wilderness area devoid of all agriculture. Certainly the region has a poor history of agricultural development with several high profile projects ending in disaster (Bauer, 1985). Cotton is amongst these ill-fated developments with the failure of the crop after 10 years production in the Ord River Irrigation Area in north-western Australia, 1963-1974. Although the industry grew to 4,500 ha from a small start, it collapsed in 1974 when an average of 40 sprays per crop were used to control *Helicoverpa armigera* that had become highly resistant to insecticides (Wilson, 1974). This example highlights the folly of sole reliance on conventional insecticides for insect pest control.

Establishing a sustainable cotton industry in northern Australia is clearly a significant challenge. The Australian Cotton Cooperative Research Centre and partner institutions, have committed resources to investigate the feasibility of sustainable cotton production tailored to the requirements of several regions in northern Australia. Key elements of research include pest avoidance, transgenic varieties, enhanced performance of beneficial insects, companion crops and pre-emptive strategies for transgene resistance management (Strickland *et al.*, 1998). This paper summarizes some aspects of research progress towards sustainable pest management systems for cotton in the semi-arid tropics of Australia.

Experimental procedure

The methods required to determine the feasibility of establishing a new cotton industry need to be multi-disciplinary and at a scale that simulates a biological system that may reasonably be expected to occur in an eventual agricultural system. Initial research was restricted to a desktop study to design a cotton production system that would provide the key factors for sustainability. These were then evaluated in the field. The critical factors decided on were:

- Winter cropping to avoid high summer populations of key pests such as pink bollworm (*Pectinophora gossypiella*), cluster caterpillar (*Spodoptera litura*), *Helicoverpa* spp. and a range of cotton loopers
- Integrated pest management (IPM), rather than regular applications of conventional insecticides
- Transgenic cottons with pest controlling genes (initially INGARD® by Monsanto, expressing a Bt gene)
- Reliable pest thresholds to minimize insecticide usage
- Pre-emptive Bt resistance management to extend the effective life of the transgenics

Some research, such as establishing pest thresholds, can be conducted in small plots. However, assessing industry feasibility necessitates that research be conducted on a semi-commercial scale as soon as possible, because returns from small plot investigations soon diminish (Robertson and Chapman, 1985). This approach requires the early involvement of farmers and commercial partners and is reflected in some of the methods used for this research.

Sites

Cotton research reported in this paper has been conducted at three winter-growing sites across northern Australia, as shown in Figure 1 (the Richmond site in Queensland is a summer- growing area and is not discussed in this paper). Each of the sites was markedly different in terms of climate, geography and pest complex. Some pest management principles apply generically but each of the three regions required the development of systems tailored to the specific needs of each area. A brief description of the sites, from west to east follows.

Broome site

Small plot research was conducted from 1996-99 at Shamrock Gardens, 160 km south of Broome, Western Australia. The largest area grown was 17 ha in 1999, but since then land has not been available due to issues associated with Native Title. The area is characterized by deep red sandy soils and sparse open woodlands. Most of the region is used for pastoral cattle production. Irrigation is from ground water resources. It is estimated that the La Grange aquifer is likely to provide a sustainable yield sufficient to irrigate about 25,000 ha. The irrigation delivery system is through buried irrigation tape.

Kununurra site

INGARD® cotton trials have been in progress at the site since 1996. Kununurra, Western Australia, is part of the Ord River Irrigation Area, which currently grows about 12,000 ha of mixed crops including sugar cane, chickpea, hybrid seed crops and horticultural crops. Stage II of the development will enable an additional 32,000 ha of irrigated cropping. The soil type is predominantly cracking clay suitable for furrow irrigation. This is the only site where large areas of experimental IPM cotton have been grown regularly, up to 960 ha being produced in a single year.

Katherine site

Katherine is located in the Daly basin, Northern Territory. The region has several soil types ranging from deep red earths to sands. The soil types are suitable for overhead irrigation or irrigation tape, but not furrow irrigation. Water is available from rivers and ground sources.

INGARD® trials have been in progress since 1996 but on a relatively small scale of up to 40 ha in any one year. Irrigated peanuts, hay production and intensive horticulture are the main agricultural activities in the region.

Research being conducted at each site and the methods being applied are outlined below.

Pest avoidance (winter cropping)

Pheromone traps were used to measure the seasonal activity of key pests at Broome, Kununurra and Katherine. AgriSense™ funnel traps were suspended above crops and the resultant moths collected and recorded fortnightly. Pheromone dispensers (AgriSense™ lures) were placed in each trap for each of the target pests. Pheromone lures were replaced on a monthly basis along with a SureGuard™ Ministrip (186 g/kg dichlorvos), which was used as the killing agent in the traps.

In addition to pheromone traps, crops were scouted at least twice weekly and pest abundance recorded using the CottonLOGIC decision support system (CSIRO, 2001). In this way pest pressure could be tracked and compared to other cotton production areas to gauge relative pest pressures from different regions.

IPM systems

Details of large-scale IPM systems research are provided in a complementary paper by Annells and Strickland in these proceedings, and are not detailed in this paper.

Pest thresholds

Methodology at Kununurra was similar for each year of the experiments. Plots were large, 21.6 m (12 beds) or 27 m (15 beds) by the paddock length (150-250 m) i.e. 0.32 to 0.68 ha. The variety sown was the most commonly attractive cultivar in each season and fertilizer and irrigation schedules were as per standard practice for the area. The trials were harvested using a John Deere cotton picker, which was modified to pick small trials.

The trials were planted as randomized complete block designs with four replications of each treatment. The treatments were spray thresholds for *Helicoverpa* larvae and the thresholds evaluated varied from year to year. Control action was taken when the mean number of larvae of four plots in the treatment reached the prescribed threshold. Scouting of all plots in all years used the presence/absence method as described in CottonLOGIC. CottonLOGIC also calculated the fixed larval thresholds but new calculations were developed for the cumulative thresholds. The cumulative threshold calculation used the same scouting data but summed some previous scouting data to give a cumulative output. An additional factor for larval size was also incorporated into the calculation. In 2001, the factor of fruit retention was also included so that high retention crops did not reach threshold as quickly as low retention crops at the same levels of pest pressure. Sprays were applied either with a high clearance tractor fitted with a spray boom and droppers, when soil conditions permitted, or with an aircraft fitted with micronaires.

Pest threshold research at Katherine focused on sucking insects, including mirids, *Creontiades dilutus* (Stal) and *C. pacificus* (Stal), green vegetable bug, *Nezara viridula* (L.) and redbanded shield bug *Piezodorus hybneri* (Gmelin). The experiments examined both the period up until first flower and the period from first flower to cutout. The trials were planted as randomized complete block designs with three (pre-flowering trial) or four (post-flowering trial) replications of each treatment. The treatments were spray thresholds for sucking insects and were set at 0.5, 1.0 and 2.0 sucking insects per meter row. An unsprayed control and an insect exclusion treatment, maintained by making applications of (200 g/l fipronil) every nine days, were also included. Control action was taken when the mean number of sucking insects of plots in the treatment reached the prescribed threshold. Scouting of all plots was conducted twice weekly, examining four, 0.5 m sections of row.

Pre-emptive Bt resistance management

Pre-emptive Bt resistance management strategies were based around the use of refuge crop areas (either rotation crops or unsprayed conventional cotton) to produce *Helicoverpa* moths that have not been exposed to Bt proteins. The premise of this concept is that the moths produced in the refuge areas will mate with resistant moths generated in the INGARD® and Bollgard II® cotton areas (Roush, 1997).

At Kununurra the number of moths produced from various crops was estimated by regularly digging for pupae and rearing them in the laboratory to measure their viability and identify species.

At Katherine moth production from transgenic cotton and other crops were estimated by placing emergence cages over crops and counting the resultant moths.

Results

Pest avoidance (winter cropping)

Pheromone traps for *Helicoverpa armigera*, *H. punctigera* and *Spodoptera litura* have been run continuously at six sites in the irrigation area at Kununurra since 1990. These pests are ubiquitous and attack a wide range of crops in northern Australia. *Pectinophora gossypiella* (pink bollworm) differs by being a pest of cotton only, and was added to the trapping grid in 1996 when the first INGARD® cotton trials commenced. The mean weekly trap catches for pink bollworm for the six-year study period are shown in Figure 2. There was a strong pattern of seasonal activity with moths being most abundant in the wet summer months (standard weeks 48-8) with mean weekly trap catches peaking at almost 300 moths/trap/week during this time. However the populations declined to very low levels, below 5 moths/week, for much of the dry winter season when the cotton trials were actively growing.

Pheromone traps for pink bollworm were also established in the Broome region. One trap was maintained at the cotton trial site (Shamrock Gardens) and another five traps were spaced at approximately 30 km intervals between Shamrock Gardens and the Broome township. The five "non-cotton" trap sites were collectively referred to as "bush sites" because they were located away from agricultural activity. Figure 3 shows the seasonal abundance of pink bollworm in a pheromone trap at the Shamrock Gardens trial site. Although total abundance was much lower than at Kununurra (Figure 2), moth numbers followed the same pattern of relatively high populations during the summer months before almost disappearing during the winter cotton growing season. Figure 4 illustrates the seasonal activity of pink bollworm in the "bush sites" where no cotton, or other crops, was grown. Pink bollworm activity followed the same pattern as described for the other sites but peak abundance was only about half that of the Shamrock Gardens site where cotton was growing during the winter months.

At Katherine a network of pheromone traps was established at a range of cropping and bush sites to examine the seasonal abundance of *H. armigera*, *H. punctigera*, *P. gossypiella* and *Spodoptera litura*. The seasonal abundance of pink bollworm mirrored that obtained at Kununurra and Broome, peaking in the wet season and falling to very low levels during the time when cotton was growing (Figure 5). Unlike Broome, only low numbers of pink bollworm moths were caught at the bush sites.

Pheromone traps were not reliable predictors of *Spodoptera litura* activity in crops so crop scouting methods were used to measure the insect's abundance. The results of monitoring for *S. litura* larval activity in INGARD® cotton crops are summarized in Figure 6. Total larvae per meter row rarely exceeded 0.5 larvae and this was considered sub-economic and not requiring control with insecticides.

Pest thresholds

Research to define spray thresholds for *Helicoverpa* was conducted at Kununurra for four seasons, from 1998 to 2001. In the first two seasons the "standard" threshold of 2 larvae/m was compared to lower thresholds and an unsprayed control. The results from these experiments are summarised in Table 1. In each of the seasons one of the lower thresholds gave a significantly higher yield than the standard threshold. However, to achieve the higher yield, an additional two insecticide applications were required.

During the 2000 and 2001 seasons, experimental cumulative thresholds were compared with the standard 2 larvae/m threshold with the aim of triggering thresholds in response to accumulated pest activity rather than specific pest densities. The results from these experiments are summarised in Table 2. *Helicoverpa* pest pressure was very low in both seasons as shown by the unsprayed control treatment, which yielded 97% of the standard threshold treatment without any sprays. Despite the low pest pressure, the cumulative 10 larvae/m treatment gave a significantly higher yield than the standard threshold treatment in 2001. Importantly, the higher yield was achieved with one less spray than the standard threshold treatment.

At Katherine, threshold studies for sucking insects were conducted in 2002. In the pre-flowering study, yield was unaffected by sucking insect populations up to 1.5 sucking insects per meter, which was the highest population recorded (Figure 7). However, in the post-flowering study, sucking insects impacted significantly on yield. Yields of unsprayed plots were approximately 30% of that obtained in plots sprayed on a threshold of 0.5 mirids/m, which did not differ significantly from plots sprayed regularly to exclude sucking insects (Figure 8).

Pre-emptive Bt resistance management

Quantifying the sources of *H. armigera* in the agricultural system is an important prerequisite to developing a resistance management strategy to preserve the efficacy of the Bt transgenes for as long as possible. Research at each site has aimed to measure the timing and emergence of moths from a range of crops that could be used as unsprayed "refuge" crops in a future resistance management strategy.

The results of potential refuge crop monitoring at the Kununurra site are summarised in Figure 9 and compared to Bollgard II® (data from 2002 season only). These data show that *H. armigera* emergence from Bollgard II® cotton is extremely low and occurred only during August in the 2002 season. The data also indicates that several crops, apart from conventional cotton, provide high numbers of viable *H. armigera* pupae. In August, sweetcorn/maize, chickpea, pigeon pea, lablab and tomato all produced more viable pupae than conventional cotton. Similarly, in September, all crops except lablab produced more pupae than conventional cotton.

The results obtained at Kununurra were mirrored at Katherine where *H. armigera* emergence from Bollgard II® was also extremely low when compared to conventional unsprayed cotton, and occurred late in the season (Figure 10). In a second trial examining potential rotation crops as sources of *H. armigera* moths, peanuts produced by far the greatest moth populations, more than twice that of sorghum and unsprayed conventional cotton (Figure 11). These results suggest that both peanuts and sorghum would make good refuge crops for transgenic cotton with both having the additional bonus of being suitable for use as rotation crops.

Discussion

The establishment of a sustainable cotton industry in the semi-arid tropics of northern Australia provides a significant challenge to researchers and industry partners. A whole farming system approach has been adopted with emphasis on sustainability, environmental neutrality and crop management tailored to the specific requirements of each potential region. Much of northern Australia may be suitable for winter (dry season) rather than the traditional summer (wet season) production. However, whilst the change in season is likely to bring sustainability benefits, it is also accompanied by unique agronomic and pest management challenges. Progress towards agronomic management and the development of robust integrated pest management systems is detailed in these proceedings through complementary papers by Yeates and Bange, and Annells and Strickland, respectively.

In this paper we summarize research aimed at enhancing cotton production sustainability by defining the techniques of pest avoidance, improved pest thresholds and progress towards developing a pre-emptive resistance management strategy for the Bt transgenes that are an essential component of the envisaged cropping system.

One of the predicted benefits of winter cropping in northern Australia was the avoidance of high pest pressure of certain insect pests. The two pests of most importance in this regard were the pink bollworm, *Pectinophora gossypiella*, and *Spodoptera litura*. Both insects were extremely damaging to experimental cotton grown in previous decades and were significant in the collapse of the only cotton industry at Kununurra in the 1960s and 1970s. Spraying to control overlapping generations of *S. litura* was considered to be the main reason for the development of resistance in *H. armigera* (Michael and Woods, 19801). In the current era, *S. litura* was also considered to be a pest of prime importance because the *Spodoptera* genus is known to be poorly controlled by the Bt gene expressed in INGARD® cotton (Moar *et al*., 1995).

Michael and Woods (1980) experimented with growing cotton utilising integrated pest management (IPM) techniques to control highly insecticide resistant *H. armigera*, after the collapse of the industry in 1974. The IPM methods included inundative releases of *Trichogramma pretiosum*, originally from California (USA), and selective insecticides and ovicides for lepidopteran pest control. These techniques were successful for the majority of the growing season but almost totally ineffective against pink bollworm attack late in the summer season. Pink bollworm is known to be highly abundant in summer at Kununurra (Flint *et al*.,1979). For these reasons, avoidance of the pest was considered to be most desirable in the development of a low insecticide sustainable pest management system.

The data summarized in Figures 2, 3, 4 and 5 confirm that growing cotton in the winter growing season at the Kununurra, Katherine and Broome sites is successful in avoiding high pest pressure from pink bollworm. Figure 2 summarizes the pheromone trap catches of pink bollworm from six sites over a 6-year period at Kununurra. During this time, a total of more than 2,000 ha of INGARD® cotton was grown during the winter production window. It is clear that the pink bollworm population remained strongly synchronized to the summer months despite host plant availability in winter.

The same pattern of seasonal abundance for pink bollworm is shown in Figures 3, 4 and 5 at Broome and Katherine. Regardless of the presence or absence of cotton, the pink bollworm shows high abundance during the summer and almost disappears during winter. The pest's close association with native malvaceous hosts that depend on summer rainfall to flower and fruit probably explains this. The insect then appears to retreat to facultative diapause during the dry winter months when hosts are extremely scarce, especially in the low rainfall areas.

Helicoverpa and mirids (mainly *Creontiades* spp.) are the major pests of INGARD® cotton grown in northern Australia. Management of *H. armigera* has been problematic for many years due to its propensity to develop resistance to insecticides. The advent of INGARD® cotton has reduced the impact of the pest but gene expression can be erratic and declines in the latter part of the growing season (Fitt, 1998). Therefore spray thresholds remain important to maximizing yield whilst avoiding excessive use of the few remaining efficacious insecticides.

The benchmark *Helicoverpa* threshold in temperate Australia is 2 larvae/m, as calculated by the CottonLOGIC model from field scouting data. The validity of this threshold for northern Australia was tested in the 1998 and 1999 seasons at Kununurra. Table 1 shows that significantly higher yields could be obtained by using lower thresholds such as 0.5 or 1 larva/m. However, two additional insecticide sprays were required to achieve the yield response and this was considered undesirable for economic and sustainability reasons.

Observations during the experiments suggested that the higher yields may have been achieved from spraying INGARD® cotton earlier rather than more frequently. It was noticed that INGARD® crops often contained "sub-threshold" larval numbers that caused considerable fruit loss but did not trigger the fixed 2 larvae/m threshold. To overcome this shortcoming in fixed thresholds, experiments were designed to evaluate *Helicoverpa* thresholds calculated with a "cumulative larval-day" formula. The cumulative larval thresholds sum the previous crop scouting data and adjust the numbers by incorporating a damage rating based on larval size. The results from trials evaluating the new thresholds are summarised in Table 2. Low pest pressure hampered the trials but significant yield differences were achieved in the 2001 trial. In this experiment the cumulative 10 larvae/m threshold achieved a 13% yield improvement compared to the standard 2 larvae/m threshold. Furthermore the improved yield was achieved with one less spray than the standard threshold, highlighting the importance of spray application timing, which is made earlier in the cumulative threshold treatments. These data are preliminary and need to be validated in high pest pressure situations but show considerable promise for *Helicoverpa* management in transgenic crops in northern Australia.

Trials conducted at Katherine demonstrated that sucking insects have the potential to reduce yields significantly (70%), even at relatively low populations from first flower onwards. The finding that it may be possible to handle relatively high populations of sucking insects early in the season is significant as it enables producers to delay chemical intervention, possibly until first flower. Despite this, the large amounts of damage sustained from first flower onwards presents researchers with a number of challenges as the need to spray sucking insects could have the effect of destroying beneficial insects that may be useful late in the season to control *Helicoverpa* and other pest species. This problem is being addressed in part through research examining the use of trap and companion crops.

Roush (1998) has developed models that predict resistance development in transgenic crops, such as INGARD® cotton, under various management scenarios. Major conclusions are that gene stacking (deploying insecticidal genes simultaneously) is preferable to sequentially introducing transgenes, and that refuge crops are critical to managing resistance development. Refuge crops are used to produce pools of unselected (mainly susceptible) moths that are available to mate with potentially resistant moths emerging from transgenic crops. These principles have been deployed in several cotton producing areas in the world, including Australia where a 30% cap on INGARD® cotton is mandatory in all areas. In addition, cotton growers in Australia must also grow certain unsprayed refuge crops, or 50% of the farm as conventional cotton, to ensure that *Helicoverpa* unselected for resistance to Bt proteins are available to mate with moths emerging from INGARD® cotton.

Much of northern Australia differs climatically from temperate Australia and resistance management strategies specific to each region must be developed before commercial production could commence. For example, diapause in *Helicoverpa* is rare in northern Australia and therefore the successful "pupae busting" program used elsewhere is not practical in northern regions and alternatives are required. A model that incorporates pest dynamics and the impact on pest abundance from the cropping system is a requirement for each new region.

Refuge crops are an important component of resistance management strategies and quantifying the production of moths from refuge crop options is critical information. Emergence from the transgenic crop must be linked to that of the refuge crops to ensure that moth emergence from both sources is synchronous and that sufficient moths emerge from refuge crops to adequately "dilute" resistant moths from the cotton crop. Preliminary data for several refuge crop options at Kununurra are presented in Figure 9. Bollgard II® cotton was only available in the 2002 season and showed very low *Helicoverpa armigera* survival with less than 1,500 moths/ha emerging from the crop and only in August. In contrast, more than 10,000 moths/ha emerged from refuge crops of maize/sweet corn, chickpea, pigeon pea, lablab and tomato during the same month. The same crops, except lablab, produced similar numbers of moths in September and have demonstrated their capacity to produce large numbers of moths synchronously with the low emergence from Bollgard II® cotton. Research at Katherine has identified peanut and sorghum as ideal refuge crop options. Further data on Bollgard II® performance is required so that a robust resistance management strategy for the region can be developed.

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Table 1. *The yield and number of sprays to control* Helicoverpa *at different fixed spray thresholds in INGARD® cotton at Ord River Irrigation Area, Western Australia, 1998 and 1999.*

	Percentage yield of standard threshold		Number of sprays	
Treatment	1998	1999	1998	1999
Standard (2 larvae/m)	100%	100%	0	3
0.5 larva/m	*110%	104%	2	4
1.0 larva/m	102%	*108%	0	5
Untreated control	-	78%	-	0

* Significantly higher yield than standard treatment at P<0.05

Table 2. *The yield and number of sprays to control* Helicoverpa *at experimental cumulative spray thresholds in INGARD® cotton at Ord River Irrigation Area, Western Australia, 2000 and 2001.*

Treatment	Percentage yield of standard threshold		Number of sprays	
	2000	2001	2000	2001
Standard (2 larvae/m)	100%	100%	2	2
Cumulative 5 larvae/m	101%	-	4	-
Cumulative 10 larvae/m	93%	*113%	2	1
Cumulative 15 larvae/m	102%	-	2	-
Cumulative 10 larvae/m + retention factor	-	106%		2
Untreated control	-	97%		0

* Significantly higher yield than standard treatment at P<0.05

Figure 1. Location of current Australian cotton growing areas and four research sites in northern Australia.

Figure 2. Mean weekly number of pink bollworm moths collected in pheromone traps at the Kununurra, Western Australia, 1996-2002.

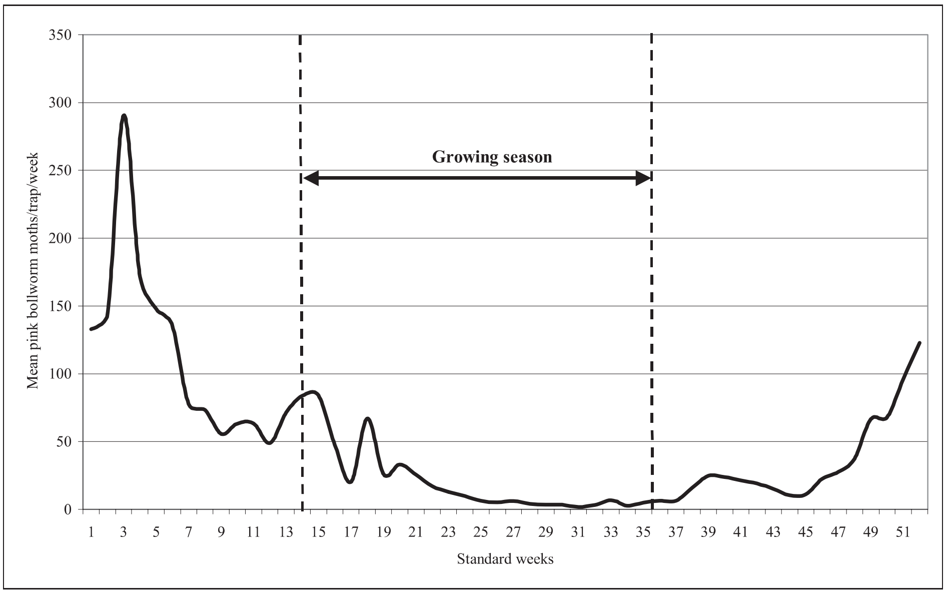

Figure 3. *Weekly number of pink bollworm moths collected in a pheromone trap at the Shamrock Gardens, Western Australia, 1998-99.*

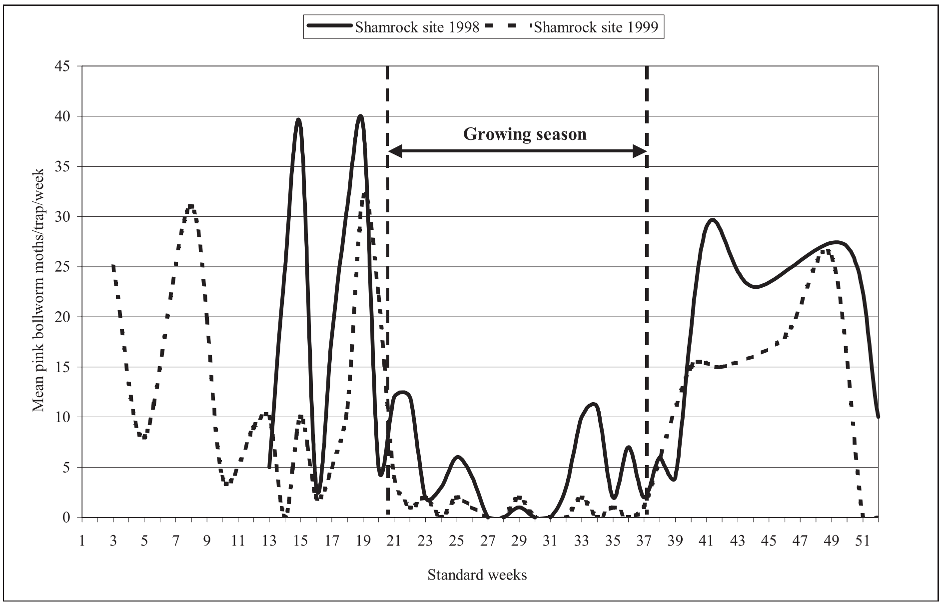

Figure 4. *Mean weekly number of pink bollworm moths collected in five pheromone traps 30-160 km north of the Shamrock Gardens site, Western Australia, 1998-99.*

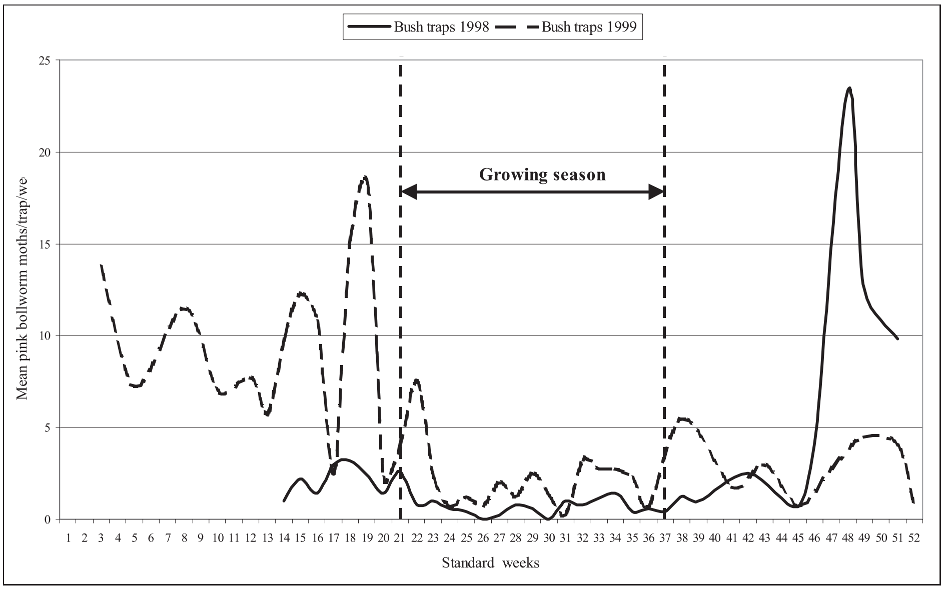

Figure 5. *Number of pink bollworm moths collected in pheromone traps at Katherine, Northern Territory, 2001-2002.*

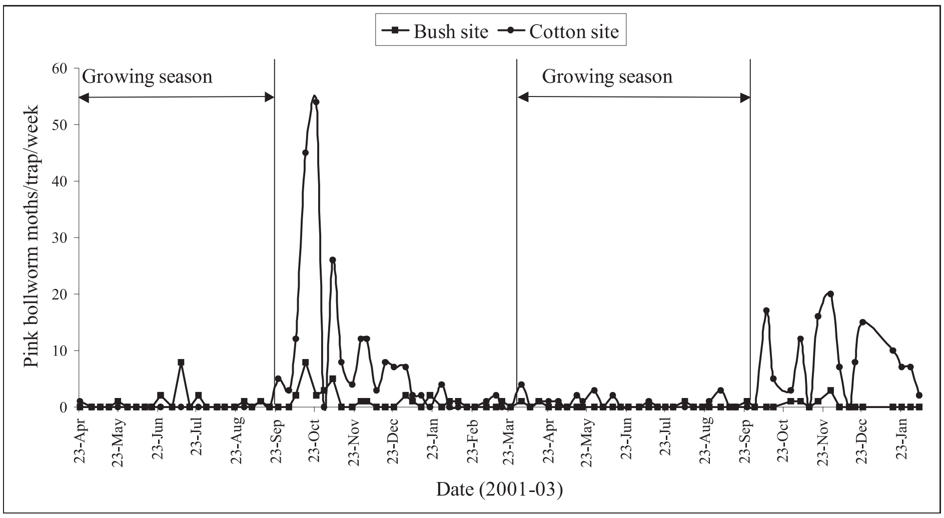

Figure 6. *Mean numbers of Spodoptera litura larvae (all instars) per meter row recorded in INGARD® cotton trials at Kununurra, Western Australia, 1999-2000.*

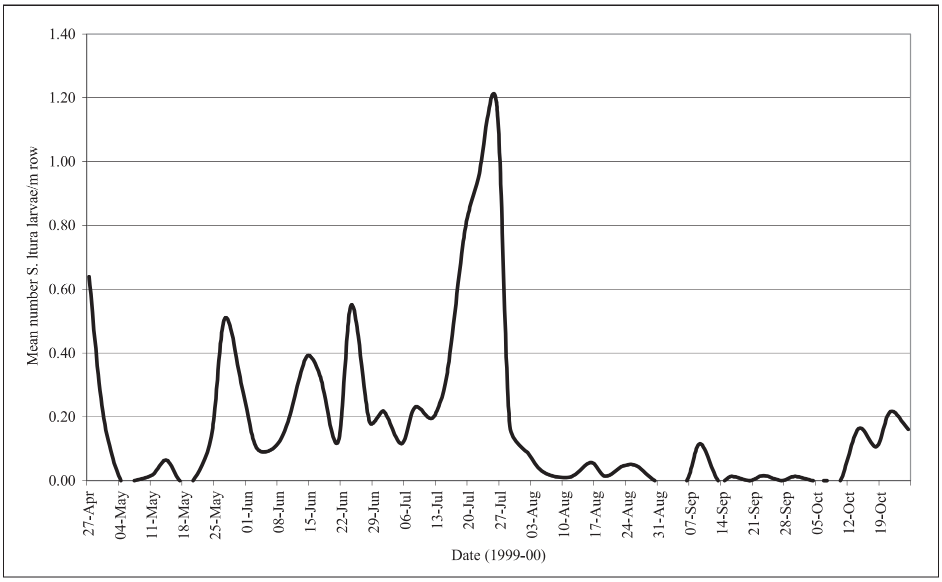

Figure 7. *Yields (227 kg lint/bale) obtained in a pre-flowering sucking insect threshold trial. The highest insect density experienced was 1.5 sucking insects /m effectively making the 2.0 insects/m treatment an unsprayed control.*

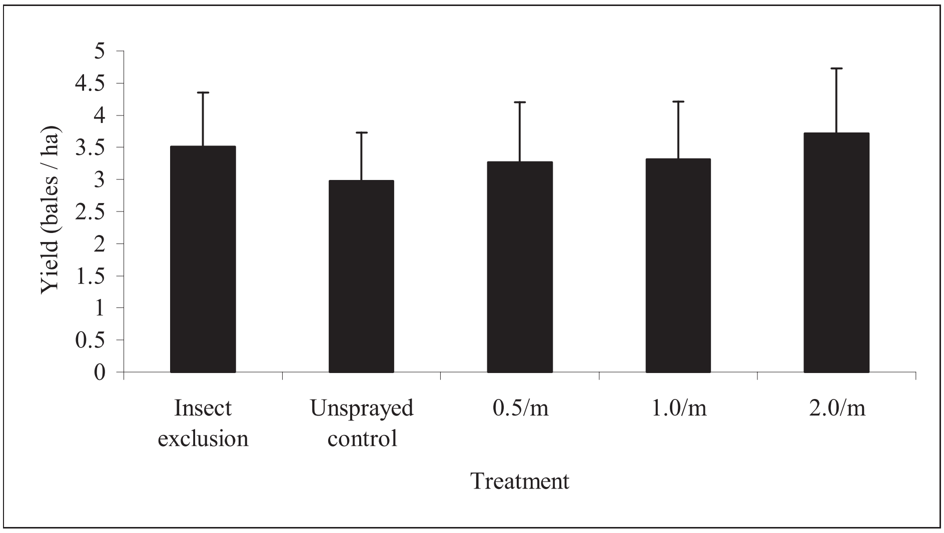

Figure 8. *Yields obtained in a post-flowering sucking insect threshold trial. The insect density in the 2.0 pests/m treatment failed to reach threshold effectively making it an unsprayed control.*

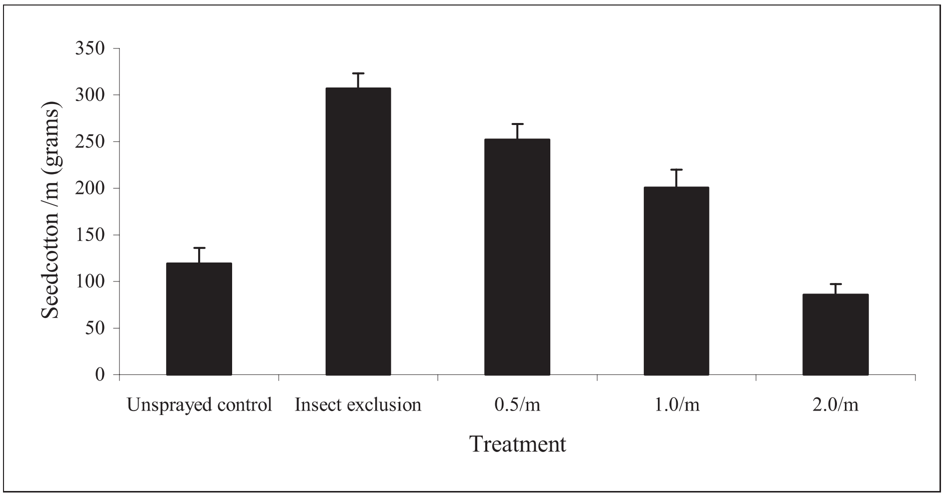

Figure 9. Mean number of viable Helicoverpa armigera *per hectare from crops grown at the Ord River Irrigation Area, Western Australia, 1999 2002. (Bollgard II® and tomato data from one season only).*

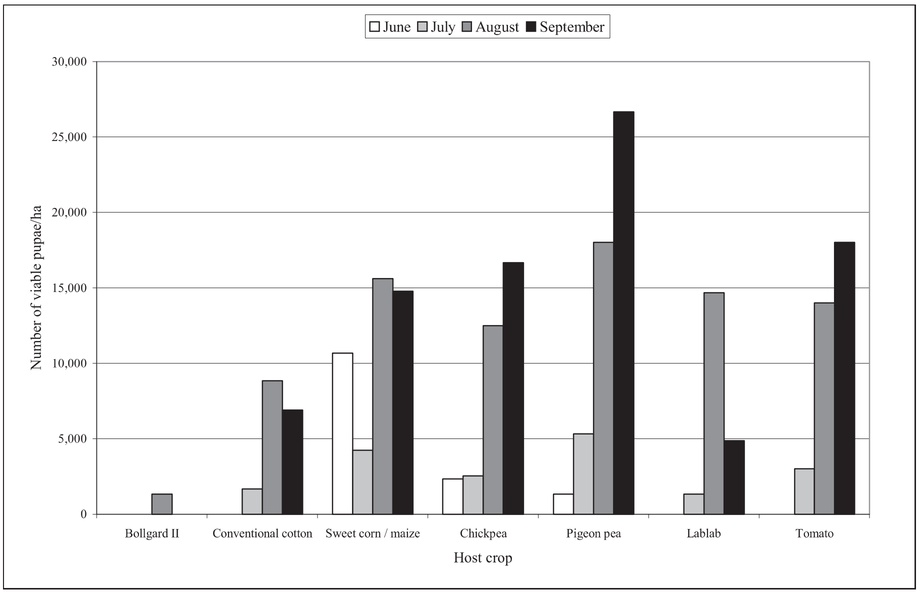

Figure 10. Cumulative Helicoverpa armigera *production in unsprayed conventional cotton and Bollgard II® cotton at Katherine Research Station, Northern Territory. Sampling was undertaken using emergence cages that were checked every 2 days and shifted every 2 weeks.*

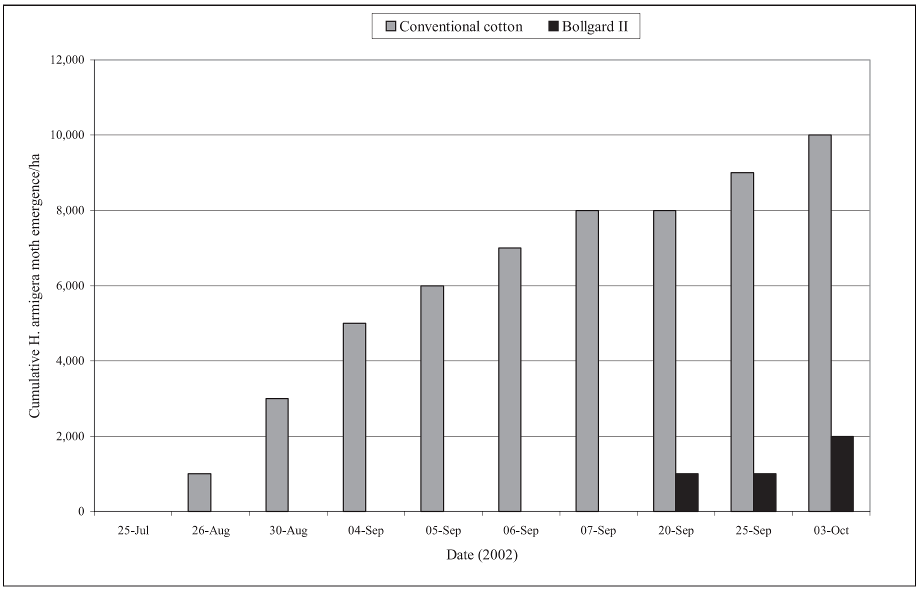

Figure 11. Cumulative Helicoverpa armigera *pupae production in peanuts, sorghum and unsprayed conventional cotton at Campbell's property (Katherine, Northern Territory). Sampling was conducted fortnightly by hand.*