Part 1 - Summary Details

CRDC Project Number: **CSP147C**

Project Title: Incorporating aphids, insecticides and early season plant compensation in IPM

Project Commencement Date: 1.7.2002 **Project Completion Date:** 31.6.2005
Research Program: On-Farm

Part 2 – Contact Details

Administrator: Jo Cain, Administration Manager
Organisation: CSIRO Plant Industry
Postal Address: Locked Bag 59, Narrabri, NSW, 2390
Ph: 02-67991513 **Fax:** 02-67931186 **E-mail:** jo.cain@csiro.au

Principal Researcher: Dr Lewis Wilson
Organisation: CSIRO Plant Industry
Postal Address: Locked Bag 59, Narrabri, NSW, 2390
Ph: 02-67991550 **Fax:** 02-67931186 **E-mail:** lewis.wilson@csiro.au

Supervisor: Dr Greg Constable
Organisation: CSIRO Plant Industry
Postal Address: Locked Bag 59, Narrabri, NSW, 2390
Ph: 02-67991522 **Fax:** 02-67931186 **E-mail:** greg.constable@csiro.au

Signature of Research Provider Representative: ______________________________

Part 3 – Final Report Guide (due 31 October 2008)

Background

This project was the sixth in a series of projects (CSP1C, CSP21C, CSP46C, CSP74C, CSP103C). These projects have been successful in developing industry management guidelines and thresholds for pests such as mites and thrips. The series has pioneered research into understanding the ecology of secondary pests, identifying the role of beneficials in regard to pest management, especially for spider mites, evaluating the IPM fit of new and existing chemistry and providing well accepted information on the early compensatory capacity of cotton. This information has been incorporated into the current Integrated Pest Management Guidelines for cotton. However, there are continuing and new challenges to our IPM systems that we need to address. This project consists of four separate but related components, each building on the outcomes of earlier projects.

Effects of aphids on cotton development and yield

Cotton aphid emerged recently as a major pest due to changes in pest management systems including reduced early season spraying (particularly with endosulfan), use of Ingard® cotton, the advent of Cotton Bunchy Top and recently detected resistance to organophosphates and carbamates in cotton aphid. The latter two issues were causing considerable nervousness in the cotton industry, which undermined both resistance management and development of IPM. As new selective aphicides and more CBT resistant cotton varieties become available, emphasis will return to the use of economic thresholds to decide when to control aphids. This will require a thorough understanding of the effects of aphids on growth and yield of cotton at different stages through the season. Project CSP103C made good progress in this area, particularly in evaluating the effects on yield of aphid populations initiated at different times through the season and in the development of reliable aphid mass rearing, artificial infestation and management techniques. However further research was required to understand a wider range of infestation timing and intensities, the timing of control and possible differences between varieties in response to aphid feeding. This will allow the potential yield effects of given aphid populations to be predicted and allow development of new thresholds and decision support tools.

Mechanisms of recovery of cotton after early damage

The recovery of cotton following early season pest damage received considerable attention in earlier projects (CSP74C and CSP103C). This included studies of the direct effects of pests, such as thrips and green mirids, as well as a wide range of experiments using simulated pest damage. The latter have included different types, timings and intensities of damage and also begun to investigate interactions with other stresses such as water stress.

Outcomes of this research were widely publicised through the industry via extensive collaboration with CRC Industry Development Officers who also conducted damage experiments in all cotton regions. This research was critical in the development of effective IPM systems for cotton by providing growers and consultants with the confidence to tolerate some damage, thereby reducing insecticide use. We propose to continue to work with the CRC IDO’s to extend research to other regions, with a particular emphasis on high retention

Bollgard II® crops and on ultra narrow row (UNR) cotton. In addition we will use more detailed experiments to monitor changes in plant growth, plant architecture, leaf structure and photosynthetic efficiency in response to pest damage. Outcomes will be improved understanding of cotton compensation in the new Bollgard II® crops, understanding of issues for UNR cotton and data to improve compensation routines in the OZCOT model.

Non-target effects of insecticides

Integrated pest management relies heavily on conservation of beneficial insects, which will help manage pests. Understanding of both the efficacy and the non-target effects of insecticides is critical for their effective use in IPM. Over the last ten years a series of projects (CSP1C, CSP21C, `CSP46C, CSP74C and CSP103C) has evaluated the non-target effects of most existing and new chemistry. This research been used to provide growers and consultants with independent information on the non-target effects of insecticides and was used to develop IPM Supporting Document 1 'Impact of insecticides and miticides on predators in cotton' which forms part of the Integrated Pest Management Guidelines for Australian Cotton. This research needs to be continued as new insecticides become available and will be even more valuable in the two-Bt-gene era as there will be increasing emphasis on selective control of all pests. This project will focus on providing basic information on the non-target effects of new chemistry. A companion project by Dallas Gibb and Viliami Heimoana (NSW Agriculture) will focus on the efficacy of new chemistry and mixtures against target pests, with emphasis on *Helicoverpa* and aphids.

Emerging minor pests

As the use of insecticides declines on farms, due to the use of Ingard® and Bollgard II® cotton and due to increasing adoption of IPM strategies, there are more frequent reports from growers and consultants of unusual minor pest problems. For instance, in fields with little broad-spectrum insecticide use, jassids often build to quite high numbers, causing significant damage to older and sometimes younger leaves. The effect of such populations on yield is probably small but remains unknown and needs to be clarified. Such situations are likely to be more common as we move to Bollgard II® cotton. This project will also include a 'flexible focus' to opportunistically collect information on the economic significance of jassids and other minor pests. This would include preliminary yield loss data and assessment of pest numbers and plant growth.

Objectives

i. *To develop detailed quantitative data relating aphid effects to cotton growth and yield and link that with Cotton LOGIC and OZCOT*

Experiments have been conducted to establish the relationship between aphids and yield loss. Relationships to predict yield loss from aphids have been developed. Linkages with OZCOT and CottonLOGIC have yet to be established. The PhD research of the project Senior Technical Officer (STO), Ms Simone Heimoana, is well underway. She has taken regular field measurements of the effect of aphids on photosynthesis of cotton and conducted field and glasshouse experiments to investigate the relationship between aphid density, honeydew and declines in photosynthesis.

ii. *To quantify the effects of insecticides on pests, predators and parasitoids.* Large replicated experiments were done in each year of the project. IPM Guidelines

Document 1 'Impact of insecticides and miticides on predators in cotton' was updated twice for the cotton industry.

iii. *To understand the mechanism by which cotton recovers from early damage and use to improve existing simulation models.*

Experiments investigating recovery from thrips damage were completed and the results have been written up and published in Annals of Botany. Data will be used to improve the OZCOT model in future. We also investigated if Bollgard II® compensated for early pest damage as well as a conventional variety and if this was influenced by sowing date. This has been completed and analysed.

iv. *To extend research on early pest damage into a range of cotton regions through collaboration with the CRC Cotton Extension Team*
A range of activities were co-ordinated with the Cotton Extension Team, including

a. *Bollgard II® experiments with IDO's*
Experiments were conducted with IDO's in four regions to test if yield of Bollgard II® cotton would be limited by high retention causing premature cutout. These have been completed, analysed and reported to industry via CottonTales in each region

b. *Ultra narrow row (UNR) and compensation.*
We investigated if UNR cotton could compensate for early damage as well as conventional cotton could, in collaboration with Evan Brown (NSW DPI) and Scott Hardwick (CSIRO Entomology). Two experiments were completed and have been written up for the Southern New South Wales Cotton Trial Book.

c. *Effect of tip damage on cotton yield and maturity at Hillston.*
We investigated if cotton grown at Hillston could compensate for early damage. This research was completed and written up for the Southern New South Wales Cotton Trial Book.

d. *Can early plant architecture of boll set be manipulated to increase yield.*
We investigated if yield could be increased in Bollgard II® by inflicting damage on young plants by cutting off the terminal and upper leaves with a whipper snipper, or causing square shedding using low rates of Prep. A first experiment was competed and analysed.

v. *Opportunistically investigate the economic significance of minor pests*
This has been achieved through the initiatives below.

e. *Late damage experiment*
We investigated whether late season damage to upper leaves could affect yield. This was completed and analysed, and further experiments planned.

f. *Do jassids affect yield?*
We assessed if jassid damage could affect photosynthesis and investigated the effect of jassids on yield in the field. This work was completed, analysed and reported to industry at a range of venues (CCA AGM, CSD Research Update). Experiments were also completed to define if jassids can reduce cotton yields. These have been completed and analysed, but further information with a wider range of jassids damage levels is required before results could be extended to industry.

Methodology

a) *To develop detailed quantitative data relating aphid effects to cotton growth and yield and link that with Cotton LOGIC and OZCOT*

Effect of aphids on yield.

Current thresholds for aphids are based on a best guess and have no scientific basis. This has not been a problem in the past because aphids were only a problem late in the season, when the risk of yield loss was low and the main threat was due to honeydew contamination of lint. As aphids have been found earlier in the season in some years there is now a need to have accurate thresholds so that growers can avoid unnecessary insecticides applications and yield loss. We initiated a series of field experiments to investigate the effects of aphids on the development and yield of cotton. As an additional component of these experiments the projects STO also made regular assessments of the relationship between aphid density and photosynthesis. The series of four experiments reported here began in 2000-01 and ran until 2003-04.

The experiments involved artificially infesting cotton with aphids at different times through the season. We have developed techniques that allowed us to generate large populations of aphids. This was done by rearing aphids in a glasshouse initially then transferring these to large field cages to further increase numbers. When required the aphids were harvested from the cages, by cutting the plants into small stem sections and placing them into paper bags. The stem sections were then distributed throughout the plots to be infested. In each experiment we aimed to generate aphid outbreaks beginning in Dec, January and February. However, due to the difficulty in producing large numbers of aphids at a given time the actual timing of infestation of plots varied between years The experiments therefore all had uninfested plots and plots infested in December, January or February. Two varieties were used in most experiments – NuOpal and Sicot289i. Experiments also included ‘control’ treatments where the aphid populations were allowed to build for a period before being controlled using aphicides to prevent further damage.

The aphid populations in the infested plots were monitored using a range of techniques with the aim of developing one that would be practical for growers and consultants to use. In the field, by scoring the number of aphids present on a 0 to 5 scale (0, 1 = 1-10, 2 = 11-20, 3 = 21-50, 4 = 51-100, 5 = >100), the degree of damage 0 = no damage, 1 = slight crinkle of young leaves, 2 = < 1/2 of young leaf crinkled, 3 = almost total curl of young leaves) and the amount of coverage of the crop with honeydew (0 = none, 1 = trace of honeydew on top canopy, 2 = bottom ½ of crop sticky, 3 = total plant sticky). We also collected leaf samples from each plot and washed them in the laboratory to obtain an accurate absolute count. Other pests were managed selectively using insecticides. The development of the cotton was monitored by taking fortnightly 0.5 metre harvests, which were partitioned into different structures and dry weight and leaf area recorded. In-field assessments of light interception were also made using a ceptometer. Yield of each plot was determined by machine harvesting the central two rows.

Photosynthesis measurements were made using a LICOR 6400 photosynthesis system. Measurements were taken at regular intervals from node 3-4 below the terminal. Aphids were washed off the leaf to be measured using a thin stream of water. This prevented them from becoming lodged in the LICOR machine. Control leaves were also washed. Measurements of the effect of increasing densities of aphids were made by taking measurements in plots at intervals over the season, as the aphid populations built up.

Results

This is a summary of key findings rather than a complete reporting of all results as there is a vast amount of data collected. We were able to generate plots with a wide range of aphid population densities. Due to seasonal differences in weather and predator abundance the actual build up of aphids varied widely between seasons. Fig. 1 shows the aphid populations generated in the 2002-03 season as an example. The variability between years is well illustrated by the differences in timing and rate of build up of the December infestations over the course of the series of experiments (Fig. 2).

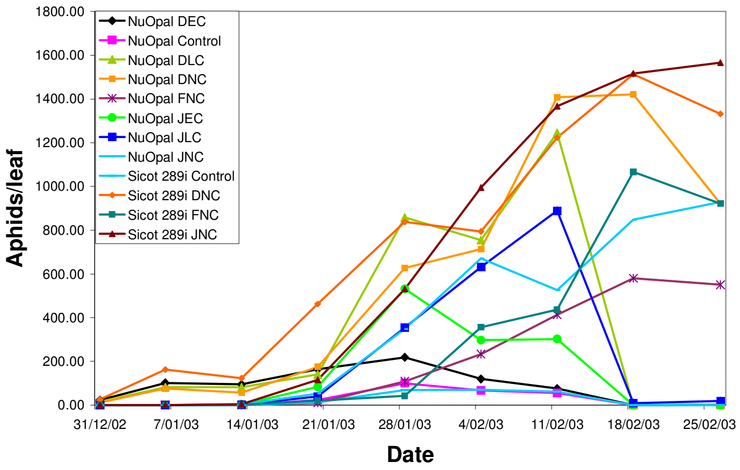

Figure 1. Mean number of aphids on leaf 3 or 4 below the terminal for the 2002-03 field experiment, ACRI.

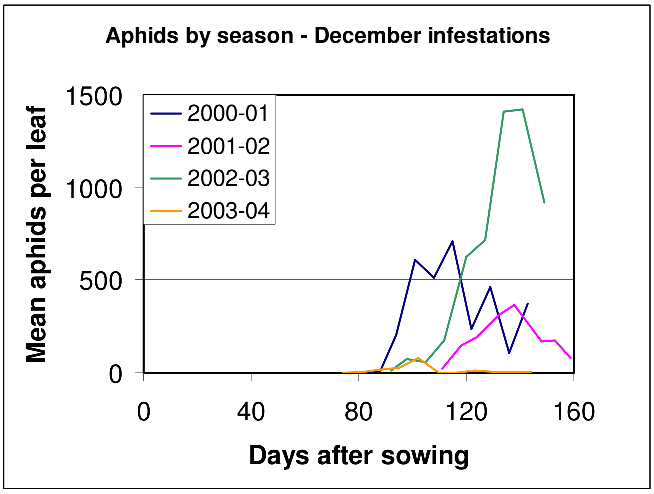

Figure 2. Differences in aphid population build-up for December artificial infestations in four different experiments

A key aim of this work was to develop thresholds for control of aphids. A first simple approach taken was to explore the possibility that yield loss could be predicted from the number of cumulative aphid days that the crop experienced, (where one aphid day is the feeding of one aphid for one day). Initially this approach was tried with the more accurate laboratory counts. Cumulative aphid days were calculated from the time of infestation until sampling ceased at about 20% of bolls open. The data show that for each experiment there is a good relationship between cumulative aphid days (CAD) and relative yield (Fig. 3) but that this varies between years. Relative yield was used to allow for differences in absolute yield level between experiments). The variation between years in the relationship between CAD and relative yield highlights a problem with using aphid days, which is that one aphid day in December is not the same, in terms of potential yield loss, as one aphid day in February. To make the relationship robust we would need to include a time component. A further disadvantage of this approach is that it is difficult to forecast ahead the potential yield loss of a given aphid population as you don't have a final estimate of cumulative aphid days.

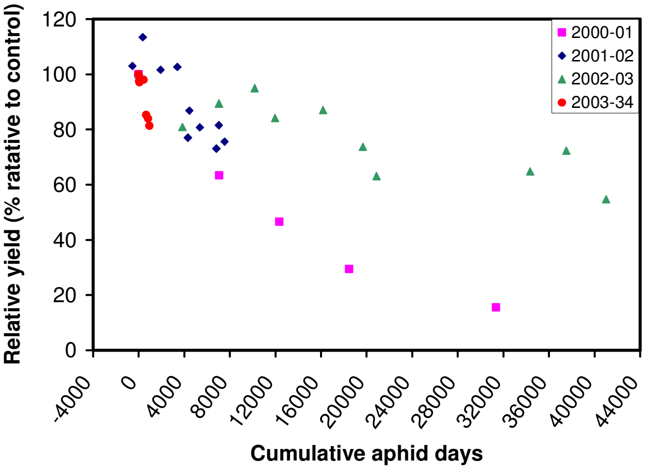

Figure 3. Relative yield of cotton against cumulative aphid days for experiments across four seasons at ACRI.

One way to overcome this problem is to use information estimating when aphids began to increase and how quickly they increased. This approach has been used previously with spider mites and proven useful. So, to investigate the concept we regressed cumulative aphid days, for successive weekly counts, against time. The slope of this relationship is the rate of increase and the x intercept is the start of increase. We did this for each individual treatment across the 4 years of experiments. The relationships were generally linear over most of their range, and late data points where the rates had declined due to poor food quality were omitted. The r^2 for relationship varied between 0.85 and 0.99 which indicate a very good fit (eg Fig. 4).

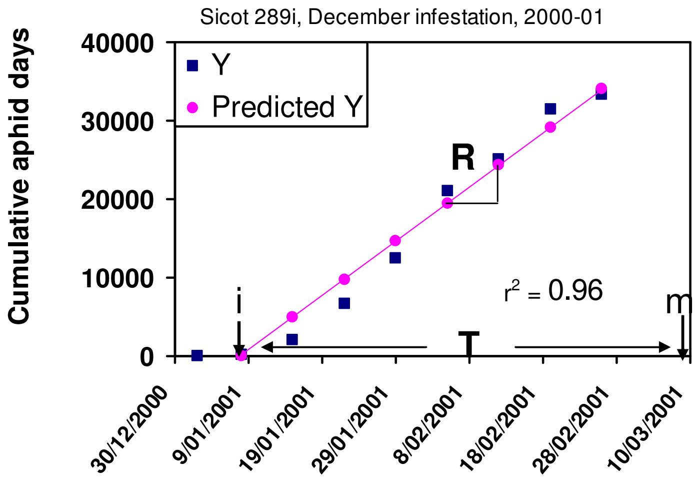

Figure 4. An example of the relationship between cumulative aphids days and time. Also shown is the rate of increase (R) which is the slope of the relationship, the start of infestation increase (i), the maturity date (m) when 60% of bolls opened and the time remaining from infestation increase to crop maturity (T).

We used a non-linear curve to describe the relationship between the rate of increase, the time remaining and relative yield. The relationship is a form of logistic growth curve which allows for some initial tolerance to aphids then a decline. The equation (equation 1) provides a good fit to the data (Figure 5).

Relative yield = $-18.3 + 123/(1 + \exp(0.014((R+1)^{0.3}*T)-305))$.... ($r^2 = 0.91$)…equation 1

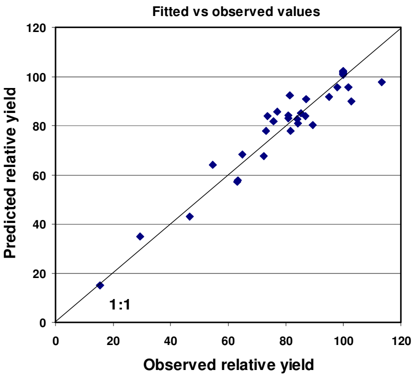

Figure 5. Observed versus predicted yield using equation 1 for the laboratory counts of aphids numbers in Experiments 1 - 4.

The equation was used to generate some curves of the expected yield loss from aphids for populations with a range of starting dates and rates of increase and showed a strong non-linear curve. Initially there is some tolerance of aphids with little effect on crop yield, but at high, prolonged infestation levels yield loss can be quite dramatic (Fig. 6).

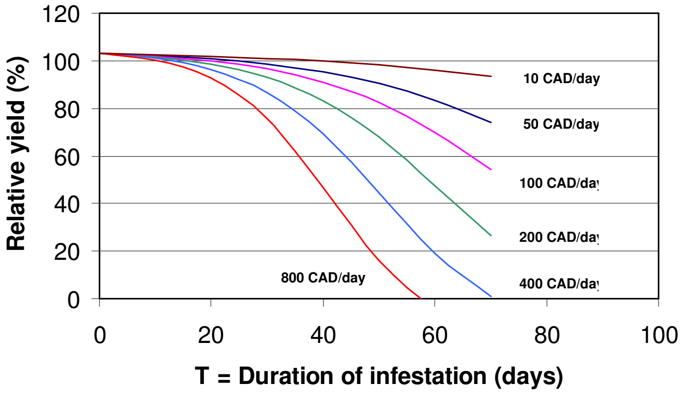

Figure 6. Predicted yield reductions using equation 1 for the laboratory counts of aphids numbers in Experiments 1 – 4 for a range of rates of increase from 10 to 400 CAD per day.

Although the relationship between aphids and relative yield was very good for the laboratory counts of aphid numbers it is important to recognise that growers and consultants will not have access to lab counts – they need something that can be counted in the field. With spider mites rate of increase was calculated as change in the % of leaves infested per day. However, earlier research in CSP145C showed that the relationship between % of leaves infested and mean number of aphids per leaf was strongly non-linear and aphid populations were highly clumped to the extent that 100% of plants was infested at a low aphid density (< 20 aphids per leaf). Observation of the yield loss data indicated that crops would reach 100% of plants infested before any yield loss was likely and hence this approach was not likely to be useful.

For the field estimation of aphid population growth we used the 1- 5 field score data of aphid numbers. From this we calculated cumulative aphid days (CAD_F) for each treatment in each experiment and also calculated the rate of increase in CAD_F , intercept and time remaining is the same manner as the lab counts. For the 'controlled' treatments we calculated the duration and time over which damage occurred.

Regression analysis showed a reasonable relationship between the rate of increase in C CAD_F and reductions in yield. An extra term was added to the equation to allow for the effect of controlling aphids at different times.

%Yield loss = R2*T*D*0.001557 ………….($r^2 = 0.70$)…………………….equation 2

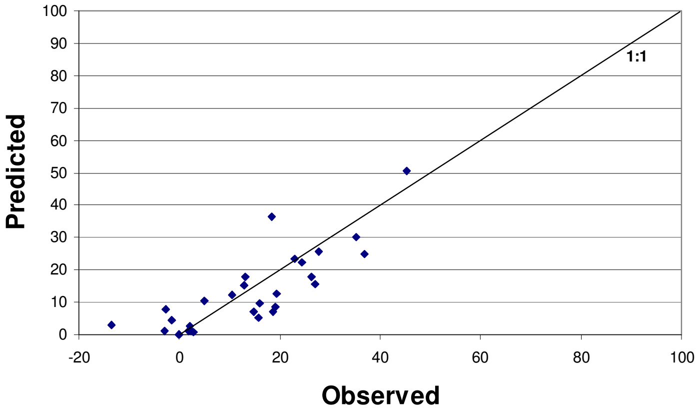

Figure 7. Observed versus predicted yield using equation 1 for the field scores of aphid abundance in Experiments 2 - 4.

Predictions from this relationship show an initial tolerance of cotton to aphids, similar to that shown with the laboratory counts (Fig. 8). Similarly, if the impact of control is included, for instance with a population that begins to increase when there are 80 days remaining in the season, there is an initial tolerance but this is less pronounced as duration and rate increase (Fig. 9). This could form the basis for a simple set of look up tables or an addition to CottonLOGIC to take into account the potential effect of aphids on cotton yield, in the absence of cotton bunchy top disease (Table 1).

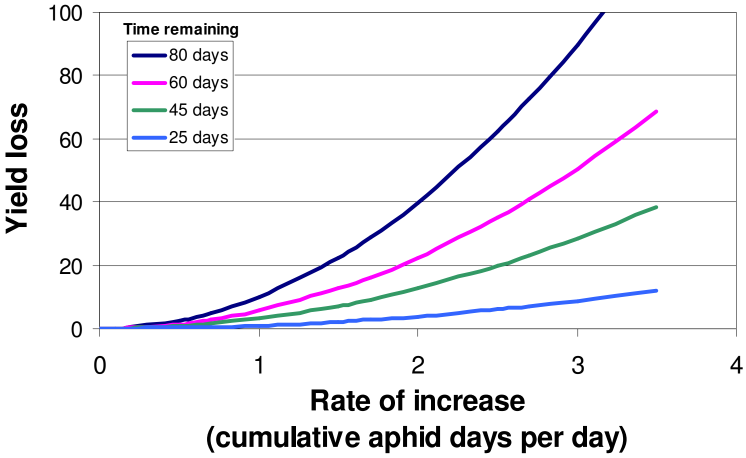

Figure 8. Predicted yield reductions using equation 2 for the field scores of aphid abundance in Experiments 2 – 4 for a range of infestation initiation times, expressed as time remaining in the season.

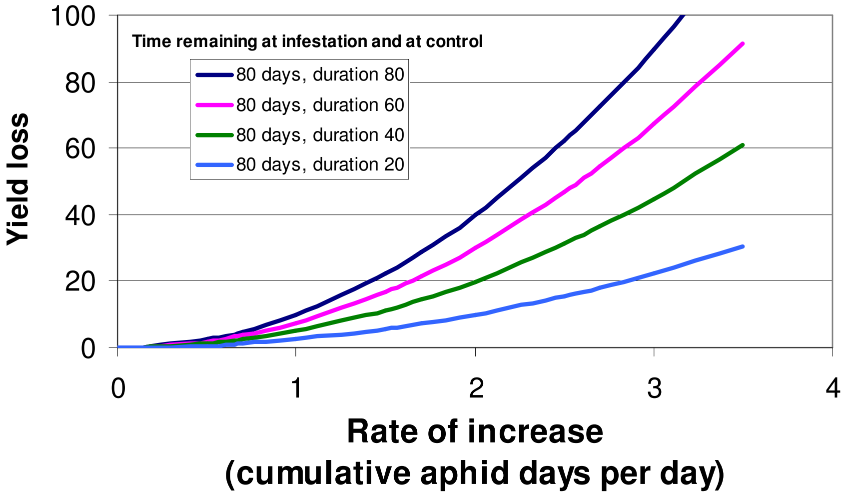

Figure 9. Predicted yield reductions using equation 2 for the field scores of aphid abundance in Experiments 2 – 4 for an infestation initiation time of 80 days before 60% open and a range of control times, expressed as duration in days that aphids were allowed to develop.

ii) Effect of aphids on photosynthesis.

As a second component of this research, Ms Simone Heimoana, the Senior Technical Officer working on this project is studying for a PhD on the effects of aphids on photosynthesis of cotton. Her research is progressing well and she has developed a number of innovative techniques and experiments. Her initial research has shown clearly that aphids do reduce the photosynthetic rate of cotton and there is a negative relationship between aphid density and photosynthetic rate which seems fairly predictable (Figure 10). A similar relationship was found between aphid density and stomatal conductance (Figure 11). However, plotting the effect on photosynthesis against the effect on conductance shows that conductance is affected more quickly than photosynthesis (Figure 12).

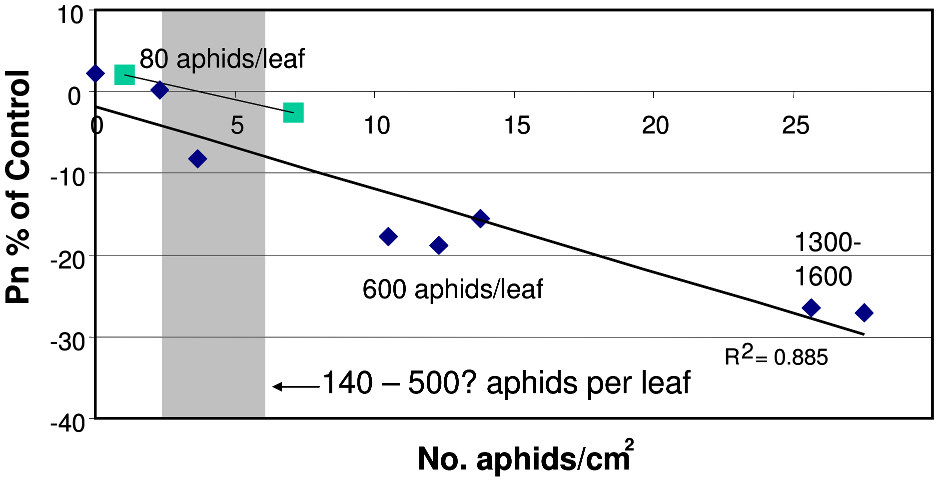

Figure 10. Effect of aphids on photosynthesis on cotton. Measurements taken on mainstem node 3 below the terminal through January and February.

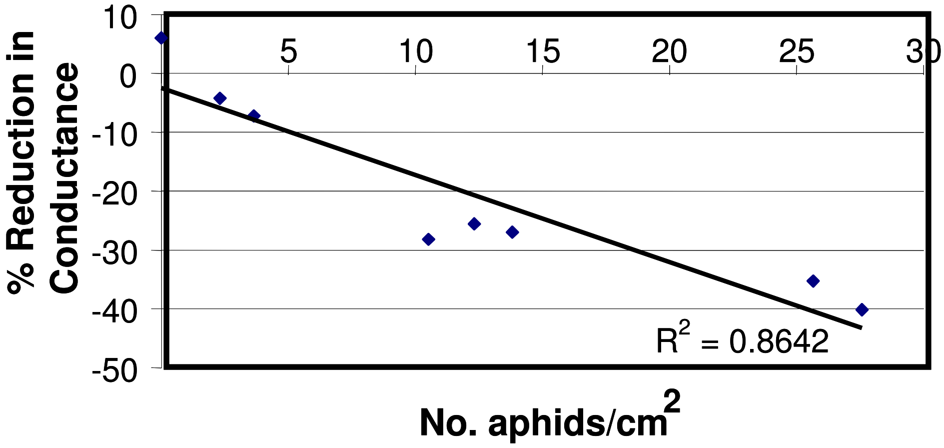

Figure 11. Effect of aphids on stomatal conductance of cotton. Measurements taken on mainstem node 3 below the terminal through January and February.

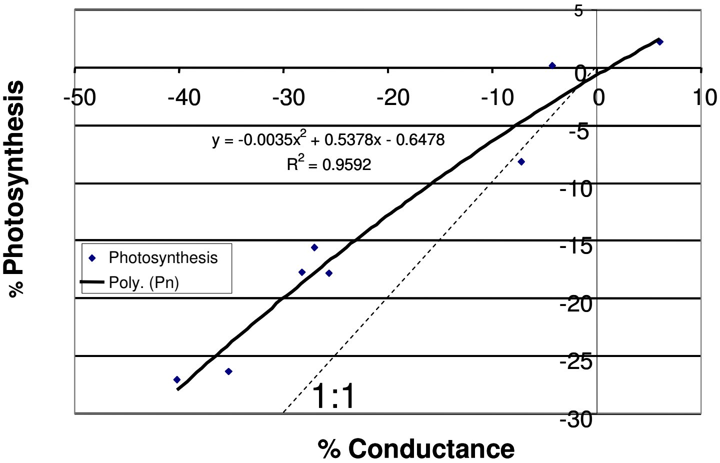

Figure 12. Relationship between reduction in photosynthetic rate and conductance caused by cotton aphids.

Ms Heimoana intends to examine in more detail the effect of aphids on photosynthesis, focussing on the time at which reductions begin to occur. She is also looking at the effects of honey dew and dust on photosynthetic rate, using both real and artificial honeydew. She has found that 3 coats of artificial honey dew reduced conductance as well as photosynthesis. Addition of dust, simulating field conditions results in a further decline in photosynthesis but not conductance, indicating that dust is affecting light penetration. She is also looking at the possibility that aphid feeding damages the phloem, preventing effective export of sugars, causing accumulation and consequent reduction in photosynthesis. Results from this research will improve our understanding of the effects of aphid on cotton growth and provide valuable training for a potential cotton entomologist.

Table 1. Potential yield losses from aphids, derived from rate of increase in cumulative aphid days, the current number of cumulative aphid days and the timing of control.

		Time remaining		80				Time remaining		60				Time remaining		40			
Days till control		0	10	20	40	60	80	0	10	20	40	60	80	0	10	20	40	60	80
Current CAD																			
20	0.1	0.9	0.9	1.0	1.0	1.1	1.2	0.8	0.9	0.9	1.0	1.1	1.1	0.7	0.8	0.8	0.9	1.0	1.0
	0.25	1.2	1.4	1.6	1.9	2.2	2.5	1.1	1.2	1.4	1.6	1.9	2.2	0.9	1.1	1.2	1.4	1.6	1.9
	0.5	1.9	2.3	2.8	3.7	4.7	5.6	1.6	1.9	2.3	3.1	3.9	4.7	1.2	1.6	1.9	2.5	3.1	3.7
	0.75	2.5	3.4	4.4	6.2	8.1	10.0	2.0	2.8	3.5	5.1	6.6	8.1	1.6	2.1	2.7	3.9	5.1	6.2
	1	3.1	4.7	6.2	9.3	12.5	15.6	2.5	3.7	5.0	7.5	10.0	12.5	1.9	2.8	3.7	5.6	7.5	9.3
	1.25	3.7	6.1	8.4	13.1	17.7	22.4	3.0	4.8	6.7	10.4	14.1	17.7	2.2	3.5	4.9	7.6	10.4	13.1
	1.5	4.4	7.6	10.9	17.4	24.0	30.5	3.4	6.0	8.6	13.7	18.8	24.0	2.5	4.4	6.2	10.0	13.7	17.4
	2	5.6	11.2	16.8	28.0	39.2	50.4	4.4	8.7	13.1	21.8	30.5	39.2	3.1	6.2	9.3	15.6	21.8	28.0
	3	8.1	20.2	32.4	56.7	81.0	105.3	6.2	15.6	24.9	43.6	62.3	81.0	4.4	10.9	17.4	30.5	43.6	56.7
40	0.1	1.5	1.6	1.6	1.8	1.9	2.1	1.4	1.5	1.6	1.7	1.9	2.0	1.4	1.4	1.5	1.6	1.8	1.9
	0.25	1.9	2.1	2.3	2.8	3.3	3.7	1.7	1.9	2.1	2.6	3.0	3.4	1.6	1.8	1.9	2.3	2.7	3.1
	0.5	2.5	3.1	3.7	5.0	6.2	7.5	2.2	2.7	3.3	4.4	5.4	6.5	1.9	2.3	2.8	3.7	4.7	5.6
	0.75	3.1	4.3	5.4	7.8	10.1	12.5	2.6	3.6	4.6	6.6	8.6	10.6	2.2	3.0	3.8	5.4	7.1	8.7
	1	3.7	5.6	7.5	11.2	14.9	18.7	3.1	4.7	6.2	9.3	12.5	15.6	2.5	3.7	5.0	7.5	10.0	12.5
	1.25	4.4	7.1	9.8	15.3	20.7	26.2	3.6	5.8	8.1	12.5	17.0	21.5	2.8	4.6	6.3	9.8	13.3	16.8
	1.5	5.0	8.7	12.5	19.9	27.4	34.9	4.0	7.1	10.1	16.2	22.3	28.3	3.1	5.4	7.8	12.5	17.1	21.8
	2	6.2	12.5	18.7	31.1	43.6	56.1	5.0	10.0	14.9	24.9	34.9	44.8	3.7	7.5	11.2	18.7	26.2	33.6
	3	8.7	21.8	34.9	61.0	87.2	113.3	6.9	17.1	27.4	48.0	68.5	89.1	5.0	12.5	19.9	34.9	49.8	64.8
80	0.1	2.7	2.9	3.0	3.3	3.6	3.8	2.7	2.8	2.9	3.2	3.5	3.7	2.6	2.7	2.9	3.1	3.4	3.7
	0.25	3.1	3.5	3.9	4.7	5.4	6.2	3.0	3.3	3.7	4.4	5.2	5.9	2.8	3.2	3.5	4.2	4.9	5.6
	0.5	3.7	4.7	5.6	7.5	9.3	11.2	3.4	4.3	5.1	6.9	8.6	10.3	3.1	3.9	4.7	6.2	7.8	9.3
	0.75	4.4	6.0	7.6	10.9	14.2	17.4	3.9	5.4	6.8	9.7	12.7	15.6	3.4	4.7	6.0	8.6	11.1	13.7
	1	5.0	7.5	10.0	14.9	19.9	24.9	4.4	6.5	8.7	13.1	17.4	21.8	3.7	5.6	7.5	11.2	14.9	18.7
	1.25	5.6	9.1	12.6	19.6	26.6	33.6	4.8	7.8	10.9	16.9	22.9	29.0	4.0	6.6	9.1	14.2	19.2	24.3
	1.5	6.2	10.9	15.6	24.9	34.3	43.6	5.3	9.3	13.2	21.2	29.1	37.1	4.4	7.6	10.9	17.4	24.0	30.5
	2	7.5	14.9	22.4	37.4	52.3	67.3	6.2	12.5	18.7	31.1	43.6	56.1	5.0	10.0	14.9	24.9	34.9	44.8
	3	10.0	24.9	39.9	69.8	99.6	129.5	8.1	20.2	32.4	56.7	81.0	105.3	6.2	15.6	24.9	43.6	62.3	81.0

b) *To quantify the effects of insecticides on pests, predators and parasitoids.* Large replicated experiments were done in each year of the project. In each experiment seven new insecticides or miticides were evaluated for their efficacy, non-target effects and risk of causing resurgence of secondary pests (mites or aphids). Over the duration of this project we evaluated; clothianidin (neonicotinoid, Sumitomo - 2 rates), NNI0001 (experimental compound, Bayer, 2 rates), NNI0001 plus thiacloprid (experimental compound plus neonicotinoid, Bayer), etoxazole (miticide, Sumitomo), Endosulfan Ultracaps (new endosulfan formulation, Bayer), acetamiprid (neonicotinoid, Dupont), carbosulfan (carbamate, CropCare), pyridalil (experimental compound, Sumitomo), semicarbazone (experimental compound, BASF), thiamethoxam (neonicotinoid, Syngenta), and novaluron (insect growth regulator). These products were all in the final stages of development prior to the decision regarding registration.

Where products were registered, such as acetamiprid (Intruder), etoxazole (Paramite) and thiamethoxam (Actara), the data, along with that of relevant collaborators, were used to update the IPM Guidelines Document 1 ‘Impact of insecticides and miticides on predators in cotton’ (Table 2) This ensured that this reference document was up-to-date for the cotton industry. As requested from the various agrichemical companies reports were prepared detailing the efficacy and non-target effects of specific insecticides. Several of these reports were used as a component of registration packages.

The table ‘Impact of insecticides and miticides on predators in cotton’ was widely circulated through the industry via publication in the Cotton Pest Management Guide, in the IPM Guidelines and on the Cotton CRC website. A significant addition to the table in 2004 was the insertion of information on the toxicity of insecticides and miticides to honey bees. This came about through CRC / CRDC initiatives to meet with beekeepers to discus and seek solutions to problems, especially loss of hives due to insecticide drift.

Table 2. Effect of insecticides and miticides on beneficials and pest resurgence in cotton, based on data derived from this project and from collaborators (Robert Mensah - NSW DPI, Martin Dillon – formerly CSIRO Entomology, Mark Wade – formerly QDPI and UQld, Brad Scholz – QDPI, Dave Murray – QDPI, Viliami Heimoana – NSW DPI and Richard Lloyd – QDPI). This version was published in the Cotton Pest Management Guide 2205/06, on the CRC Website and an earlier version appeared in the IPM Guidelines.

		Target Pest(s)						Beneficials																		Pest resurgence [12]			
									Predatory beetles				Predatory bugs							Hymenoptera								
Insecticides (in increasing rank order of impact on beneficials)	Rate (g ai / ha)	Helicoverpa	Mites	Mirids	Aphids	Thrips	Persistence[8]	Overall Ranking[10]	Total[1]	Red & Blue beetle	Minute 2-spt lady beetle	Other lady beetles	Total[2]	Damsel bugs	Big-eyed Bugs	Other Predatory bugs	Apple Dimpling	Lacewing adults	Spiders	Total (wasps)	Trichogramma	Ants	Thrips	Mite	Aphid	Helicoverpa	Toxicity to bees [14]
Bt[11]		✓					very short	very low	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL				VL
NP Virus		✓					very short	very low	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL				VL
Pirimicarb	250				✓		short	very low	VL	VL	VL	VL	L	L	M	VL	VL	VL	VL	VL	M	VL	L				VL
PSO (Canopy)[16]	2%	✓			✓		short	very low	VL	L	L	VL	VL	VL	VL	VL	VL	VL	L	VL	VL	H	VL				VL
Methoxyfenozide	400	✓					medium-long	very low	L	VL	VL	L	L	L	L	VL	VL	VL	VL	VL	VL	VL	VL				VL
Etoxazole	38.5		✓				short	low	VL	VL	-	L	VL	VL	VL	VL	VL	VL	M	L	VL	VL	L				VL
Dicofol[3]	960		✓				long	low	L	-	-	-	L	-	-	-	L	-	L	-	-	-	VL				VL
Amorphous silica[17]	2500	✓					short	low	L	L	-	M	M	-	VL	-	L	L	L	L	-	M	VL				-
Spinosad	96	✓					medium	low	VL	M	L	VL	M	L	H	VL	L	VL	VL	M	H	H	H	+ve			H[15]
Diafenthiuron	350		✓		✓		medium	low	M	H	VL	M	L	M	VL	L	H	VL	L	L	VL	H	L			+ve	M
Pymetrozine	150				✓		short	low	M	M	M	M	L	L	L	VL	H	M	L	L	L	M	VL				VL
Indoxacarb[13]	127.5	✓		✓			medium	low	H[14]	L	VH	VH	L	L	L	L	VH	L	VL	L	VL	VH	VL		+ve		H[15]
Abamectin	5.4	✓[6]	✓				medium	moderate	L	M	H	VL	M	L	M	M	H	VL	M	M	M	H	M				H
Emamectin	8.4	✓					medium	moderate	L	VL	M	VL	H	H	H	H	H	L	M	M	M	VL	M				H
Endosulfan (low)	367.5	✓		✓	✓	✓	medium	moderate	M	VL	VH	M	M	M	M	L	H	L	M	VL	-	VH	H				M[15]
Propargite	1500		✓				medium	moderate	M	H	H	M	M	H	VL	VL	L	VL	M	M	H	H	M		+ve	+ve	L
Acetamiprid	22.5				✓		medium	moderate	M	M	VH	H	M	M	H	M	VH	L	VL	L	H	VH	VH				M[15]
Amitraz	400	✓	✓[9]				medium	moderate	H	M	VH	H	L	-	-	-	H	VL	M	M	L	H	M				L
Fipronil (low)	12.5			✓		✓	medium	moderate	L	VL	H	L	L	H	L	L	VH	VL	M	M	M	VH	VH		+ve	+ve	VH
Chlorfenapyr (low)	200	✓	✓				medium	moderate	M	L	VH	VL	M	VL	H	H	VH	L	L	M	VH	H	M				H
Thiamethoxam	100				✓		medium	moderate	H	H	H	H	M	M	M	H	H	M	VL	M	H	VH	H	+ve		+ve	H
Endosulfan (high)	735	✓		✓	✓	✓	medium	moderate	M	VL	VH	M	M	M	M	M	H	L	M	L	VH	VH	H				M[15]
Fipronil (high)	25			✓		✓	medium	moderate	L	VL	H	L	M	H	H	L	VH	VL	M	M	M	VH	VH	+ve		+ve	VH
Imidacloprid	49			✓	✓		medium	moderate	H	L	VH	H	H	M	H	L	VH	L	L	L	M	H	H	+ve		+ve	M
Methomyl	169	✓					very short	high	H	L	VH	VH	M	L	VH	L	VH	M	M	M	H	H	H	+ve			H[15]
Thiodicarb	750	✓					long	high	VH	M	VH	VH	M	M	L	L	VH	VL	M	M	M	M	H	+ve	+ve		M[15]
Chlorfenapyr (high)	400	✓	✓				medium	high	H	M	VH	L	H	H	H	H	VH	L	M	M	VH	VH	M		+ve		H
OP's[5]		✓	✓	✓	✓	✓	short-medium	high	H	M	H	H	H	M	H	H	VH	L	M	H	H	VH	H	+ve			H
Carbaryl[3]							short	high	H	-	-	-	H	-	-	-	-	-	-	-	-	-	H	-	-	-	H
Pyrethroids[4]		✓	✓[7]	✓[7]			long	very high	VH	-	-	-	VH	-	-	-	VH	VH	VH	VH	VH	VH	VH	+ve	+ve	+ve	H

c) *To understand the mechanism by which cotton recovers from early damage and use to improve existing simulation models.*

i) *Thrips*

These experiments investigated how cotton recovers from early season thrips damage (in collaboration with Dr Tom Lei). Leaf area of cotton seedlings can be reduced by as much as 50% by early season thrips infestations, but it is well documented that plants can regain the difference in leaf area once infestation ceases (compensation). The processes involved in the recovery have not been identified. Hypotheses include enhancement of the photosynthetic rate of the damaged leaves, more efficient leaf construction (i.e. more leaf area per unit of dry matter invested in new leaves), and more branching. This 2-yr field study examined these hypotheses and found that thrips-affected plants recovered from a 30% reduction in total leaf area. During the recovery period, repeated measurements of gas exchange, leaf morphology and individual leaf areas at all nodes were made to assess their contribution to the recovery.

Recovery was not achieved through the previously proposed mechanisms. The pattern of nodal development indicated that the duration of leaf expansion of the smaller deformed leaves was shorter than that of control leaves possibly because they had fewer cells. The production and expansion of healthy upper node leaves in thrips- affected plants could, therefore, begin sooner; about 1 to 2.5 nodes in advance of control plants (see Fig. 13). The proposed process of recovery was evident but weaker in the second year where thrips numbers were higher.

We concluded that thrips affected plants overcame the leaf area disparity through an accelerated ontogeny of main stem leaves. By completing the expansion of smaller but normally-functioning lower node leaves earlier, resources were made available to the unfolding of larger upper node leaves in advance of control plants. The generality of this mode of plant resistance in pest damage remains to be determined. We found that recovery occurs through accelerated ontogeny, which means that thrips damaged plants stop growing damaged leaves earlier, because these leaves are smaller, which allows faster expansion of new leaves.

These experiments have been written up and published in Annals of Botany (see Appendix). This information was presented by Tom Lei at a range of grower and consultant meetings.

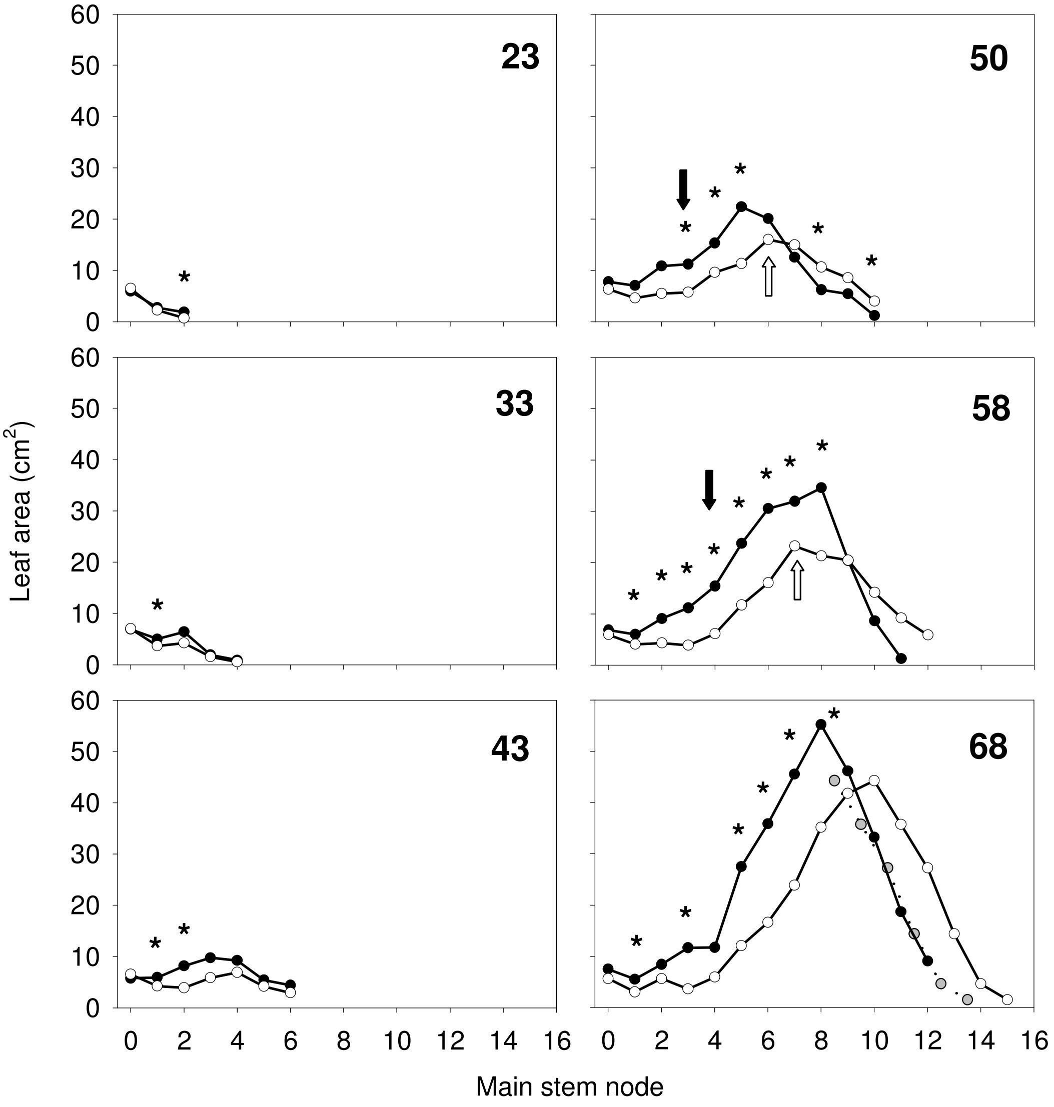

Figure 13. Leaf area development at individual main stem nodes (cotyledon = node 0) through the thrips infestation and recovery periods for control (solid circles) and thrips-infested (open circles) plants in year 1 (2001-02). The number in each panel represents the date of sampling (in days after sowing). Values represent mean of four plots at 5 plants per plot; * indicates differences in leaf area between control and infested plants that were significant at $P<0.05$. Arrows indicate the uppermost fully expanded leaf in control (solid) and infested (open) plants. The line formed by the grey circles in Fig. 4a at 68 DAS shows the correspondence in leaf area between treatment and control when nodal leaf area of infested plants was shifted 2.5 nodes to the left.

ii) *Bollgard II® and compensation*

We investigated if Bollgard II® compensated for early pest damage as well as a conventional variety and if this was affected by sowing date. This was done because some growers and consultants had expressed concerns that Bollgard II® would not compensate as effectively as conventional varieties. This perception probably arose as a result of high yield obtained with some Bollgard II® crops which had with relatively high retention levels, hence the expectation that high retention is required to get high yields from Bollgard II®.

We did an experiment with two varieties (Sicot 189R and Sicot 289BR) and three sowing dates ranging from early October, early November to late November. Damage treatments imposed included tipping out all plants at 4 true leaves, removal of all fruit from the first 4

fruiting branches, both tipping out and fruit removal or undamaged (control).

We found that later sowing dates had significantly lower yields (S1= 240, S2 = 206, S3 = 167 g lint/m^2) and fewer bolls (S1= 129.2, S2 = 122.7, S3 = 109.7 bolls/m^2). Crop development times were affected variably, with the second sowing data having the longest developmental time (S1= 176.7, S2 = 181.2, S3 = 172.8 days) (the lower yields in the later sowings meant that maturity time, in days from sowing to 60% open was about the same). Cultivar also had a significant effect, with the Bollgard II® variety having significantly higher yield (Conv = 194.3, Bollgard II® = 215.1 g lint/m^2) more bolls (Conv = 113.1, Bollgard II® = 127.3 g lint/m^2) and shorter developmental period (Conv = 178.7, Bollgard II® = 175.1 days). Damage caused reduced yield and boll number and increased developmental time (Table 3). Fruit loss and tipping had small but significant effects on yield while the combination reduced yield substantially. Fruit loss delayed maturity by about 9 days, which is similar to other research results (Wilson et al, 2004), and the effect of fruit damage and tipping was additive, as previously found.

Table 3. Effect of damage on yield, boll number and cotton developmental period.

Damage	Yield (g lint/m2)	Bolls (number/m2)	Developmental time (days)
Control	217.2	125.8	169.9
Fruit	210.6	119.7	179.3
Tipping	208.8	125.6	173.5
F + T	182.2	109.7	184.9
LSD	6.8	10.5	2.5

There were also significant interactions between sowing date and cultivar for yield and boll number, whereby the reduction in yield and boll number with later sowings was less with Bollgard II® (Table 4).

Table 4. Interaction between variety and sowing date for yield and boll number, ACRI, 2003-04.

	Yield (g lint/m^2)			Bolls (number/m^2)		
	Sowing			Sowing		
Variety	1	2	3	1	2	3
Conv.	237.9	197.8	147.2	127.2	118.2	93.9
BGII	242.9	214.5	187.8	131.3	127.1	123.5
LSD		21.2			10.64	

There was also a significant interaction between damage and sowing date for yield and crop development (Table 5). Yields were generally more strongly reduced by damage in the latest sowing date, while for crop development sowing 2 took longer to develop but was less affected by fruit or tip damage than on the other sowing dates.

Table 5. Interaction between damage and sowing date for yield and maturity (developmental period), ACRI, 2003-04.

	Yield (g lint/m^2)			Development period (days)		
	Sowing			Sowing		
Damage	1	2	3	1	2	3
Control	244.6	210.1	196.8	169.8	173.0	166.8
Fruit	242.7	213.8	175.3	181.2	185.2	171.5
Tipping	243.5	207.8	175.1	172.5	175.5	172.7
F + T	230.7	193.0	122.9	183.4	191.0	180.3
LSD		23.6			5.0	

Critically however, there was no interaction between damage and variety for yield, boll number or development period. This indicates that the conventional and Bollgard II® varieties responded similarly to damage across sowing dates, and confirms that the compensatory capacity of Bollgard II® is probably at least as good as that of conventional cotton.

d) *To extend research on early pest damage into a range of cotton regions through collaboration with the CRC Cotton Extension Team*

i) Bollgard II® *experiments with IDO's*

Early experience with BGII crops by researchers and consultants showed that in some cases early season fruit retention could be very high. There were concerns that yield of Bollgard II® cotton could be limited by high early retention causing premature cutout. If so there was the opportunity to evaluate if this could be prevented by delaying initial fruit set until plants had a larger canopy. Meetings with-in CSIRO identified this as a research question and we initiated experiments in collaboration with the National Cotton Extension Team to evaluate this risk.

Experiments were conducted with IDO's in 8 regions (Hillston, Gwydir, McIntyre, Upper Namoi, Dalby, Lower Namoi and St George) to test if high retention of BGII crops limited yield. These experiments had two designs – influenced by the availability of the IDO's time. The first design, 'Tip and Fruit' (Hillston, Gwydir, MacIntyre and upper Namoi) tested the effect of high retention by comparing with crops where we artificially manipulated plants by removing the terminals (tipping) to delay fruiting and change plant structure, by removing the first four fruiting branches to delay fruiting and increase early vegetative growth and the combination of these two types of damage. The second design, 'fruit only' (Dalby, Lower Namoi and St George) tested the effects of early fruit loss, either removing all friout from the first 4 or first 6 fruiting branches.

ii) At the Tip and Fruit sites the control treatments has fruit retention of between 81.8 and 85.3% just before removal of fruit. Across the four sites we found a strong site effect on yield, and maturity date, as expected (Table 6a). We found no treatment effect on yield, but a significant delay in maturity (Table 6b). With all damage treatments delaying yield by 1 to 8 days. There was no interaction between site and treatment.

Table 6a. Effect of damage treatment on yield.

	Yield (g lint/m^2)				
Damage treatment	MacIntyre	Gwydir	Upper Namoi	Hillston	Treatment means
Control (undamaged)	220.0	251.5	247.1	162.0	220.2
Tipped	196.9	302.8	218.4	163.7	220.5
Fruit removal from 1st 4 fruiting branches	209.8	281.3	222.8	174.1	222.0
Tipped and fruit removal	205.6	271.3	225.2	182.4	221.1
LSD (treatment)					37.2(ns)
Site means	208.1	276.7	228.4	170.6	
LSD (site)	16.5				
LSD (site x treatment)	35.2 (ns)				

Table 6b. Effect of damage treatment on maturity

	Days later maturing (60% bolls open) than control				
Damage treatment	MacIntyre	Gwydir	Upper Namoi	Hillston	Treatment means
Control (undamaged)	0	0	0	0	0
Tipped	3.3	7.8	0.9	3.4	4.3
Fruit removal from 1st 4 fruiting branches	7.6	7.0	7.6	1.7	3.8
Tipped and fruit removal	4.3	6.1	5.0	1.9	6.0
LSD (treatment)					1.2
Site means	3.8	5.2	3.4	1.8	
LSD (site)	2.3				
LSD (site x treatment)	4.1 (ns)				

At the Fruit Only sites there were significant differences between sites in yield. There was no effect of treatment on yield but a significant effect on crop maturity and an interaction with site (Table 7). Damage caused a delay in maturity compared with the undamaged control. The interaction is due to a low effect of fruit damage at 4 fruiting branches at one site (Upper Namoi, Table 7).

Table 7a. Effect of damage treatment on yield.

	Yield (g lint/m^2)			
Damage treatment	Dalby	Lower Namoi	St George	Treatment means
Control (undamaged)	186.2	176.0	243.8	202.0
Fruit removal from 1st 4 fruiting branches	215.8	178.2	224.4	206.2
Fruit removal from 1st 6 fruiting branches	197.2	178.3	194.2	189.9
LSD (treatment)				25.0 (ns)
Site means	199.7	177.5	220.8	
LSD (site)		24.3		
LSD (site x treatment)		39.79(ns)		

Table 7b. Effect of damage treatment on maturity.

	Days later maturing (60% bolls open) than control			
Damage treatment	Dalby	Lower Namoi	St George	Treatment means
Control (undamaged)	0	0	0	0
Fruit removal from 1st 4 fruiting branches	6.4	2.6	4.5	4.5
Fruit removal from 1st 6 fruiting branches	7.5	8.6	8.0	8.0
LSD (treatment)				2.8
Site means	4.6	3.7	4.2	
LSD (site)		1.2 (ns)		
LSD (site x treatment)		3.0		

We found no evidence of premature cut-out in these experiments, although retention levels were not particularly high and all crops had good growing conditions which would not be likely to generate the high retention and slow growth scenario that might lead to premature cut-out. Nevertheless, it is clear from our results that Bollgard II® crops can compensate well from damage, though with a delay of similar levels to a conventional crop, based on past experiments. These experiments have served to provide IDO's, growers and consultants with experience with the response of crops to damage and also first hand experience with Bollgard II® crops (this work was done before BGII was widely available).

iii) *Ultra narrow row (UNR) and compensation.*

In the more central cotton regions cotton planted on conventional 1m row spacing have been shown to compensate strongly for early damage – often with no loss of yield or delay in maturity. This allows growers to tolerate some early damage, rather than prevent it using insecticides, and hence reduces costs and helps conserve beneficials that will help control pests. In cooler regions such as the Macquarie Valley, compensation is often not as strong as in warmer regions, and though plants do compensate there is a higher risk of some delay in maturity (≈3-4 days) , which can in some years also lead to a reduction in yield (≈ 0 – 5%). Growers in the Hillston region face a short, hot season. One strategy to maximize the use of the solar radiation available has been to use UNR cotton, in an attempt to grow a high yield with shortened crop duration. There has been concern that early damage to UNR cotton will cause delayed maturity, thereby undermining the benefits. In these experiments we compare the response of both UNR and conventional row spacing (1m) cotton to early tip damage and fruit loss.

The trial was carried out at Merrowie in 2002-03 and again in 2003-04. A replicated design was used with planting configuration (UNR or conventional 1m beds) in a split-plot design with the damage treatments arranged randomly within each split-plot. Cotton was planted on the 5th October 2002 (Sicala V3rri) and on the 6th October 2004 (Bollgard 12B). Damage treatments were: Fruit removal (FR), Tip damage at node 2 (Tip2), Tip damage at node 6 (Tip6), Tip damage at node 8 (Tip 8) and Untreated control (Control). The tip out treatment was applied to all three crop rows in each plot when plants had reached the designated true leaf stage. Tip out involved the removal of the terminal using a pair of curved forceps. Fruit damage was inflicted to by removing all fruit from the first four fruiting branches. Weekly maturity picks from 1 m in the centre row were conducted from first boll opening. These recorded the number of bolls picked and the total boll weight. Samples were sent for ginning to ACRI in Narrabri.

The results for the two experiments had some similarities and some differences. In 2002-03 the conventional cotton and the UNR cotton had similar yields, while in 2003-04 the the UNR out-yielded the conventional 1m beds (See Figures 14 and 15). Comparing the effect of damage on yields of UNR and conventional showed no difference in 2002-03 – though there is a trend for yield to be maintained after damage in the conventional, and to decline with damage in the UNR (Figure 14). A similar pattern is evident in 2003-04 where there was no effect of damage on yield for the conventional, but in the UNR two damage treatments (Fruit removal and tipping at node 8) yielded significantly less than the undamaged control (Figure 15).

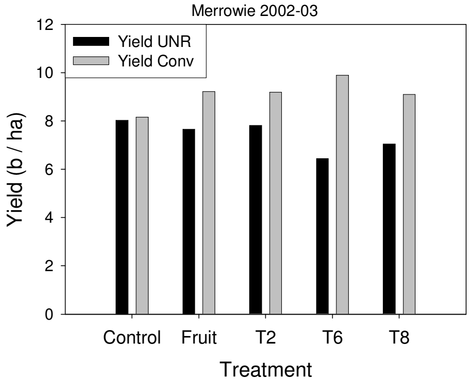

Figure 14. Damage did not cause a significant yield reduction in either UNR or conventional cotton in 2002-03.

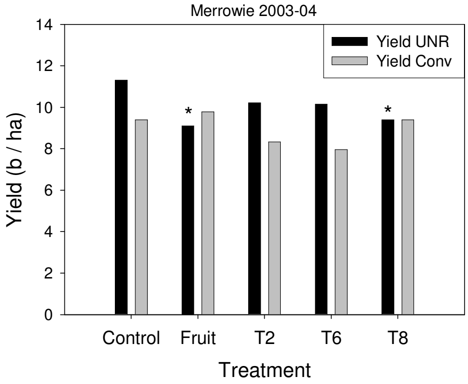

Figure 15. Damage did not cause a significant yield reduction in conventional cotton in 2003-04 but did significantly reduce yield in UNR (indicated by asterisks – these treatments are significantly different to the control UNR).

In a combined analysis across both years there is a strong trend (P = 0.07) for damage to have no effect on yield in conventional but to consistently cause a reduction in yield in UNR (Fig 16). An exception to this is the tipping at node 2 which had no effect on yield in either conventional or UNR configurations.

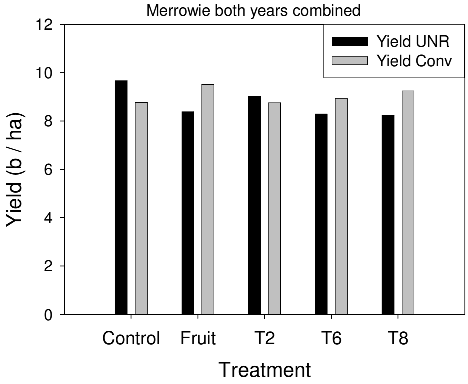

Figure 16. Across both years there was a trend for damage to have no effect on yield in conventional but to reduce yield in UNR.

Row configuration had no significant effect on crop maturity data. In other words the UNR matured at the same time as the conventional 1m beds (look at the control treatments in Figs 17 and 18).

In 2002-03 the fruit removal and tipping at node 6 or 8 caused similar significant delays in maturity in both UNR and conventional 1m beds (Figure 17). However, tipping at node 2 led to earlier maturity in both planting configurations.

In 2003-04 the fruit damage and tipping at node 8 (and node 6 in conventional) caused delays in maturity in both UNR and conventional of about 8 to 10 days. Tipping at node 2 did not affect maturity date (Figure 18).

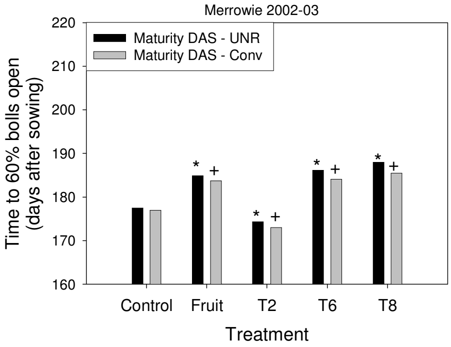

Figure 17. Damage to early fruit or tipping at nodes 6 or 8 caused a significant delay in maturity in UNR and conventional (indicated by asterisks or crosses).

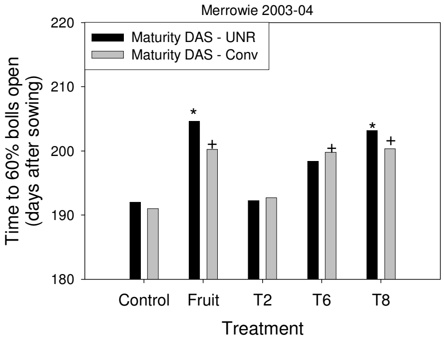

Figure 18. Damage to early fruit or tipping at nodes 8 (and 6 in conventional) caused a significant delay in maturity in UNR and conventional (indicated by asterisks or crosses).

Looking across both years combined there was a significant treatment effect of treatment on yield but the response was the same for both row configurations. Tipping at node 2 did not cause delay, but fruit removal or tipping at node 6 or 8 caused a delay of about 9 days (Fig 19).

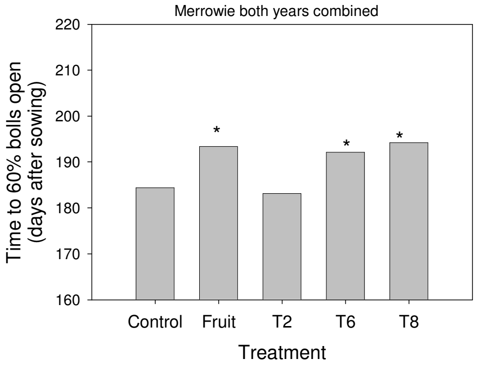

Figure 19. Damage to early fruit or tipping at nodes 6 or 8 caused a similar significant delay in maturity in both UNR and conventional (indicated by asterisks).

The results show that early damage has little effect on the yield of cotton grown on conventional 1m beds, whereas similar damage tend to cause a reduction in yield in UNR cotton. Damage caused similar delays in maturity in both UNR and conventional with the early fruit loss and node 6 or node 8 tip damage treatments causing about 9 days delay. In terms of IPM this means that tolerating early damage in cotton on a 1m row spacing probably won't affect yield but may cause delay in maturity. This delay may in some years translate into a yield reduction as well. In UNR cotton protection from early damage would appear more important as both yield and maturity could be affected.

iv) *Effect of tip damage on cotton yield and maturity at Hillston.*

Experiments in warm cotton regions, such as the Namoi and Gwydir Valleys, have found that tip damage has little effect on either yield or maturity date of cotton unless the damage is very severe. Early fruit loss didn't affect yield but did cause a delay in maturity of 7 days. For cooler regions the situation may be different. Experiments in the Macquarie Valley have shown less consistent recovery of plants from early tip damage, with both yield and maturity date sometimes negatively affected. The experiments reported here were designed to investigate the recovery of cotton in the Hillston Region after tip damage and early fruit loss. In this region the shorter growing period may limit the capacity of plants to recover from damage. Any delay in crop development could therefore potentially have a greater effect on yield. We also considered the effect of later tip damage events and early fruit loss.

Trial sites were selected at the properties 'Lachlan' and 'Gundaline'. The cotton was grown on a conventional row spacing and managed according to the growers normal practice. Sicala V3rri was sown at Gundaline on the 1st October, 2002 and Bollgard 12B was sown on the 25th September at Lachlan Farming. Pests (insects and weeds) were controlled as required. The varieties were Ingard® that had been treated with Temik to avoid damage by early season sucking insects. There were 5 treatments by 4 reps totalling 20 plots, (each plot was 2 x 3 m). The trial design was a Randomised Block design. Treatments were: Fruit removal (FR), Tip damage at node 2 (Tip2), Tip damage at node 6 (Tip6), Tip damage at node 8 (Tip 8) and Untreated control (Control).

The tip out treatment was applied to all three crop rows in each plot when plants had reached the designated true leaf stage. Tip out involved the removal of the terminal using a pair of curved forceps. Fruit damage was inflicted to by removing all fruit from the first three fruiting branches. Weekly maturity picks from 1 m in the centre row were conducted from first boll opening. These recorded the number of bolls picked and the total boll weight. Samples were sent for ginning to ACRI in Narrabri. A final plant map was recorded after the last maturity pick to consider the effect of damage treatments on plant growth and structure.

Damage did not affect yield at Gundaline or Lachlan Farming (Figs 20 and 21). Neither fruit removal nor tip damage had any effect on the number of bolls per metre or crop yield. Crop maturity was affected with tip damage at node 6 or 8 causing a significant delay in maturity of 3 to 4 days at Gundaline (Fig 22) and tip damage at node 8 causing almost 7 days delay at Lachlan Farming (Fig 23).

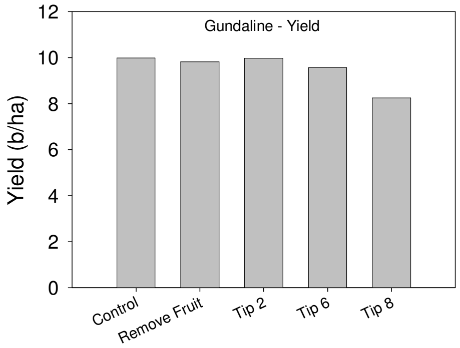

Figure 20. Damage treatments did not affect yield at Gundaline.

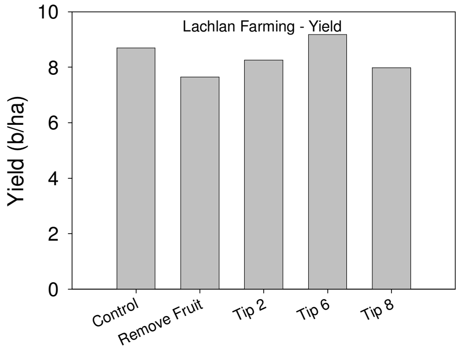

Figure 21. Damage treatments did not affect yield at Lachlan Farming.

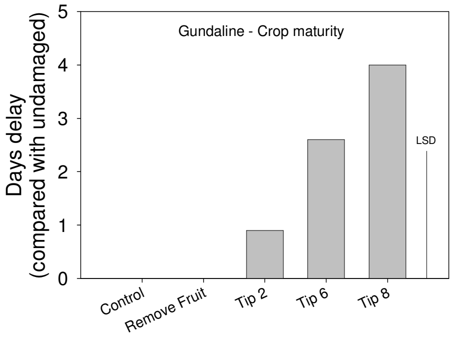

Figure 22. Tip damage at nodes 6 or node 8 caused a significant delay in maturity of about 3 to 4 days at Gundaline.

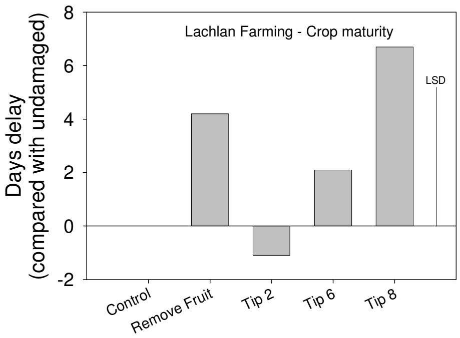

Figure 23. Tip damage at node 8 caused a significant delay in maturity of about 6 days at Lachlan Farming.

The results suggest that cotton sown on conventional 1m beds has quite strong capacity to recover from early tip damage in the Hillston region. However, later tip damage, at nodes 6 or 8, carries a higher risk of delayed maturity. Although it was not the case in this season, such a delay in some seasons could result in boll maturation under cooler conditions and therefore carry a risk of yield loss, and possibly reduced fibre quality as well. Further simple experiments over successive years could help confirm this result.

v) *Can early plant architecture or boll set be manipulated to increase yield.* We investigated if yield could be increase in Bollgard II® by inflicting damage on young plants by cutting off the terminal and upper leaves with a whipper snipper, and also explored the practicality of causing some square shedding using low rates of Prep. Our hypothesis was that inflicting tip damage or causing square shedding would allow plants to develop a bigger structure and carry more fruit. None of the treatments improved yield nor did they cause delayed maturity (Table 8). The higher Prep rates did cause some fruit shed.

Table 8. Effect of damage treatment on yield and maturity.

		Prep treatments			Tip treatments		
	Control	Prep 1 (0.28 g ai/ha)	Prep 2 (0.14 g ai/ha)	Prep 3 (0.07 g ai/ha)	Tipped at 6 nodes	Tipped at 12 nodes	*P*
Yield (machine harvested, b/ha)	12.1	10.9	10.7	11.2	10.6	11.0	0.27
Maturity (days after sowing)	171.5	172.5	170.9	171.7	171.6	173.4	0.65

e) *Opportunistically investigate the economic significance of minor pests*

i) *Late damage experiment*

There is growing concern amongst grower and consultants about late season damage from pests such as thrips, that cause leaf distortion, and jassids, that cause whitening up the upper leaf surface. These pests are normally not a problem late season in conventional crops as they are controlled by insecticides applied against other pests. However in low spray conventional crops and especially in Bollgard II® crops number can build up to the point that crops receive considerable damage, for instance up to 80% of the leaf area severely damaged by jassids. A further factor is the recording of western flower thrips in cotton regions. This species causes damage similar to other thrips but is also resistant to some insecticides, which may make it harder to manage and may necessitate a resistance management strategy if it becomes a frequent problem. Growers need information on the response of crops to such late season damage. The challenge for crop mangemange is to balance the beneficial value of thrips in controlling spider mites, the value of the damage these pests cause, the costs of their control, including non-target effects that may necessitate later control of secondary pests.

We investigated whether late season damage to upper leaves could affect yield by cutting off the top 25 cm of growth from plots or removing the top six mainstem node leaves or leaving plants undamaged) control) of cotton that was at cut-out. This simulates a worst case scenario of complete loss of the upper part of the canopy. A randomised block design was used with 5 replicates. Maturity picks were done to estimate yield and maturity effects. We found that although differences were not significant they indicated potential yield loss and this issue should be investigated further (Table 9). For 2005-06 we have developed a physiological framework to explore how manipulation of the size and photosynthetic rate of later leaves, which are the youngest and most photosynthetically active on the plant, can be manipulated to increase yield (with Steve Yeates and Greg Constable) and also to understand effects of damage on potential yield.

Table 9. Effect of late season damage treatment on yield and crop maturity.

	Treatment			
	Control	Top 25 cm removed	Top 6 mainstem nodes removed	P
Maturity (days after sowing reached 60% bolls open)	187.2	185.6	186.9	0.40
Yield (g lint/ha)	254.0	209.1	196.1	0.09

Do jassids affect yield?

Jassids have emerged as a more frequent, though intermittent, problem in the late season in crops with low or very selective spray regimes, especially Bollgard II®. Earlier studies showed that severe jassid damage (about 80% of the upper surface of the upper leaves damaged) could reduce the photosynthetic rate of cotton leaves by about 20%. We have been trying to follow this through by investigating if jassids can cause reductions in yield. We set up experiments in each year of this project but jassid numbers were very low in the first two years. In 1004-05 jassid numbers in a field at ACRI were higher so we took the opportunity to set up a simple field experiment to see if they affected yield.

We used a simple replicated design, with treatments being:
Untreated = Jassids
Control 1 = no Jassids from now (control with Pegasus)
Control 2 = no jassids from 3 weeks from now
Control 3 = no jassids from 5 weeks from now.

We used plots large enough that we could machine pick to obtain the most realistic yield results. Jassid numbers were scored using a sweep net sample from each plot as they are too flighty to count *in situ* (20 sweeps per 18 m plot). We score damage symptoms on leaves 3, 6 and 10 on 10 plants per plot both upper and lower surface. The damage score was based on % of leaf surface estimated to be damaged; 1 = 0 – 10 %, 2 = 11 – 20, 3 = 21 – 40, 4 = 41 – 60, 5 = 61 – 80, 6 = 81- 100).

We were successful in generating highly significant differences between treatments in damage (e.g. Fig 24 for average upper leaf surface damage), though the damage scores never rose about a score of 2 (10-20% leaf area damaged). Similarly we were successful in generating differences in jassid numbers between treatments (Fig 25 for average jassid score per plot). Our results showed no significant effects of jassids on yield (Control 1 = 8.6 b/ha, Control 2 = 7.9 b/ha, Control 3 = 7.5 b/ha and untreated = 7.7 b/ha)), though there was a trend toward those plots with the highest number if jassids having lower yields. Plotting jassid numbers or damage against yield suggests that there is a relationship between jassids and yield loss (Fig 26). We will continue this research in 2005-06 to try to refine thresholds.

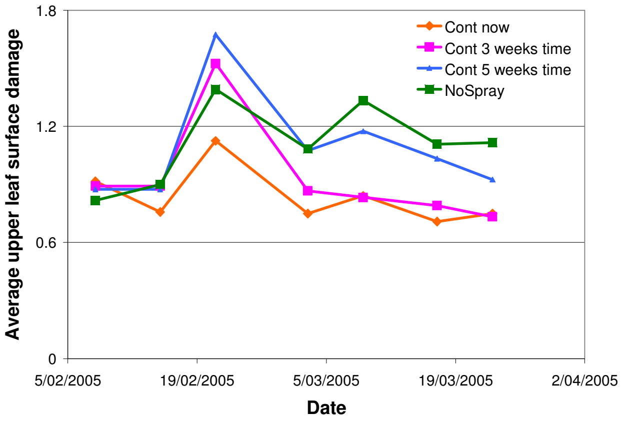

Figure 24. Average leaf damage score for different jassid control treatments, averaged across nodes 3, 6 and 10 for each date.

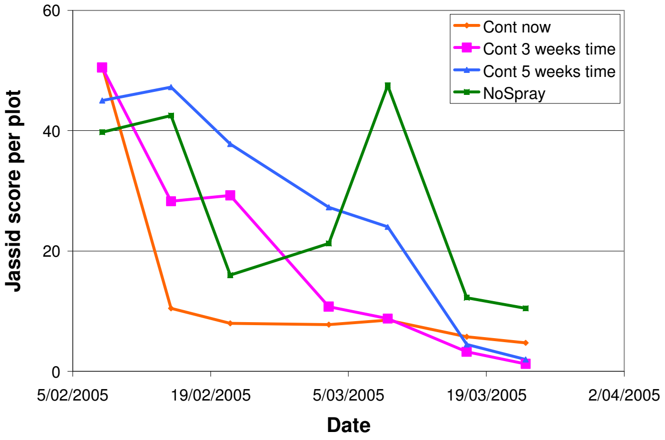

Figure 25. Average jassid numbers per sweep net sample per plot for different jassid control treatments for each date.

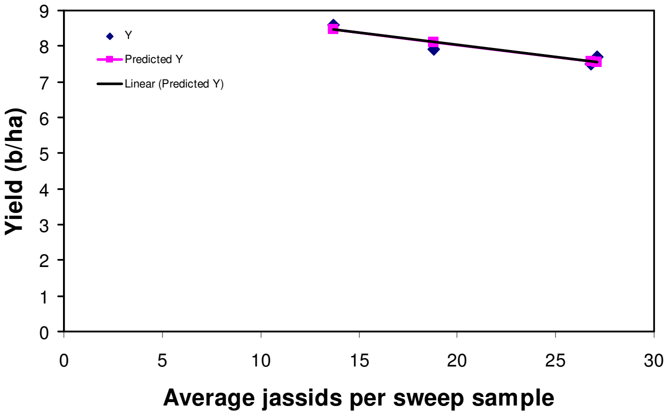

Figure 26. Regression of yield against average jassid numbers per sweep net sample per plot showing statistically significant trendline ($r^2 = 0.8$).

Conclusion

a) Aphids can reduce the photosynthetic rate of cotton, reducing yield and development. A statistical relationship predicting yield loss from aphid densities has been developed and used to produce look-up charts to estimate potential yield losses from this pest.

b) A table summarising the effects of all currently available insecticides and miticides on beneficial predators and parasites was developed and has been updated regularly with data from this project, as well as that from collaborators. This table (IPM Supporting Document 1 'Impact of insecticides and miticides on predators in cotton') has been widely distributed and used throughout the industry and served as a template for other crops.

c) Cotton can recover from damage by thrips through a process known as 'accelerated ontogeny'. This information can be used to update thrips compensation routines under development in the OZCOT cotton simulation model.

d) Bollgard II® cotton varieties can compensate as well as or better than conventional varieties.

e) A range of activities were co-ordinated with the Cotton Extension Team which helped increase their knowledge of cotton compensation, provided first hand experience with Bollgard II® and provided valuable additional research data. Outcomes from experiments were (i) cotton with early retention levels of 80-85% showed no indication of premature cut-out and treatments to manipulate plant growth to avoid this problem did not increase yield but did cause delay ii) UNR cotton is less able to compensate for early damage than cotton on conventional 1 m beds. 3) In conventional cotton in a cool region (Hillston) later tip damage, at nodes 6 or 8, carries a higher risk of delayed maturity.

f) Cotton growth can be manipulated using mechanical or chemical damage (Prep) but these did not increase yield.

g) Late season damage to younger leaves may have a greater effect on yield than expected and should be investigated further.

h) Jassid damage may affect the yield of cotton. An initial experiment showed a negative linear relationship between jassid density and yield. This should be investigated further.

Outputs

This project has provided the cotton industry with information to better manage aphids, to select insecticides to more closely match the pest situation and to conserve beneficials, and to better manage compensation in Bollgard II® and to better manage late season pest damage. All of these advances help growers and consultants to manage pest in cotton with greater knowledge and confidence that will allow better decisions. This help address the CRDC three outputs via, better yields (profitability) through improved pest management decisions, by selection of more selective insecticides and by better understanding of pest thresholds and the role of beneficials to reduce insecticide use (and this has been well documented elsewhere), and thereby also help to contribute to a more sustainable cotton industry essential to the well being of small rural communities.

Summary

a) *technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.)*

Development of look-up table for establishing if aphids will affect yield loss. Development of look up charts to understand effects of insecticides on beneficials. Development of on-line version of the Cotton Pest and Beneficial Guide.

b) *other information developed from research (eg discoveries in methodology, equipment design, etc.)*
Development of methods for mass rearing aphids and manipulation of populations for yield loss experiments
Development of techniques to evaluate the effects of late season damage on aphids
Development of techniques to investigate the effects of aphids on photosynthesis in cotton

Further Activities

(a) *to further develop or to exploit the project technology.*
Most of the findings from this research have been disseminated to industry already via industry conferences, field days, the Cotton Pest Management Guide and Cotton CRC Research Reviews.

(b) *for the future presentation and dissemination of the project outcomes.*
The key opportunity for this project is to finalise, and develop an extension plan for the aphid / yield loss outcomes. This could be via the Australian Cottongrower, Cotton LOGIC, Cotton Tales and interactions with the National Cotton Extension Team. There is also a great opportunity to involve IDO's and interested consultants in growers in experiments to help understand the effects of late season damage on yield. Simple protocols could be developed, similar to the approach taken previously with early damage.

(c) *for future research.*
This has already been addressed in the development of e new project 'Supporting IPM for Future Cotton Systems'. This project has the specific aims to;
i) Define the economic significance of emerging pests such as jassids and late season thrips.
ii) Determine the non-target effects of new insecticides and new low beneficial impact options and the risk for resurgence of secondary pests
iii) Understand the effect of variety, crop agronomy and predation on development of aphid populations.

Publications

Refereed papers and conference papers

Wilson, L.J., Sadras, V.O., Heimoana, S.C. and Gibb, D. (2003) How to succeed by doing nothing: Cotton compensation after simulated early pest damage. Crop Science 43, 2125- 2134

Wilson, L.J., Mensah, R.K. and Fitt, G.P. (2004) IPM in Australian cotton. In: Proceedings of the World Cotton Research Conference III, Cape Town, South Africa, March 2003.

Lei, T.T. and Wilson, L.J. (2004) Recovery of leaf area through accelerated shoot allometry in thrips damaged cotton seedlings. Annals of Botany 94, 179-186.

Reddall, A.A., Sadras, V.O., Wilson, L.J. and Gregg, P.C. (2004) Physiological responses of cotton (*Gossypium hirsutum* L.) to two-spotted mite (*Tetranychus urticae* Koch) damage. Crop Science 44, 835-846

Wilson, L.J., Mensah, R.K. and Fitt, G.P. (2004) Implementing IPM in Australian cotton. In: Novel Approaches to Insect Pest Management in Field and Protected Crops, A. Rami Horowitz and I. Ishaaya (eds), Springer-Verlag, Berlin, pp 97-118.

G.A. Herron, J. Rophail and L. J. Wilson (2004) Chlorfenapyr resistance in two-spotted spider mite (Acari: Tetranychidae) from Australian cotton. Experimental and Applied Acarology. 34:315-321

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Whitehouse, M.E.A., Wilson, L.J. and Fitt, G.P. (2005) A comparison of arthropod communities in transgenic Bt and conventional cotton in Australia. Environmental Entomology 35: 1224-1241.

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G.A. Herron and L.J. Wilson (2004) The management of cotton aphid (Aphis gossypii Glover) in Australian cotton. International Congress of Entomology, Brisbane, August 2004.

TT Lei, B Duggan, M Khan & LJ Wilson (2004) Responses of cotton to actual and simulated green mirid boll damage. International Congress of Entomology, Brisbane, August 2004.

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Wilson, L.J., Lei, T.T. and Takenaka. A. (2004) Compensation for pest damage: Linking pest and damage based thresholds. International Congress of Entomology, Brisbane, August 2004.

Extension materials

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Deutscher and Wilson (2003) Pest and Beneficial Guide. WWW tool (http://www.cotton.pi.csiro.au/insects.htm)

Lei , T., Baguley, K., Cameron, D. and Wilson, L. (2003) Can high yield potential crops recover from pest damage. Aust. Cottongrower 24(7) 50-51

Franzmann, B., Smith, L., Trackson, K. and Wilson L. (2004) The silverfly: A predator of cotton aphid. Aust. Cottongrower 25(1): 24-26.

Rossiter, L., Wilson, L., Larsen, D., Pyke, B., Gunning, R., Herron, G., and Kelly, D. (2003) Insecticde resistance. Where are we now? Australian Cotton CRC Information Sheet.

Wilson, Lei and Heimoana (2003) How much tip damage can you stand? CSD Trial results booklet pp 94-96.Farrell, T., Wilson, L., Mensah, R. and Dillon, M. (2004) Key insect and mite pests of Australian cotton. Cotton Pest Management Guide 2004-2005, pp 1 – 9. CRC and NSW DPI Publication.

Wilson, L., Mensah, R., Johnson, A. and Deutscher, S. (2004) Integrated Pest Management (IPM) guidelines for Australian cotton. Cotton Pest Management Guide 2004-2005, pp 16 – 29. CRC and NSW DPI Publication.

Rossiter, L., Gunning, R., Herron, G., Larsen, D., Pyke, B., and Wilson, L. (2004) Insecticide resistance management strategy for conventional cotton 2004-05. Cotton Pest Management Guide 2004-2005, pp 1 – 9. CRC and NSW DPI Publication.

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Khan, M., Kelly, D., Hickman, M., Mensah, R., Brier, H. and Wilson, L. (2004) Mirid management in Australia cotton (Australian Cotton CRC Research Review. No. 15.

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Farrell, T., Mensah, R., Wilson, L., and Dillon, M. (2005) Key insect and mite pests of Australian cotton. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 1-17

Wilson, L., Deuscher, S., Mensah, R., and Johnson, A. (2005) Integrated pest management (IPM) guidelines for Australian cotton II. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 18-31

Rossiter, L., Farrell, T., Larsen, D., Kauter, G., Downes, S. and Wilson, L. (2005) Insecticide resistance management strategy for 2005-06. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 32-36

Downes, S., Wilson, L., Kauter, G. and Farrell, T. (2005) Preamble to the resistance management plan for Bollgard II® 2005-06. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 37-46.

Online Resources

The project principal researcher was a significant contributor to each of the following on-line resources.

Cotton pest and beneficial guide (http://www.cotton.crc.org.au/insects.htm)

Cotton pest management guide (http://www.agric.nsw.gov.au/reader/cotton-pest-management)

Mirid ecology in Australian cotton (http://www.cotton.crc.org.au/Assets/PDFFiles/miridec.pdf)

Mirid management in Australian cotton (http://www.cotton.crc.org.au/Assets/PDFFiles/miridmgt.pdf)

Integrated pest management guidelines for cotton production systems in Australia
(http://www.cotton.crc.org.au/Assets/PDFFiles/IPMGL05/IPMGLFor.pdf)

Insecticide resistance; where are we now?
(http://www.cotton.crc.org.au/Assets/PDFFiles/resist03.pdf)

Impact of insecticides and miticides on predators in cotton. October 2005 update
(http://www.cotton.crc.org.au/Assets/PDFFiles/IPMGL99/IPMSD01.pdf)

Impact on the cotton industry.

The results and conclusions from this project will contribute substantially to improving our understanding of the effects of pests and their damage on cotton yield and maturity, and will improve the use and selection of insecticides. Importantly this project has evolved from earlier projects to address emerging issues, such as aphids and late season damage from jassids and thrips and compensation and effects of high retention in Bollgard II® crops.

Executive Summary

Over the past 10 years the rapid uptake of IPM and transgenic cotton has allowed a dramatic reduction in the use of insecticides in cotton. However, new technologies bring new challenges, and amongst these for Bollgard II® cotton and IPM systems is the emergence of pests that were previously controlled by insecticides applied against other pests. A further challenge is the potential for high retention in Bollgard II® crops which may affect compensatory capacity and potentially limit yield through premature cut-out. This project has addressed four broad areas of relevance in the Bollgard II® era.

1) The effect of aphids on cotton photosynthesis and yield.
Our research has shown clearly that aphids can reduce the photosynthetic rate of cotton, resulting in reduced yield and development. A statistical relationship predicting yield loss from aphid densities has been developed and used to produce look-up charts to estimate potential yield losses from this pest. This relationship will be used to enhance the CottonLOGIC decision support tool.

2) Effect of insecticides and miticides on predators and parasites.
A table summarising the effects of all currently available insecticides and miticides on beneficial predators and parasites was developed and updated regularly with data from this project, as well as that from collaborators. This table (IPM Supporting Document 1 'Impact of insecticides and miticides on predators in cotton') has been widely distributed and used throughout the industry and served as a template for other crops.

3) Effect of early damage on Bollgard II® and UNR cotton.
We found that cotton can recover from damage by thrips through a process known as 'accelerated ontogeny'. This is when the plant ceased development of damage leaves early in order to speed up the development of new, undamaged leaves to recover leaf area. This information will be used to update thrips compensation routines under development in the OZCOT cotton simulation model. A range of experiments were co-ordinated with the Cotton Extension Team. Outcomes from experiments were (i) Bollgard II® cotton varieties can compensate as well as or better than conventional varieties (ii) cotton with early retention levels of 80-85% showed no indication of premature cut-out and treatments to manipulate plant growth to avoid this problem did not increase yield but did cause delay iii) UNR cotton is less able to compensate for early damage than cotton on conventional 1 m beds (iv) in conventional cotton in a cool region (Hillston) later tip damage, at nodes 6 or 8, carries a higher risk of delayed maturity. Outcomes of this research have been extended to industry and have also increased IDO and crop manageger's knowledge of cotton compensation and provided valuable additional research data

4) Emerging pests and late season damage.
We found that late season damage to younger leaves (i.e. removal of the top 25 cm or top 6 main stem leaves) may have a greater effect on yield than expected. This raises questions about late season thresholds for leaf damaging as opposed to fruit damaging pests and should be investigated further. We also investigated the effect of jassids on cotton yield and found a initial experiment showed a negative linear relationship between jassid density and yield. This should be investigated further.

CSIRO

CSIRO Plant Industry
Cotton Research Unit
and
Australian Cotton CRC

FINAL REPORT

Project title: Incorporating aphids, insecticides and early season plant compensation in IPM

Project code: CSP147C

Research organisation: CSIRO Plant Industry

Principal researcher:
Dr Lewis Wilson
CSIRO Plant Industry
PO Box 59
Narrabri 2390 (Phone 02-67991550)

Supervisor:
Dr Greg Constable
CSIRO Plant Industry
PO Box 59
Narrabri 2390 (Phone 02-67991522)

Cotton CRC

A final report prepared for the Cotton Research and Development Corporation

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Australian Government

Cotton Research and Development Corporation

Annual, Progress and Final Reports

Part 1 - Summary Details

REPORTS

Please use your TAB key to complete Parts 1 & 2.

CRDC Project Number: **CSP147C**
Annual Report: ☐ Due 30-September
Progress Report: ☐ Due 31-January
Final Report: ☒ Due 30-September-2005

Project Title: Incorporating aphids, insecticides and early season plant compensation in IPM

Project Commencement Date: 1.7.2002 **Project Completion Date:** 31.6.2005
Research Program: 3 Crop Protection

Part 2 – Contact Details

Administrator: Jo Cain, Administration Manager
Organisation: CSIRO Plant Industry
Postal Address: Locked Bag 59, Narrabri, NSW, 2390
Ph: 02-67991513 **Fax:** 02-67931186 **E-mail:** jo.cain@csiro.au

Principal Researcher: Dr Lewis Wilson
Organisation: CSIRO Plant Industry
Postal Address: Locked Bag 59, Narrabri, NSW, 2390
Ph: 02-67991550 **Fax:** 02-67931186 **E-mail:** lewis.wilson@csiro.au

Supervisor: Dr Greg Constable
Organisation: CSIRO Plant Industry
Postal Address: Locked Bag 59, Narrabri, NSW, 2390
Ph: 02-67991522 **Fax:** 02-67931186 **E-mail:** greg.constable@csiro.au

Signature of Research Provider Representative: G Constable

Executive Summary

Incorporating aphids, insecticides and early season plant compensation in IPM

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Our research has shown clearly that aphids can reduce the photosynthetic rate of cotton, resulting in reduced yield and development. A statistical relationship predicting yield loss from aphid densities has been developed and used to produce look-up charts to estimate potential yield losses from this pest. This relationship will be used to enhance the CottonLOGIC decision support tool.

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A table summarising the effects of all currently available insecticides and miticides on beneficial predators and parasites was developed and updated regularly with data from this project, as well as that from collaborators. This table (IPM Supporting Document 1 'Impact of insecticides and miticides on predators in cotton') has been widely distributed and used throughout the industry and served as a template for other crops.

3) Effect of early damage on Bollgard II® and UNR cotton.
We found that cotton can recover from damage by thrips through a process known as 'accelerated ontogeny'. This is when the plant ceased development of damage leaves early in order to speed up the development of new, undamaged leaves to recover leaf area. This information will be used to update thrips compensation routines under development in the OZCOT cotton simulation model. A range of experiments were co-ordinated with the Cotton Extension Team. Outcomes from experiments were (i) Bollgard II® cotton varieties can compensate as well as or better than conventional varieties (ii) cotton with early retention levels of 80-85% showed no indication of premature cut-out and treatments to manipulate plant growth to avoid this problem did not increase yield but did cause delay iii) UNR cotton is less able to compensate for early damage than cotton on conventional 1 m beds (iv) in conventional cotton in a cool region (Hillston) later tip damage, at nodes 6 or 8, carries a higher risk of delayed maturity. Outcomes of this research have been extended to industry and have also increased IDO and crop manageger's knowledge of cotton compensation and provided valuable additional research data

4) Emerging pests and late season damage.
We found that late season damage to younger leaves (i.e. removal of the top 25 cm or top 6 main stem leaves) may have a greater effect on yield than expected. This raises questions about late season thresholds for leaf damaging as opposed to fruit damaging pests and should be investigated further. We also investigated the effect of jassids on cotton yield and found a initial experiment showed a negative linear relationship between jassid density and yield. This should be investigated further.

1. Outline the background to the project.

This project was the sixth in a series of projects (CSP1C, CSP21C, CSP46C, CSP74C, CSP103C). These projects have been successful in developing industry management guidelines and thresholds for pests such as mites and thrips. The series has pioneered research into understanding the ecology of secondary pests, identifying the role of beneficials in regard to pest management, especially for spider mites, evaluating the IPM fit of new and existing chemistry and providing well accepted information on the early compensatory capacity of cotton. This information has been incorporated into the current Integrated Pest Management Guidelines for cotton. However, there are continuing and new challenges to our IPM systems that we need to address. This project consists of four separate but related components, each building on the outcomes of earlier projects.

Effects of aphids on cotton development and yield

Cotton aphid emerged recently as a major pest due to changes in pest management systems including reduced early season spraying (particularly with endosulfan), use of Ingard® cotton, the advent of Cotton Bunchy Top and recently detected resistance to organophosphates and carbamates in cotton aphid. The latter two issues were causing considerable nervousness in the cotton industry, which undermined both resistance management and development of IPM. As new selective aphicides and more CBT resistant cotton varieties become available, emphasis will return to the use of economic thresholds to decide when to control aphids. This will require a thorough understanding of the effects of aphids on growth and yield of cotton at different stages through the season. Project CSP103C made good progress in this area, particularly in evaluating the effects on yield of aphid populations initiated at different times through the season and in the development of reliable aphid mass rearing, artificial infestation and management techniques. However further research was required to understand a wider range of infestation timing and intensities, the timing of control and possible differences between varieties in response to aphid feeding. This will allow the potential yield effects of given aphid populations to be predicted and allow development of new thresholds and decision support tools.

Mechanisms of recovery of cotton after early damage

The recovery of cotton following early season pest damage received considerable attention in earlier projects (CSP74C and CSP103C). This included studies of the direct effects of pests, such as thrips and green mirids, as well as a wide range of experiments using simulated pest damage. The latter have included different types, timings and intensities of damage and also begun to investigate interactions with other stresses such as water stress.

Outcomes of this research were widely publicised through the industry via extensive collaboration with CRC Industry Development Officers who also conducted damage experiments in all cotton regions. This research was critical in the development of effective IPM systems for cotton by providing growers and consultants with the confidence to tolerate some damage, thereby reducing insecticide use. We propose to continue to work with the CRC IDO's to extend research to other regions, with a particular emphasis on high retention Bollgard II® crops and on ultra narrow row (UNR) cotton. In addition we will use more detailed experiments to monitor changes in plant growth, plant architecture, leaf structure and photosynthetic efficiency in response to pest damage. Outcomes will be improved understanding of cotton compensation in the new

Bollgard II® crops, understanding of issues for UNR cotton and data to improve compensation routines in the OZCOT model.

Non-target effects of insecticides
Integrated pest management relies heavily on conservation of beneficial insects, which will help manage pests. Understanding of both the efficacy and the non-target effects of insecticides is critical for their effective use in IPM. Over the last ten years a series of projects (CSP1C, CSP21C, `CSP46C, CSP74C and CSP103C) has evaluated the non-target effects of most existing and new chemistry. This research been used to provide growers and consultants with independent information on the non-target effects of insecticides and was used to develop IPM Supporting Document 1 'Impact of insecticides and miticides on predators in cotton' which forms part of the Integrated Pest Management Guidelines for Australian Cotton. This research needs to be continued as new insecticides become available and will be even more valuable in the two-Bt-gene era as there will be increasing emphasis on selective control of all pests. This project will focus on providing basic information on the non-target effects of new chemistry. A companion project by Dallas Gibb and Viliami Heimoana (NSW Agriculture) will focus on the efficacy of new chemistry and mixtures against target pests, with emphasis on *Helicoverpa* and aphids.

Emerging minor pests
As the use of insecticides declines on farms, due to the use of Ingard® and Bollgard II® cotton and due to increasing adoption of IPM strategies, there are more frequent reports from growers and consultants of unusual minor pest problems. For instance, in fields with little broad-spectrum insecticide use, jassids often build to quite high numbers, causing significant damage to older and sometimes younger leaves. The effect of such populations on yield is probably small but remains unknown and needs to be clarified. Such situations are likely to be more common as we move to Bollgard II® cotton. This project will also include a 'flexible focus' to opportunistically collect information on the economic significance of jassids and other minor pests. This would include preliminary yield loss data and assessment of pest numbers and plant growth.

2. List the project objectives and the extent to which these have been achieved.

i. *To develop detailed quantitative data relating aphid effects to cotton growth and yield and link that with Cotton LOGIC and OZCOT*
Experiments have been conducted to establish the relationship between aphids and yield loss. Relationships to predict yield loss from aphids have been developed. Linkages with OZCOT and CottonLOGIC have yet to be established. The PhD research of the project Senior Technical Officer (STO), Ms Simone Heimoana, is well underway. She has taken regular field measurements of the effect of aphids on photosynthesis of cotton and conducted field and glasshouse experiments to investigate the relationship between aphid density, honeydew and declines in photosynthesis.

ii. *To quantify the effects of insecticides on pests, predators and parasitoids.*
Large replicated experiments were done in each year of the project. IPM Guidelines Document 1 'Impact of insecticides and miticides on predators in cotton' was updated twice for the cotton industry.

iii. *To understand the mechanism by which cotton recovers from early damage and use to improve existing simulation models.*
Experiments investigating recovery from thrips damage were completed and the results have been written up and published in Annals of Botany. Data will be used to

improve the OZCOT model in future. We also investigated if Bollgard II® compensated for early pest damage as well as a conventional variety and if this was influenced by sowing date. This has been completed and analysed.

iv. *To extend research on early pest damage into a range of cotton regions through collaboration with the CRC Cotton Extension Team*
A range of activities were co-ordinated with the Cotton Extension Team, including

a. *Bollgard II® experiments with IDO's*
Experiments were conducted with IDO's in four regions to test if yield of Bollgard II® cotton would be limited by high retention causing premature cutout. These have been completed, analysed and reported to industry via CottonTales in each region

b. *Ultra narrow row (UNR) and compensation.*
We investigated if UNR cotton could compensate for early damage as well as conventional cotton could, in collaboration with Evan Brown (NSW DPI) and Scott Hardwick (CSIRO Entomology). Two experiments were completed and have been written up for the Southern New South Wales Cotton Trial Book.

c. *Effect of tip damage on cotton yield and maturity at Hillston.*
We investigated if cotton grown at Hillston could compensate for early damage. This research was completed and written up for the Southern New South Wales Cotton Trial Book.

d. *Can early plant architecture of boll set be manipulated to increase yield.*
We investigated if yield could be increased in Bollgard II® by inflicting damage on young plants by cutting off the terminal and upper leaves with a whipper snipper, or causing square shedding using low rates of Prep. A first experiment was competed and analysed.

v. *Opportunistically investigate the economic significance of minor pests*
This has been achieved through the initiatives below.

a. *Late damage experiment*
We investigated whether late season damage to upper leaves could affect yield. This was completed and analysed, and further experiments planned.

b. *Do jassids affect yield?*
We assessed if jassid damage could affect photosynthesis and investigated the effect of jassids on yield in the field. This work was completed, analysed and reported to industry at a range of venues (CCA AGM, CSD Research Update). Experiments were also completed to define if jassids can reduce cotton yields. These have been completed and analysed, but further information with a wider range of jassids damage levels is required before results could be extended to industry.

3. Background, methodology, results and discussion.

a) *To develop detailed quantitative data relating aphid effects to cotton growth and yield and link that with Cotton LOGIC and OZCOT*
i) Effect of aphids on yield.
Current thresholds for aphids are based on a best guess and have no scientific basis. This has not been a problem in the past because aphids were only a problem late in the season, when the risk of yield loss was low and the main threat was due to honeydew

contamination of lint. As aphids have been found earlier in the season in some years there is now a need to have accurate thresholds so that growers can avoid unnecessary insecticides applications and yield loss. We initiated a series of field experiments to investigate the effects of aphids on the development and yield of cotton. As an additional component of these experiments the projects STO also made regular assessments of the relationship between aphid density and photosynthesis. The series of four experiments reported here began in 2000-01 and ran until 2003-04.

Methodology

The experiments involved artificially infesting cotton with aphids at different times through the season. We have developed techniques that allowed us to generate large populations of aphids. This was done by rearing aphids in a glasshouse initially then transferring these to large field cages to further increase numbers. When required the aphids were harvested from the cages, by cutting the plants into small stem sections and placing them into paper bags. The stem sections were then distributed throughout the plots to be infested. In each experiment we aimed to generate aphid outbreaks beginning in Dec, January and February. However, due to the difficulty in producing large numbers of aphids at a given time the actual timing of infestation of plots varied between years The experiments therefore all had uninfested plots and plots infested in December, January or February. Two varieties were used in most experiments – NuOpal and Sicot289i. Experiments also included 'control' treatments where the aphid populations were allowed to build for a period before being controlled using aphicides to prevent further damage.

The aphid populations in the infested plots were monitored using a range of techniques with the aim of developing one that would be practical for growers and consultants to use. In the field, by scoring the number of aphids present on a 0 to 5 scale (0, 1 = 1-10, 2 = 11-20, 3 = 21-50, 4 = 51-100, 5 = >100), the degree of damage 0 = no damage, 1 = slight crinkle of young leaves, 2 = < 1/2 of young leaf crinkled, 3 = almost total curl of young leaves) and the amount of coverage of the crop with honeydew (0 = none, 1 = trace of honeydew on top canopy, 2 = bottom ½ of crop sticky, 3 = total plant sticky). We also collected leaf samples from each plot and washed them in the laboratory to obtain an accurate absolute count. Other pests were managed selectively using insecticides. The development of the cotton was monitored by taking fortnightly 0.5 metre harvests, which were partitioned into different structures and dry weight and leaf area recorded. In-field assessments of light interception were also made using a ceptometer. Yield of each plot was determined by machine harvesting the central two rows.

Photosynthesis measurements were made using a LICOR 6400 photosynthesis system. Measurements were taken at regular intervals from node 3-4 below the terminal. Aphids were washed off the leaf to be measured using a thin stream of water. This prevented them from becoming lodged in the LICOR machine. Control leaves were also washed. Measurements of the effect of increasing densities of aphids were made by taking measurements in plots at intervals over the season, as the aphid populations built up.

Results

This is a summary of key findings rather than a complete reporting of all results as there is a vast amount of data collected. We were able to generate plots with a wide range of aphid population densities. Due to seasonal differences in weather and predator abundance the actual build up of aphids varied widely between seasons. Fig. 1 shows the aphid populations generated in the 2002-03 season as an example. The variability between years is well illustrated by the differences in timing and rate of build up of the

December infestations over the course of the series of experiments (Fig. 2).

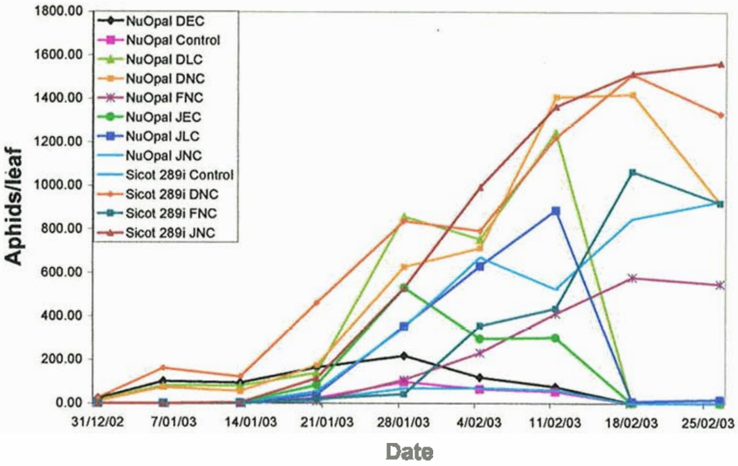

Figure 1. Mean number of aphids on leaf 3 or 4 below the terminal for the 2002-03 field experiment, ACRI.

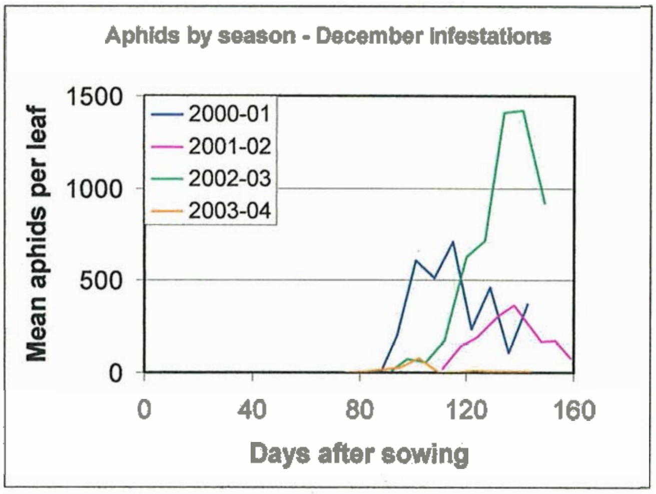

Figure 2. Differences in aphid population build-up for December artificial infestations in four different experiments

A key aim of this work was to develop thresholds for control of aphids. A first simple approach taken was to explore the possibility that yield loss could be predicted from the number of cumulative aphid days that the crop experienced, (where one aphid day is the feeding of one aphid for one day). Initially this approach was tried with the more accurate laboratory counts. Cumulative aphid days were calculated from the time of infestation until sampling ceased at about 20% of bolls open. The data show that for each experiment there is a good relationship between cumulative aphid days (CAD) and relative yield (Fig. 3) but that this varies between years. Relative yield was used to allow for differences in absolute yield level between experiments). The variation between years in the relationship between CAD and relative yield highlights a problem with using aphid days, which is that one aphid day in December is not the same, in terms of potential yield loss, as one aphid day in February. To make the relationship robust we would need to include a time component. A further disadvantage of this approach is that it is difficult to forecast ahead the potential yield loss of a given aphid population as you don't have a final estimate of cumulative aphid days.

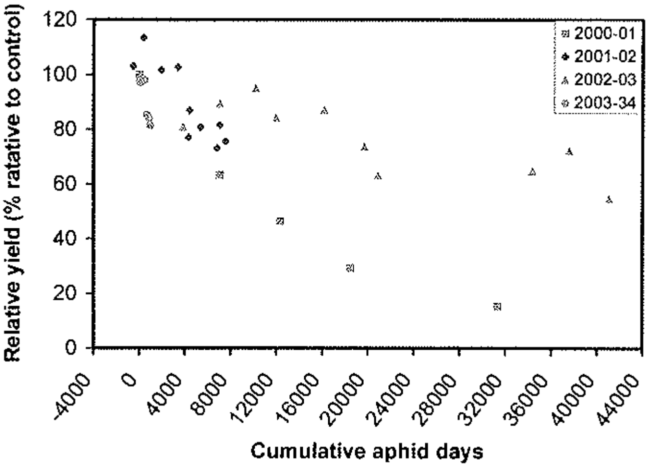

Figure 3. Relative yield of cotton against cumulative aphid days for experiments across four seasons at ACRI.

One way to overcome this problem is to use information estimating when aphids began to increase and how quickly they increased. This approach has been used previously with spider mites and proven useful. So, to investigate the concept we regressed cumulative aphid days, for successive weekly counts, against time. The slope of this relationship is the rate of increase and the x intercept is the start of increase. We did this for each individual treatment across the 4 years of experiments. The relationships were generally linear over most of their range, and late data points where the rates had declined due to poor food quality were omitted. The r^2 for relationship varied between 0.85 and 0.99 which indicate a very good fit (eg Fig. 4).

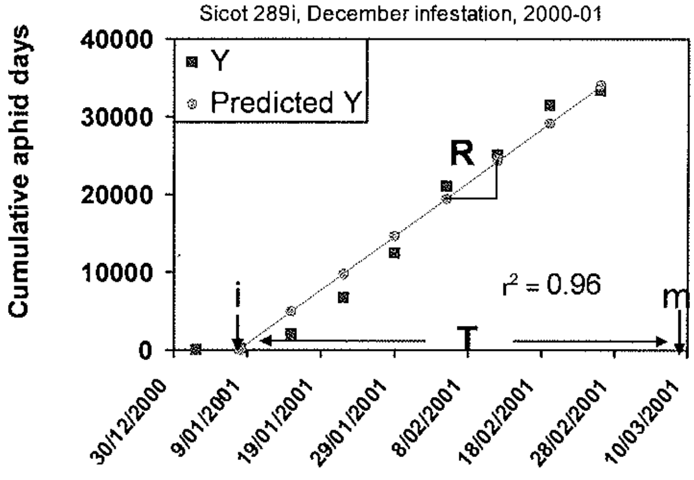

Figure 4. An example of the relationship between cumulative aphids days and time. Also shown is the rate of increase (R) which is the slope of the relationship, the start of infestation increase (i), the maturity date (m) when 60% of bolls opened and the time remaining from infestation increase to crop maturity (T).

We used a non-linear curve to describe the relationship between the rate of increase, the time remaining and relative yield. The relationship is a form of logistic growth curve which allows for some initial tolerance to aphids then a decline. The equation (equation 1) provides a good fit to the data (Figure 5).

Relative yield = $-18.3 + 123/(1 + \exp(0.014((R+1)^{0.3}*T)-305))$.... ($r^2 = 0.91$)...equation 1

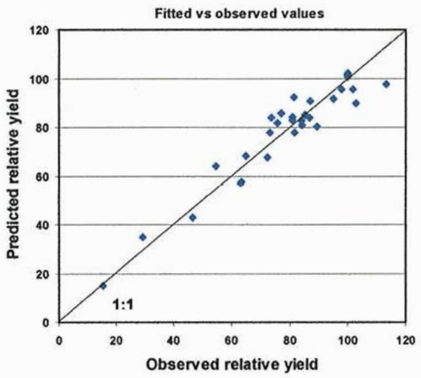

Figure 5. Observed versus predicted yield using equation 1 for the laboratory counts of aphids numbers in Experiments 1 - 4.

The equation was used to generate some curves of the expected yield loss from aphids for populations with a range of starting dates and rates of increase and showed a strong non-linear curve. Initially there is some tolerance of aphids with little effect on crop yield, but at high, prolonged infestation levels yield loss can be quite dramatic (Fig. 6).

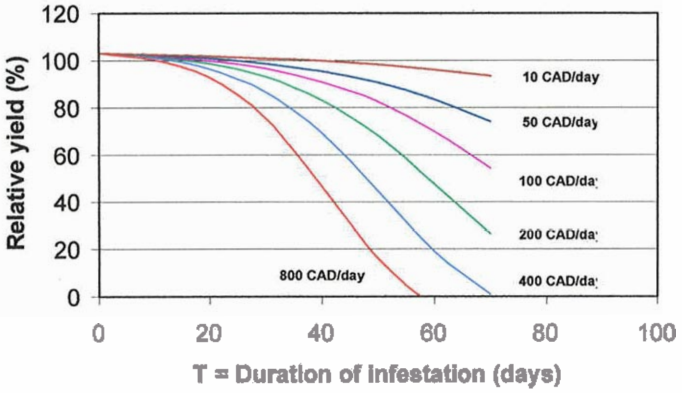

Figure 6. Predicted yield reductions using equation 1 for the laboratory counts of aphids numbers in Experiments 1 – 4 for a range of rates of increase from 10 to 400 CAD per day.

Although the relationship between aphids and relative yield was very good for the laboratory counts of aphid numbers it is important to recognise that growers and consultants will not have access to lab counts – they need something that can be counted in the field. With spider mites rate of increase was calculated as change in the % of leaves infested per day. However, earlier research in CSP145C showed that the relationship between % of leaves infested and mean number of aphids per leaf was strongly non-linear and aphid populations were highly clumped to the extent that 100% of plants was infested at a low aphid density (< 20 aphids per leaf). Observation of the yield loss data indicated that crops would reach 100% of plants infested before any yield loss was likely and hence this approach was not likely to be useful.

For the field estimation of aphid population growth we used the 1- 5 field score data of aphid numbers. From this we calculated cumulative aphid days (CAD_F) for each treatment in each experiment and also calculated the rate of increase in CAD_F, intercept and time remaining is the same manner as the lab counts. For the 'controlled' treatments we calculated the duration and time over which damage occurred.

Regression analysis showed a reasonable relationship between the rate of increase in C CAD_F and reductions in yield. An extra term was added to the equation to allow for the effect of controlling aphids at different times.

%Yield loss = R2*T*D*0.001557 ....($r^2 = 0.70$)........................equation 2

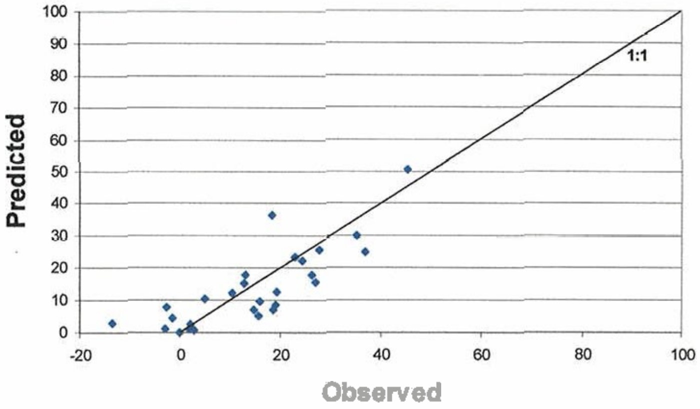

Figure 7. Observed versus predicted yield using equation 1 for the field scores of aphid abundance in Experiments 2 - 4.

Predictions from this relationship show an initial tolerance of cotton to aphids, similar to that shown with the laboratory counts (Fig. 8). Similarly, if the impact of control is included, for instance with a population that begins to increase when there are 80 days remaining in the season, there is an initial tolerance but this is less pronounced as duration and rate increase (Fig. 9). This could form the basis for a simple set of look up tables or an addition to CottonLOGIC to take into account the potential effect of aphids on cotton yield, in the absence of cotton bunchy top disease (Table 1).

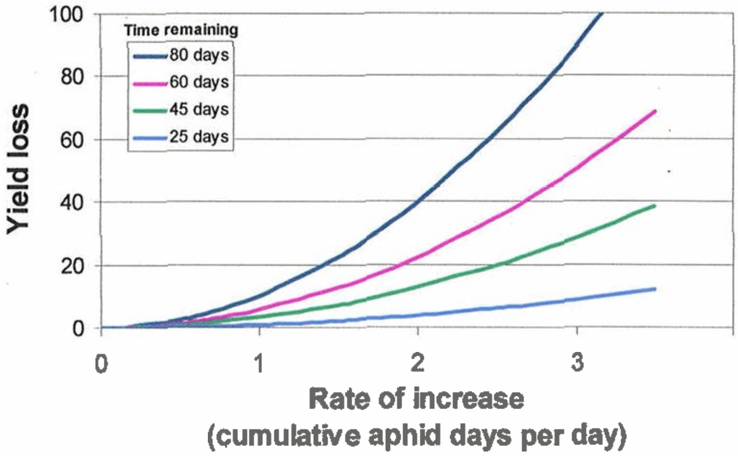

Figure 8. Predicted yield reductions using equation 2 for the field scores of aphid abundance in Experiments 2 – 4 for a range of infestation initiation times, expressed as time remaining in the season.

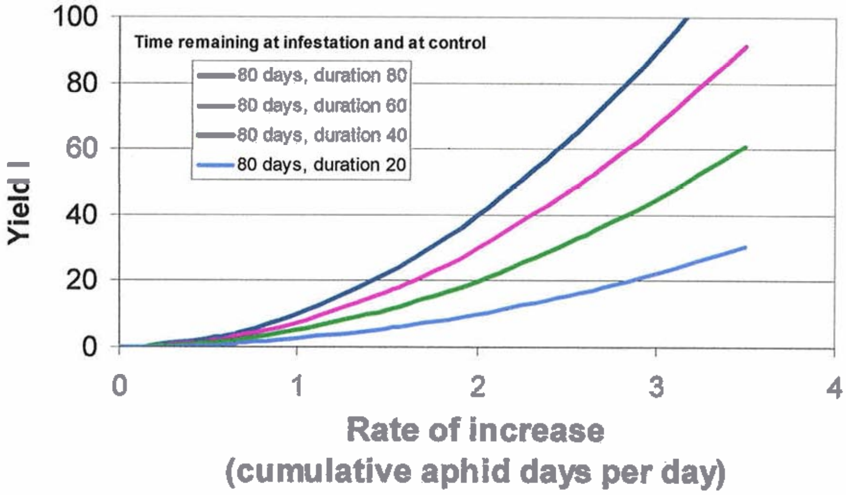

Figure 9. Predicted yield reductions using equation 2 for the field scores of aphid abundance in Experiments 2 – 4 for an infestation initiation time of 80 days before 60% open and a range of control times, expressed as duration in days that aphids were allowed to develop.

ii) Effect of aphids on photosynthesis.

As a second component of this research, Ms Simone Heimoana, the Senior Technical Officer working on this project is studying for a PhD on the effects of aphids on photosynthesis of cotton. Her research is progressing well and she has developed a number of innovative techniques and experiments. Her initial research has shown clearly that aphids do reduce the photosynthetic rate of cotton and there is a negative relationship between aphid density and photosynthetic rate which seems fairly predictable (Figure 10). A similar relationship was found between aphid density and stomatal conductance (Figure 11). However, plotting the effect on photosynthesis against the effect on conductance shows that conductance is affected more quickly than photosynthesis (Figure 12).

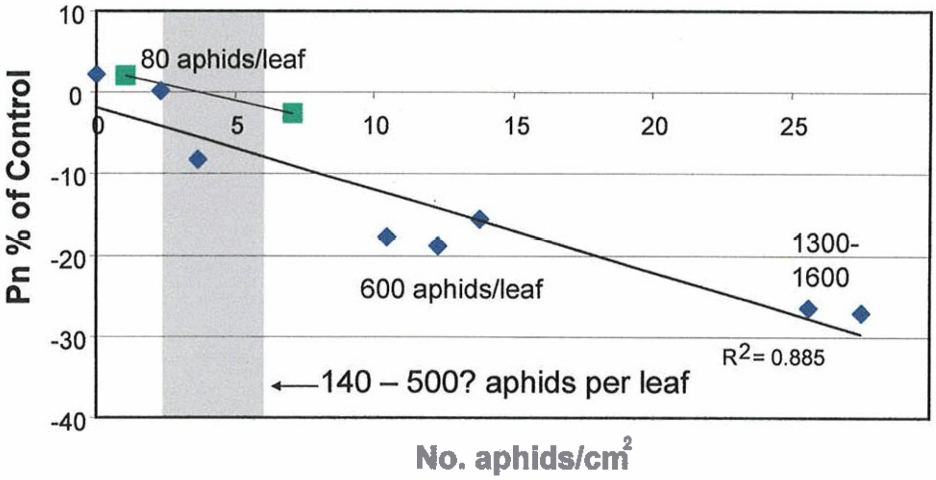

Figure 10. Effect of aphids on photosynthesis on cotton. Measurements taken on mainstem node 3 below the terminal through January and February.

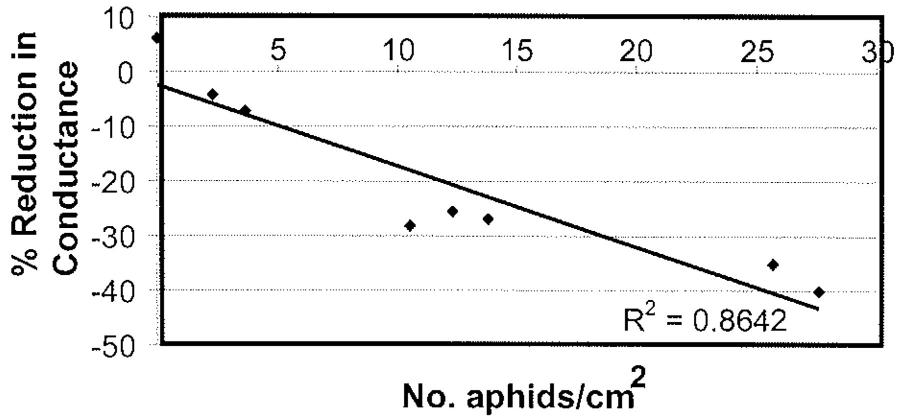

Figure 11. Effect of aphids on stomatal conductance of cotton. Measurements taken on mainstem node 3 below the terminal through January and February.

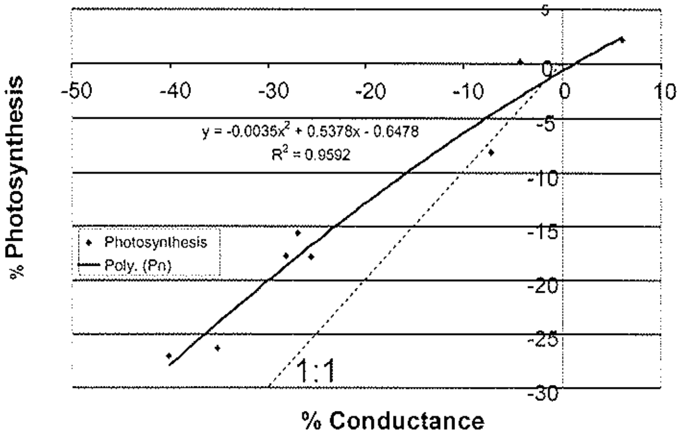

Figure 12. Relationship between reduction in photosynthetic rate and conductance caused by cotton aphids.

Ms Heimoana intends to examine in more detail the effect of aphids on photosynthesis, focussing on the time at which reductions begin to occur. She is also looking at the effects of honey dew and dust on photosynthetic rate, using both real and artificial honeydew. She has found that 3 coats of artificial honey dew reduced conductance as well as photosynthesis. Addition of dust, simulating field conditions results in a further decline in photosynthesis but not conductance, indicating that dust is affecting light penetration. She is also looking at the possibility that aphid feeding damages the phloem, preventing effective export of sugars, causing accumulation and consequent reduction in photosynthesis. Results from this research will improve our understanding of the effects of aphid on cotton growth and provide valuable training for a potential cotton entomologist.

Table 1. Potential yield losses from aphids, derived from rate of increase in cumulative aphid days, the current number of cumulative aphid days and the timing of control.

		Time remaining		80				Time remaining		60				Time remaining		40			
Days till control		0	10	20	40	60	80	0	10	20	40	60	80	0	10	20	40	60	80
Current CAD																			
20	0.1	0.9	0.9	1.0	1.0	1.1	1.2	0.8	0.9	0.9	1.0	1.1	1.1	0.7	0.8	0.8	0.9	1.0	1.0
	0.25	1.2	1.4	1.6	1.9	2.2	2.5	1.1	1.2	1.4	1.6	1.9	2.2	0.9	1.1	1.2	1.4	1.6	1.9
	0.5	1.9	2.3	2.8	3.7	4.7	5.6	1.6	1.9	2.3	3.1	3.9	4.7	1.2	1.6	1.9	2.5	3.1	3.7
	0.75	2.5	3.4	4.4	6.2	8.1	10.0	2.0	2.8	3.5	5.1	6.6	8.1	1.6	2.1	2.7	3.9	5.1	6.2
	1	3.1	4.7	6.2	9.3	12.5	15.6	2.5	3.7	5.0	7.5	10.0	12.5	1.9	2.8	3.7	5.6	7.5	9.3
	1.25	3.7	6.1	8.4	13.1	17.7	22.4	3.0	4.8	6.7	10.4	14.1	17.7	2.2	3.5	4.9	7.6	10.4	13.1
	1.5	4.4	7.6	10.9	17.4	24.0	30.5	3.4	6.0	8.6	13.7	18.8	24.0	2.5	4.4	6.2	10.0	13.7	17.4
	2	5.6	11.2	16.8	28.0	39.2	50.4	4.4	8.7	13.1	21.8	30.5	39.2	3.1	6.2	9.3	15.6	21.8	28.0
	3	8.1	20.2	32.4	56.7	81.0	105.3	6.2	15.6	24.9	43.6	62.3	81.0	4.4	10.9	17.4	30.5	43.6	56.7
40	0.1	1.5	1.6	1.6	1.8	1.9	2.1	1.4	1.5	1.6	1.7	1.9	2.0	1.4	1.4	1.5	1.6	1.8	1.9
	0.25	1.9	2.1	2.3	2.8	3.3	3.7	1.7	1.9	2.1	2.6	3.0	3.4	1.6	1.8	1.9	2.3	2.7	3.1
	0.5	2.5	3.1	3.7	5.0	6.2	7.5	2.2	2.7	3.3	4.4	5.4	6.5	1.9	2.3	2.8	3.7	4.7	5.6
	0.75	3.1	4.3	5.4	7.8	10.1	12.5	2.6	3.6	4.6	6.6	8.6	10.6	2.2	3.0	3.8	5.4	7.1	8.7
	1	3.7	5.6	7.5	11.2	14.9	18.7	3.1	4.7	6.2	9.3	12.5	15.6	2.5	3.7	5.0	7.5	10.0	12.5
	1.25	4.4	7.1	9.8	15.3	20.7	26.2	3.6	5.8	8.1	12.5	17.0	21.5	2.8	4.6	6.3	9.8	13.3	16.8
	1.5	5.0	8.7	12.5	19.9	27.4	34.9	4.0	7.1	10.1	16.2	22.3	28.3	3.1	5.4	7.8	12.5	17.1	21.8
	2	6.2	12.5	18.7	31.1	43.6	56.1	5.0	10.0	14.9	24.9	34.9	44.8	3.7	7.5	11.2	18.7	26.2	33.6
	3	8.7	21.8	34.9	61.0	87.2	113.3	6.9	17.1	27.4	48.0	68.5	89.1	5.0	12.5	19.9	34.9	49.8	64.8
80	0.1	2.7	2.9	3.0	3.3	3.6	3.8	2.7	2.8	2.9	3.2	3.5	3.7	2.6	2.7	2.9	3.1	3.4	3.7
	0.25	3.1	3.5	3.9	4.7	5.4	6.2	3.0	3.3	3.7	4.4	5.2	5.9	2.8	3.2	3.5	4.2	4.9	5.6
	0.5	3.7	4.7	5.6	7.5	9.3	11.2	3.4	4.3	5.1	6.9	8.6	10.3	3.1	3.9	4.7	6.2	7.8	9.3
	0.75	4.4	6.0	7.6	10.9	14.2	17.4	3.9	5.4	6.8	9.7	12.7	15.6	3.4	4.7	6.0	8.6	11.1	13.7
	1	5.0	7.5	10.0	14.9	19.9	24.9	4.4	6.5	8.7	13.1	17.4	21.8	3.7	5.6	7.5	11.2	14.9	18.7
	1.25	5.6	9.1	12.6	19.6	26.6	33.6	4.8	7.8	10.9	16.9	22.9	29.0	4.0	6.6	9.1	14.2	19.2	24.3
	1.5	6.2	10.9	15.6	24.9	34.3	43.6	5.3	9.3	13.2	21.2	29.1	37.1	4.4	7.6	10.9	17.4	24.0	30.5
	2	7.5	14.9	22.4	37.4	52.3	67.3	6.2	12.5	18.7	31.1	43.6	56.1	5.0	10.0	14.9	24.9	34.9	44.8
	3	10.0	24.9	39.9	69.8	99.6	129.5	8.1	20.2	32.4	56.7	81.0	105.3	6.2	15.6	24.9	43.6	62.3	81.0

b) *To quantify the effects of insecticides on pests, predators and parasitoids.* Large replicated experiments were done in each year of the project. In each experiment seven new insecticides or miticides were evaluated for their efficacy, non-target effects and risk of causing resurgence of secondary pests (mites or aphids). Over the duration of this project we evaluated; clothianidin (neonicotinoid, Sumitomo - 2 rates), NNI0001 (experimental compound, Bayer, 2 rates), NNI0001 plus thiacloprid (experimental compound plus neonicotinoid, Bayer), etoxazole (miticide, Sumitomo), Endosulfan Ultracaps (new endosulfan formulation, Bayer), acetamiprid (neonicotinoid, Dupont), carbosulfan (carbamate, CropCare), pyridalil (experimental compound, Sumitomo), semicarbazone (experimental compound, BASF), thiamethoxam (neonicotinoid, Syngenta), and novaluron (insect growth regulator). These products were all in the final stages of development prior to the decision regarding registration.

Where products were registered, such as acetamiprid (Intruder), etoxazole (Paramite) and thiamethoxam (Actara), the data, along with that of relevant collaborators, were used to update the IPM Guidelines Document 1 'Impact of insecticides and miticides on predators in cotton' (Table 2) This ensured that this reference document was up-to-date for the cotton industry. As requested from the various agrichemical companies reports were prepared detailing the efficacy and non-target effects of specific insecticides. Several of these reports were used as a component of registration packages.

The table 'Impact of insecticides and miticides on predators in cotton' was widely circulated through the industry via publication in the Cotton Pest Management Guide, in the IPM Guidelines and on the Cotton CRC website. A significant addition to the table in 2004 was the insertion of information on the toxicity of insecticides and miticides to honey bees. This came about through CRC / CRDC initiatives to meet with beekeepers to discus and seek solutions to problems, especially loss of hives due to insecticide drift.

Table 2. Effect of insecticides and miticides on beneficials and pest resurgence in cotton, based on data derived from this project and from collaborators (Robert Mensah - NSW DPI, Martin Dillon – formerly CSIRO Entomology, Mark Wade – formerly QDPI and UQld, Brad Scholz – QDPI, Dave Murray – QDPI, Viliami Heimoana – NSW DPI and Richard Lloyd – QDPI). This version was published in the Cotton Pest Management Guide 2205/06, on the CRC Website and an earlier version appeared in the IPM Guidelines.

		Target Pest(s)						Beneficials																	Pest resurgence[12]			
									Predatory beetles				Predatory bugs							Hymenoptera							
Insecticides (in increasing rank order of impact on beneficials)	Rate (g ai / ha)	Helicoverpa	Mites	Mirids	Aphids	Thrips	Persistence[8]	Overall Ranking[10]	Total[1]	Red & Blue beetle	Minute 2-spt lady beetle	Other lady beetles	Total[2]	Damsel bugs	Big-eyed Bugs	Other Predatory bugs	Apple Dimpling	Lacewing adults	Spiders	Total (wasps)	Trichogramma	Ants	Thrips	Mite	Aphid	Helicoverpa	Toxicity to bees[14]
Bt[11]		✓					very short	very low	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL				VL
NP Virus		✓					very short	very low	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL				VL
Pirimicarb	250				✓		short	very low	VL	VL	VL	VL	L	L	M	VL	VL	VL	VL	VL	M	VL	L				VL
PSO (Canopy)[16]	2%	✓			✓		short	very low	VL	L	L	VL	VL	VL	VL	VL	VL	VL	L	VL	VL	H	VL				VL
Methoxyfenozide	400	✓					medium-long	very low	L	VL	VL	L	L	L	L	VL	VL	VL	VL	VL	VL	VL	VL				VL
Etoxazole	38.5		✓				short	low	VL	VL	-	L	VL	VL	VL	VL	VL	VL	M	L	VL	VL	L				VL
Dicofol[3]	960		✓				long	low	L	-	-	-	L	-	-	-	L	-	L	-	-	-	VL				VL
Amorphous silica[17]	2500	✓					short	low	L	L	-	M	M	-	VL	-	L	L	L	L	-	M	VL				-
Spinosad	96	✓					medium	low	VL	M	L	VL	M	L	H	VL	L	VL	VL	M	H	H	H	+ve			H[15]
Diafenthiuron	350		✓		✓		medium	low	M	H	VL	M	L	M	VL	L	H	VL	L	L	VL	H	L			+ve	M
Pymetrozine	150				✓		short	low	M	M	M	M	L	L	L	VL	H	M	L	L	L	M	VL				VL
Indoxacarb[13]	127.5	✓		✓			medium	low	H[14]	L	VH	VH	L	L	L	L	VH	L	VL	L	VL	VH	VL		+ve		H[15]
Abamectin	5.4	✓[6]	✓				medium	moderate	L	M	H	VL	M	L	M	M	H	VL	M	M	M	H	M				H
Emamectin	8.4	✓					medium	moderate	L	VL	M	VL	H	H	H	H	H	L	M	M	M	VL	M				H
Endosulfan (low)	367.5	✓		✓	✓	✓	medium	moderate	M	VL	VH	M	M	M	M	L	H	L	M	VL	-	VH	H				M[15]
Propargite	1500		✓				medium	moderate	M	H	H	M	M	H	VL	VL	L	VL	M	M	H	H	M		+ve	+ve	L
etamiprid	22.5				✓		medium	moderate	M	M	VH	H	M	M	H	M	VH	L	VL	L	H	VH	VH				M[15]
	400	✓	✓[9]				medium	moderate	H	M	VH	H	L	-	-	-	H	VL	M	M	L	H	M				L
Fipronil (low)	12.5			✓		✓	medium	moderate	L	VL	H	L	L	H	L	L	VH	VL	M	M	M	VH	VH		+ve	+ve	VH
Chlorfenapyr (low)	200	✓	✓				medium	moderate	M	L	VH	VL	M	VL	H	H	VH	L	L	M	VH	H	M				H
Thiamethoxam	100				✓		medium	moderate	H	H	H	H	M	M	M	H	H	M	VL	M	H	VH	H	+ve		+ve	H
Endosulfan (high)	735	✓		✓	✓	✓	medium	moderate	M	VL	VH	M	M	M	M	M	H	L	M	L	VH	VH	H				M[15]
Fipronil (high)	25			✓		✓	medium	moderate	L	VL	H	L	M	H	H	L	VH	VL	M	M	M	VH	VH	+ve		+ve	VH
Imidacloprid	49			✓	✓		medium	moderate	H	L	VH	H	H	M	H	L	VH	L	L	L	M	H	H	+ve		+ve	M
Methomyl	169	✓					very short	high	H	L	VH	VH	M	L	VH	L	VH	M	M	M	H	H	H	+ve			H[15]
Thiodicarb	750	✓					long	high	VH	M	VH	VH	M	M	L	L	VH	VL	M	M	M	M	H	+ve	+ve		M[15]
lorfenapyr (high)	400	✓	✓				medium	high	H	M	VH	L	H	H	H	H	VH	L	M	M	VH	VH	M		+ve		H
		✓	✓	✓	✓	✓	short-medium	high	H	M	H	H	H	M	H	H	VH	L	M	H	H	VH	H	+ve			H
Carbaryl[3]							short	high	H	-	-	-	H	-	-	-	-	-	-	-	-	-	H	-	-	-	H
rethroids[4]		✓	✓[7]	✓[7]			long	very high	VH	-	-	-	VH	-	-	-	VH	VH	VH	VH	VH	VH	VH	+ve	+ve	+ve	H

c) *To understand the mechanism by which cotton recovers from early damage and use to improve existing simulation models.*

i) *Thrips*

These experiments investigated how cotton recovers from early season thrips damage (in collaboration with Dr Tom Lei). Leaf area of cotton seedlings can be reduced by as much as 50% by early season thrips infestations, but it is well documented that plants can regain the difference in leaf area once infestation ceases (compensation). The processes involved in the recovery have not been identified. Hypotheses include enhancement of the photosynthetic rate of the damaged leaves, more efficient leaf construction (i.e. more leaf area per unit of dry matter invested in new leaves), and more branching. This 2-yr field study examined these hypotheses and found that thrips-affected plants recovered from a 30% reduction in total leaf area. During the recovery period, repeated measurements of gas exchange, leaf morphology and individual leaf areas at all nodes were made to assess their contribution to the recovery.

Recovery was not achieved through the previously proposed mechanisms. The pattern of nodal development indicated that the duration of leaf expansion of the smaller deformed leaves was shorter than that of control leaves possibly because they had fewer cells. The production and expansion of healthy upper node leaves in thrips-affected plants could, therefore, begin sooner; about 1 to 2.5 nodes in advance of control plants (see Fig. 13). The proposed process of recovery was evident but weaker in the second year where thrips numbers were higher.

We concluded that thrips affected plants overcame the leaf area disparity through an accelerated ontogeny of main stem leaves. By completing the expansion of smaller but normally-functioning lower node leaves earlier, resources were made available to the unfolding of larger upper node leaves in advance of control plants. The generality of this mode of plant resistance in pest damage remains to be determined. We found that recovery occurs through accelerated ontogeny, which means that thrips damaged plants stop growing damaged leaves earlier, because these leaves are smaller, which allows faster expansion of new leaves.

These experiments have been written up and published in Annals of Botany (see Appendix). This information was presented by Tom Lei at a range of grower and consultant meetings.

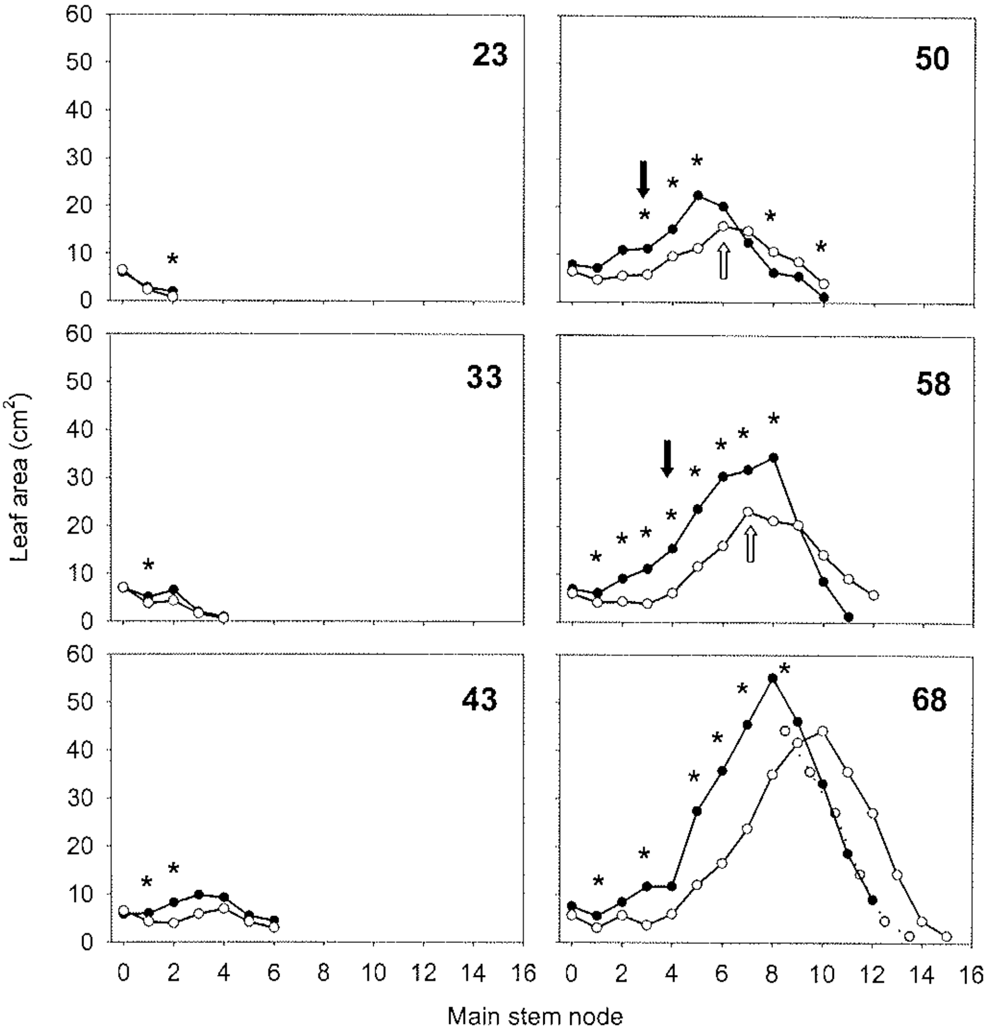

Figure 13. Leaf area development at individual main stem nodes (cotyledon = node 0) through the thrips infestation and recovery periods for control (solid circles) and thrips-infested (open circles) plants in year 1 (2001-02). The number in each panel represents the date of sampling (in days after sowing). Values represent mean of four plots at 5 plants per plot; * indicates differences in leaf area between control and infested plants that were significant at $P<0.05$. Arrows indicate the uppermost fully expanded leaf in control (solid) and infested (open) plants. The line formed by the grey circles in Fig. 4a at 68 DAS shows the correspondence in leaf area between treatment and control when nodal leaf area of infested plants was shifted 2.5 nodes to the left.

ii) *Bollgard II® and compensation*

We investigated if Bollgard II® compensated for early pest damage as well as a conventional variety and if this was affected by sowing date. This was done because some growers and consultants had expressed concerns that Bollgard II® would not compensate as effectively as conventional varieties. This perception probably arose as a result of high yield obtained with some Bollgard II® crops which had with relatively high retention levels, hence the expectation that high retention is required to get high yields from Bollgard II®.

We did an experiment with two varieties (Sicot 189R and Sicot 289BR) and three sowing dates ranging from early October, early November to late November. Damage treatments imposed included tipping out all plants at 4 true leaves, removal of all fruit from the first 4 fruiting branches, both tipping out and fruit removal or undamaged (control).

We found that later sowing dates had significantly lower yields (S1= 240, S2 = 206, S3 = 167 g lint/m^2) and fewer bolls (S1= 129.2, S2 = 122.7, S3 = 109.7 bolls/m^2). Crop development times were affected variably, with the second sowing data having the longest developmental time (S1= 176.7, S2 = 181.2, S3 = 172.8 days) (the lower yields in the later sowings meant that maturity time, in days from sowing to 60% open was about the same). Cultivar also had a significant effect, with the Bollgard II® variety having significantly higher yield (Conv = 194.3, Bollgard II® = 215.1 g lint/m^2) more bolls (Conv = 113.1, Bollgard II® = 127.3 g lint/m^2) and shorter developmental period (Conv = 178.7, Bollgard II® = 175.1 days). Damage caused reduced yield and boll number and increased developmental time (Table 3). Fruit loss and tipping had small but significant effects on yield while the combination reduced yield substantially. Fruit loss delayed maturity by about 9 days, which is similar to other research results (Wilson et al, 2004), and the effect of fruit damage and tipping was additive, as previously found.

Table 3. Effect of damage on yield, boll number and cotton developmental period.

Damage	Yield (g lint/m2)	Bolls (number/m2)	Developmental time (days)
Control	217.2	125.8	169.9
Fruit	210.6	119.7	179.3
Tipping	208.8	125.6	173.5
F + T	182.2	109.7	184.9
LSD	6.8	10.5	2.5

There were also significant interactions between sowing date and cultivar for yield and boll number, whereby the reduction in yield and boll number with later sowings was less with Bollgard II® (Table 4).

Table 4. Interaction between variety and sowing date for yield and boll number, ACRI, 2003-04.

	Yield (g lint/m^2)			Bolls (number/m^2)		
	Sowing			Sowing		
Variety	1	2	3	1	2	3
Conv.	237.9	197.8	147.2	127.2	118.2	93.9
BGII	242.9	214.5	187.8	131.3	127.1	123.5
LSD		21.2			10.64	

There was also a significant interaction between damage and sowing date for yield and crop development (Table 5). Yields were generally more strongly reduced by damage in the latest sowing date, while for crop development sowing 2 took longer to develop but was less affected by fruit or tip damage than on the other sowing dates.

Table 5. Interaction between damage and sowing date for yield and maturity (developmental period), ACRI, 2003-04.

	Yield (g lint/m^2)			Development period (days)		
	Sowing			Sowing		
Damage	1	2	3	1	2	3
Control	244.6	210.1	196.8	169.8	173.0	166.8
Fruit	242.7	213.8	175.3	181.2	185.2	171.5
Tipping	243.5	207.8	175.1	172.5	175.5	172.7
F + T	230.7	193.0	122.9	183.4	191.0	180.3
LSD		23.6			5.0	

Critically however, there was no interaction between damage and variety for yield, boll number or development period. This indicates that the conventional and Bollgard II® varieties responded similarly to damage across sowing dates, and confirms that the compensatory capacity of Bollgard II® is probably at least as good as that of conventional cotton.

d) *To extend research on early pest damage into a range of cotton regions through collaboration with the CRC Cotton Extension Team*

i) Bollgard II® *experiments with IDO's*

Early experience with BGII crops by researchers and consultants showed that in some cases early season fruit retention could be very high. There were concerns that yield of Bollgard II® cotton could be limited by high early retention causing premature cutout. If so there was the opportunity to evaluate if this could be prevented by delaying initial fruit set until plants had a larger canopy. Meetings with-in CSIRO identified this as a research question and we initiated experiments in collaboration with the National Cotton Extension Team to evaluate this risk.

Experiments were conducted with IDO's in 8 regions (Hillston, Gwydir, McIntyre, Upper Namoi, Dalby, Lower Namoi and St George) to test if high retention of BGII crops limited yield. These experiments had two designs – influenced by the availability of the IDO's time. The first design, 'Tip and Fruit' (Hillston, Gwydir, MacIntyre and upper Namoi) tested the effect of high retention by comparing with crops where we artificially manipulated plants by removing the terminals (tipping) to delay fruiting and change plant structure, by removing the first four fruiting branches to delay fruiting and increase early vegetative growth and the combination of these two types of damage. The second design, 'fruit only' (Dalby, Lower Namoi and St George) tested the effects of early fruit loss, either removing all friout from the first 4 or first 6 fruiting branches.

At the Tip and Fruit sites the control treatments has fruit retention of between 81.8

and 85.3% just before removal of fruit. Across the four sites we found a strong site effect on yield, and maturity date, as expected (Table 6a). We found no treatment effect on yield, but a significant delay in maturity (Table 6b). With all damage treatments delaying yield by 1 to 8 days. There was no interaction between site and treatment.

Table 6a. Effect of damage treatment on yield.

	Yield (g lint/m^2)				
Damage treatment	MacIntyre	Gwydir	Upper Namoi	Hillston	Treatment means
Control (undamaged)	220.0	251.5	247.1	162.0	220.2
Tipped	196.9	302.8	218.4	163.7	220.5
Fruit removal from 1st 4 fruiting branches	209.8	281.3	222.8	174.1	222.0
Tipped and fruit removal	205.6	271.3	225.2	182.4	221.1
LSD (treatment)					37.2(ns)
Site means	208.1	276.7	228.4	170.6	
LSD (site)		16.5			
LSD (site x treatment)		35.2 (ns)			

Table 6b. Effect of damage treatment on maturity

	Days later maturing (60% bolls open) than control				
Damage treatment	MacIntyre	Gwydir	Upper Namoi	Hillston	Treatment means
Control (undamaged)	0	0	0	0	0
Tipped	3.3	7.8	0.9	3.4	4.3
Fruit removal from 1st 4 fruiting branches	7.6	7.0	7.6	1.7	3.8
Tipped and fruit removal	4.3	6.1	5.0	1.9	6.0
LSD (treatment)					1.2
Site means	3.8	5.2	3.4	1.8	
LSD (site)		2.3			
LSD (site x treatment)		4.1 (ns)			

At the Fruit Only sites there were significant differences between sites in yield. There was no effect of treatment on yield but a significant effect on crop maturity and an interaction with site (Table 7). Damage caused a delay in maturity compared with the undamaged control. The interaction is due to a low effect of fruit damage at 4 fruiting branches at one site (Upper Namoi, Table 7).

Table 7a. Effect of damage treatment on yield.

	Yield (g lint/m^2)			
Damage treatment	Dalby	Lower Namoi	St George	Treatment means
Control (undamaged)	186.2	176.0	243.8	202.0
Fruit removal from 1st 4 fruiting branches	215.8	178.2	224.4	206.2
Fruit removal from 1st 6 fruiting branches	197.2	178.3	194.2	189.9
LSD (treatment)				25.0 (ns)
Site means	199.7	177.5	220.8	
LSD (site)		24.3		
LSD (site x treatment)		39.79(ns)		

Table 7b. Effect of damage treatment on maturity.

	Days later maturing (60% bolls open) than control			
Damage treatment	Dalby	Lower Namoi	St George	Treatment means
Control (undamaged)	0	0	0	0
Fruit removal from 1st 4 fruiting branches	6.4	2.6	4.5	4.5
Fruit removal from 1st 6 fruiting branches	7.5	8.6	8.0	8.0
LSD (treatment)				2.8
Site means	4.6	3.7	4.2	
LSD (site)		1.2 (ns)		
LSD (site x treatment)		3.0		

We found no evidence of premature cut-out in these experiments, although retention levels were not particularly high and all crops had good growing conditions which would not be likely to generate the high retention and slow growth scenario that might lead to premature cut-out. Nevertheless, it is clear from our results that Bollgard II® crops can compensate well from damage, though with a delay of similar levels to a conventional crop, based on past experiments. These experiments have served to provide IDO's, growers and consultants with experience with the response of crops to damage and also first hand experience with Bollgard II® crops (this work was done before BGII was widely available).

ii) *Ultra narrow row (UNR) and compensation.*

In the more central cotton regions cotton planted on conventional 1m row spacing have been shown to compensate strongly for early damage – often with no loss of yield or delay in maturity. This allows growers to tolerate some early damage, rather than prevent it using insecticides, and hence reduces costs and helps conserve beneficials that will help control pests. In cooler regions such as the Macquarie Valley, compensation is often not as strong as in warmer regions, and though plants do compensate there is a higher risk of some delay in maturity (≈3-4 days) , which can in some years also lead to a reduction in yield (≈ 0 – 5%). Growers in the Hillston region face a short, hot season. One strategy to maximize the use of the solar radiation available has been to use UNR cotton, in an attempt to grow a high yield with shortened crop duration. There has been concern that early damage to UNR cotton will cause delayed maturity, thereby undermining the benefits. In these experiments we compare the response of both UNR and conventional row spacing (1m) cotton to early tip damage and fruit loss.

The trial was carried out at Merrowie in 2002-03 and again in 2003-04. A replicated design was used with planting configuration (UNR or conventional 1m beds) in a split-plot design with the damage treatments arranged randomly within each split-plot. Cotton was planted on the 5th October 2002 (Sicala V3rri) and on the 6th October 2004 (Bollgard 12B). Damage treatments were: Fruit removal (FR), Tip damage at node 2 (Tip2), Tip damage at node 6 (Tip6), Tip damage at node 8 (Tip 8) and Untreated control (Control). The tip out treatment was applied to all three crop rows in each plot when plants had reached the designated true leaf stage. Tip out involved the removal of the terminal using a pair of curved forceps. Fruit damage was inflicted to by removing all fruit from the first four fruiting branches. Weekly maturity picks from 1 m in the centre row were conducted from first boll opening. These recorded the number of bolls picked and the total boll weight. Samples were sent for ginning to ACRI in Narrabri.

The results for the two experiments had some similarities and some differences. In 2002-03 the conventional cotton and the UNR cotton had similar yields, while in 2003-04 the the UNR out-yielded the conventional 1m beds (See Figures 14 and 15). Comparing the effect of damage on yields of UNR and conventional showed no difference in 2002-03 – though there is a trend for yield to be maintained after damage in the conventional, and to decline with damage in the UNR (Figure 14). A similar pattern is evident in 2003-04 where there was no effect of damage on yield for the conventional, but in the UNR two damage treatments (Fruit removal and tipping at node 8) yielded significantly less than the undamaged control (Figure 15).

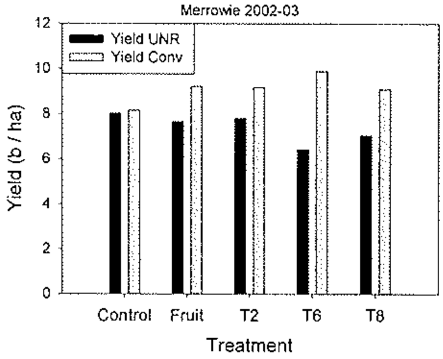

Figure 14. Damage did not cause a significant yield reduction in either UNR or conventional cotton in 2002-03.

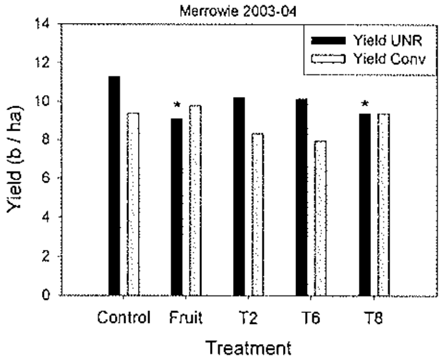

Figure 15. Damage did not cause a significant yield reduction in conventional cotton in 2003-04 but did significantly reduce yield in UNR (indicated by asterisks – these treatments are significantly different to the control UNR).

In a combined analysis across both years there is a strong trend (P = 0.07) for damage to have no effect on yield in conventional but to consistently cause a reduction in yield in UNR (Fig 16). An exception to this is the tipping at node 2 which had no effect on yield in either conventional or UNR configurations.

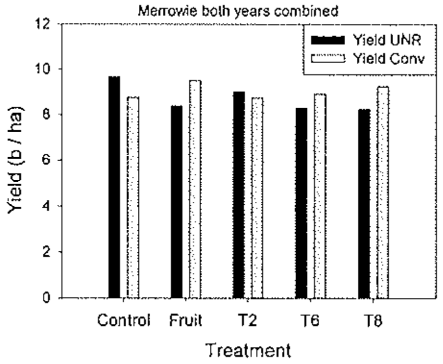

Figure 16. Across both years there was a trend for damage to have no effect on yield in conventional but to reduce yield in UNR.

Row configuration had no significant effect on crop maturity data. In other words the UNR matured at the same time as the conventional 1m beds (look at the control treatments in Figs 17 and 18).

In 2002-03 the fruit removal and tipping at node 6 or 8 caused similar significant delays in maturity in both UNR and conventional 1m beds (Figure 17). However, tipping at node 2 led to earlier maturity in both planting configurations.

In 2003-04 the fruit damage and tipping at node 8 (and node 6 in conventional) caused delays in maturity in both UNR and conventional of about 8 to 10 days. Tipping at node 2 did not affect maturity date (Figure 18).

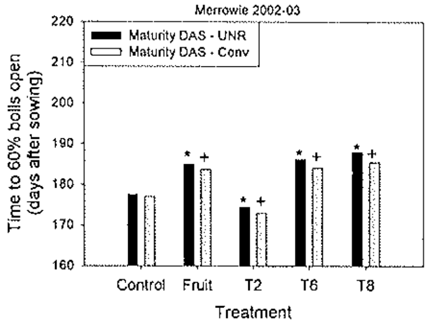

Figure 17. Damage to early fruit or tipping at nodes 6 or 8 caused a significant delay in maturity in UNR and conventional (indicated by asterisks or crosses).

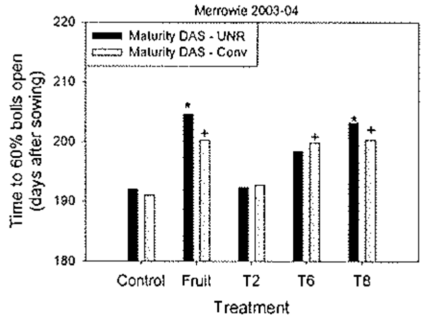

Figure 18. Damage to early fruit or tipping at nodes 8 (and 6 in conventional) caused a significant delay in maturity in UNR and conventional (indicated by asterisks or crosses).

Looking across both years combined there was a significant treatment effect of treatment on yield but the response was the same for both row configurations. Tipping at node 2 did not cause delay, but fruit removal or tipping at node 6 or 8 caused a delay of about 9 days (Fig 19).

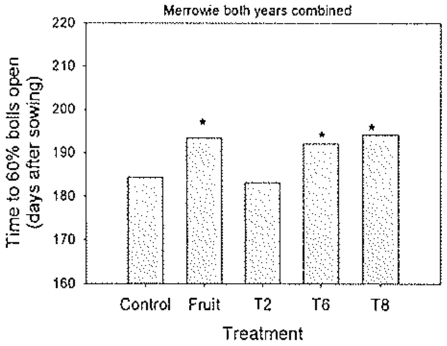

Figure 19. Damage to early fruit or tipping at nodes 6 or 8 caused a similar significant delay in maturity in both UNR and conventional (indicated by asterisks).

The results show that early damage has little effect on the yield of cotton grown on conventional 1m beds, whereas similar damage tend to cause a reduction in yield in UNR cotton. Damage caused similar delays in maturity in both UNR and conventional with the early fruit loss and node 6 or node 8 tip damage treatments causing about 9 days delay. In terms of IPM this means that tolerating early damage in cotton on a 1m row spacing probably won't affect yield but may cause delay in maturity. This delay may in some years translate into a yield reduction as well. In UNR cotton protection from early damage would appear more important as both yield and maturity could be affected.

iii) *Effect of tip damage on cotton yield and maturity at Hillston.*

Experiments in warm cotton regions, such as the Namoi and Gwydir Valleys, have found that tip damage has little effect on either yield or maturity date of cotton unless the damage is very severe. Early fruit loss didn't affect yield but did cause a delay in maturity of 7 days. For cooler regions the situation may be different. Experiments in the Macquarie Valley have shown less consistent recovery of plants from early tip damage, with both yield and maturity date sometimes negatively affected. The experiments reported here were designed to investigate the recovery of cotton in the Hillston Region after tip damage and early fruit loss. In this region the shorter growing period may limit the capacity of plants to recover from damage. Any delay in crop development could therefore potentially have a greater effect on yield. We also considered the effect of later tip damage events and early fruit loss.

Trial sites were selected at the properties 'Lachlan' and 'Gundaline'. The cotton was grown on a conventional row spacing and managed according to the growers normal practice. Sicala V3rri was sown at Gundaline on the 1st October, 2002 and Bollgard 12B was sown on the 25th September at Lachlan Farming. Pests (insects and weeds) were controlled as required. The varieties were Ingard® that had been treated with Temik to avoid damage by early season sucking insects. There were 5 treatments by 4 reps totalling 20 plots, (each plot was 2 x 3 m). The trial design was a Randomised Block design. Treatments were: Fruit removal (FR), Tip damage at node 2 (Tip2), Tip damage at node 6 (Tip6), Tip damage at node 8 (Tip 8) and Untreated control (Control).

The tip out treatment was applied to all three crop rows in each plot when plants had reached the designated true leaf stage. Tip out involved the removal of the terminal using a pair of curved forceps. Fruit damage was inflicted to by removing all fruit from the first three fruiting branches. Weekly maturity picks from 1 m in the centre row were conducted from first boll opening. These recorded the number of bolls picked and the total boll weight. Samples were sent for ginning to ACRI in Narrabri. A final plant map was recorded after the last maturity pick to consider the effect of damage treatments on plant growth and structure.

Damage did not affect yield at Gundaline or Lachlan Farming (Figs 20 and 21). Neither fruit removal nor tip damage had any effect on the number of bolls per metre or crop yield. Crop maturity was affected with tip damage at node 6 or 8 causing a significant delay in maturity of 3 to 4 days at Gundaline (Fig 22) and tip damage at node 8 causing almost 7 days delay at Lachlan Farming (Fig 23).

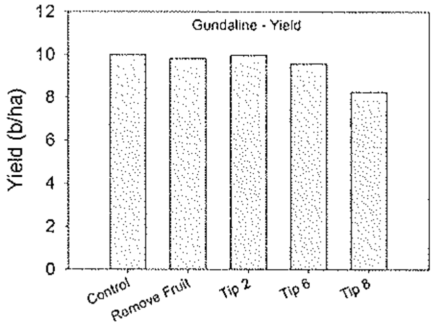

Figure 20. Damage treatments did not affect yield at Gundaline.

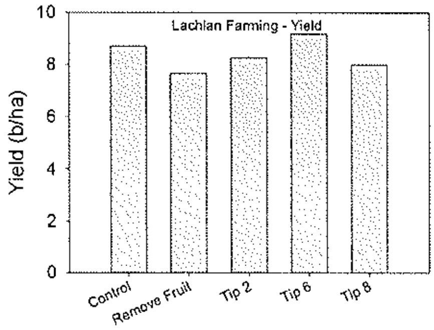

Figure 21. Damage treatments did not affect yield at Lachlan Farming.

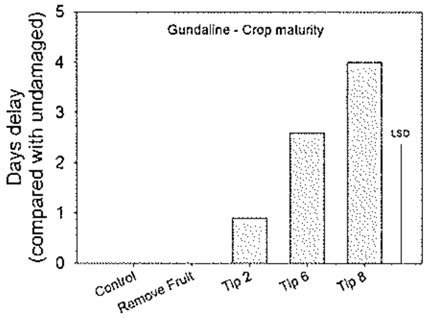

Figure 22. Tip damage at nodes 6 or node 8 caused a significant delay in maturity of about 3 to 4 days at Gundaline.

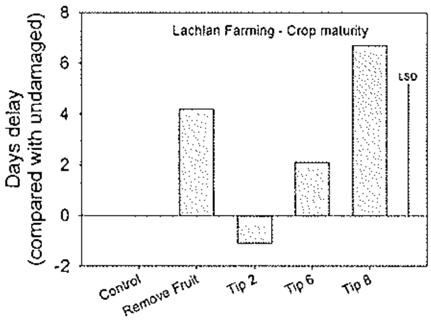

Figure 23. Tip damage at node 8 caused a significant delay in maturity of about 6 days at Lachlan Farming.

The results suggest that cotton sown on conventional 1m beds has quite strong capacity to recover from early tip damage in the Hillston region. However, later tip damage, at nodes 6 or 8, carries a higher risk of delayed maturity. Although it was not the case in this season, such a delay in some seasons could result in boll maturation under cooler conditions and therefore carry a risk of yield loss, and possibly reduced fibre quality as well. Further simple experiments over successive years could help confirm this result.

iv) *Can early plant architecture or boll set be manipulated to increase yield.* We investigated if yield could be increase in Bollgard II® by inflicting damage on young plants by cutting off the terminal and upper leaves with a whipper snipper, and also explored the practicality of causing some square shedding using low rates of Prep. Our hypothesis was that inflicting tip damage or causing square shedding would allow plants to develop a bigger structure and carry more fruit. None of the treatments improved yield nor did they cause delayed maturity (Table 8). The higher Prep rates did cause some fruit shed.

Table 8. Effect of damage treatment on yield and maturity.

		Prep treatments			Tip treatments		
	Control	Prep 1 (0.28 g ai/ha)	Prep 2 (0.14 g ai/ha)	Prep 3 (0.07 g ai/ha)	Tipped at 6 nodes	Tipped at 12 nodes	*P*
Yield (machine harvested, b/ha)	12.1	10.9	10.7	11.2	10.6	11.0	0.27
Maturity (days after sowing)	171.5	172.5	170.9	171.7	171.6	173.4	0.65

e) *Opportunistically investigate the economic significance of minor pests*

i) *Late damage experiment*

There is growing concern amongst grower and consultants about late season damage from pests such as thrips, that cause leaf distortion, and jassids, that cause whitening up the upper leaf surface. These pests are normally not a problem late season in conventional crops as they are controlled by insecticides applied against other pests. However in low spray conventional crops and especially in Bollgard II® crops number can build up to the point that crops receive considerable damage, for instance up to 80% of the leaf area severely damaged by jassids. A further factor is the recording of western flower thrips in cotton regions. This species causes damage similar to other thrips but is also resistant to some insecticides, which may make it harder to manage and may necessitate a resistance management strategy if it becomes a frequent problem. Growers need information on the response of crops to such late season damage. The challenge for crop mangemange is to balance the beneficial value of thrips in controlling spider mites, the value of the damage these pests cause, the costs of their control, including non-target effects that may necessitate later control of secondary pests.

We investigated whether late season damage to upper leaves could affect yield by cutting off the top 25 cm of growth from plots or removing the top six mainstem node leaves or leaving plants undamaged) control) of cotton that was at cut-out. This simulates a worst case scenario of complete loss of the upper part of the canopy. A randomised block design was used with 5 replicates. Maturity picks were done to estimate yield and maturity effects. We found that although differences were not significant they indicated potential yield loss and this issue should be investigated further (Table 9). For 2005-06 we have developed a physiological framework to explore how manipulation of the size and photosynthetic rate of later leaves, which are the youngest and most photosynthetically active on the plant, can be manipulated to increase yield (with Steve Yeates and Greg Constable) and also to understand effects of damage on potential yield.

Table 9. Effect of late season damage treatment on yield and crop maturity.

	Treatment			
	Control	Top 25 cm removed	Top 6 mainstem nodes removed	P
Maturity (days after sowing reached 60% bolls open)	187.2	185.6	186.9	0.40
Yield (g lint/ha)	254.0	209.1	196.1	0.09

Do jassids affect yield?

Jassids have emerged as a more frequent, though intermittent, problem in the late season in crops with low or very selective spray regimes, especially Bollgard II®. Earlier studies showed that severe jassid damage (about 80% of the upper surface of the upper leaves damaged) could reduce the photosynthetic rate of cotton leaves by about 20%. We have been trying to follow this through by investigating if jassids can cause reductions in yield. We set up experiments in each year of this project but jassid numbers were very low in the first two years. In 1004-05 jassid numbers in a field at ACRI were higher so we took the opportunity to set up a simple field experiment to see if they affected yield.

We used a simple replicated design, with treatments being:
Untreated = Jassids
Control 1 = no Jassids from now (control with Pegasus)
Control 2 = no jassids from 3 weeks from now
Control 3 = no jassids from 5 weeks from now.

We used plots large enough that we could machine pick to obtain the most realistic yield results. Jassid numbers were scored using a sweep net sample from each plot as they are too flighty to count *in situ* (20 sweeps per 18 m plot). We score damage symptoms on leaves 3, 6 and 10 on 10 plants per plot both upper and lower surface. The damage score was based on % of leaf surface estimated to be damaged; 1 = 0 – 10 %, 2 = 11 – 20, 3 = 21 – 40, 4 = 41 – 60, 5 = 61 – 80, 6 = 81- 100).

We were successful in generating highly significant differences between treatments in damage (e.g. Fig 24 for average upper leaf surface damage), though the damage scores never rose about a score of 2 (10-20% leaf area damaged). Similarly we were successful in generating differences in jassid numbers between treatments (Fig 25 for average jassid score per plot). Our results showed no significant effects of jassids on yield (Control 1 = 8.6 b/ha, Control 2 = 7.9 b/ha, Control 3 = 7.5 b/ha and untreated = 7.7 b/ha)), though there was a trend toward those plots with the highest number if jassids having lower yields. Plotting jassid numbers or damage against yield suggests that there is a relationship between jassids and yield loss (Fig 26). We will continue this research in 2005-06 to try to refine thresholds.

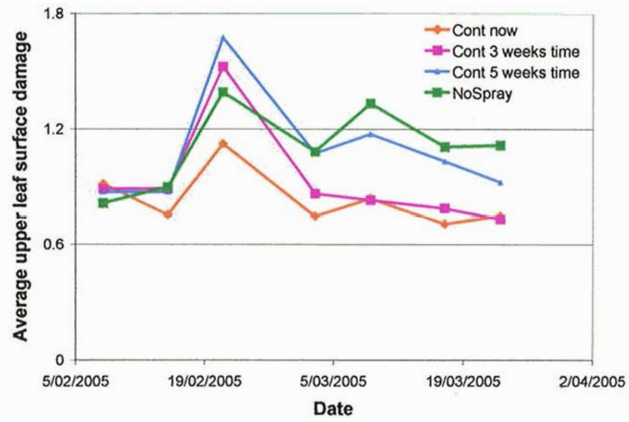

Figure 24. Average leaf damage score for different jassid control treatments, averaged across nodes 3, 6 and 10 for each date.

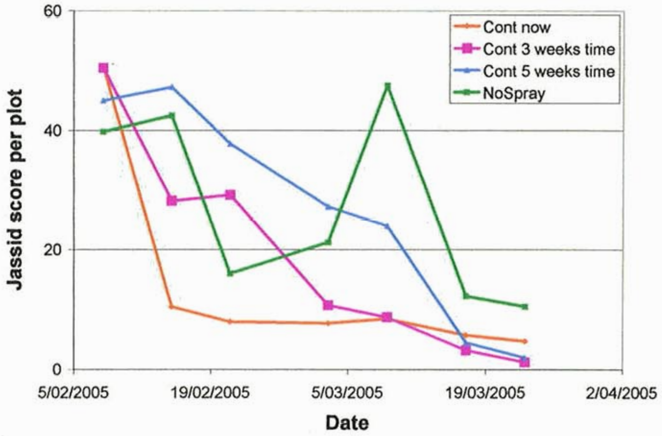

Figure 25. Average jassid numbers per sweep net sample per plot for different jassid control treatments for each date.

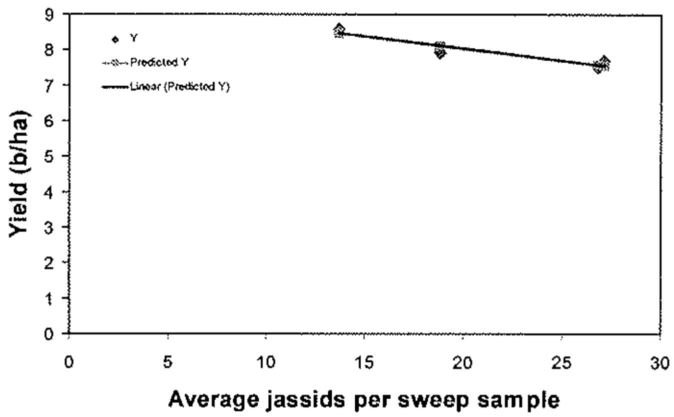

Figure 26. Regression of yield against average jassid numbers per sweep net sample per plot showing statistically significant trendline ($r^2 = 0.8$).

Provide a conclusion as to research outcomes compared with objectives. What are the "take home messages"?

a) Aphids can reduce the photosynthetic rate of cotton, reducing yield and development. A statistical relationship predicting yield loss from aphid densities has been developed and used to produce look-up charts to estimate potential yield losses from this pest.

b) A table summarising the effects of all currently available insecticides and miticides on beneficial predators and parasites was developed and has been updated regularly with data from this project, as well as that from collaborators. This table (IPM Supporting Document 1 'Impact of insecticides and miticides on predators in cotton') has been widely distributed and used throughout the industry and served as a template for other crops.

c) Cotton can recover from damage by thrips through a process known as 'accelerated ontogeny'. This information can be used to update thrips compensation routines under development in the OZCOT cotton simulation model.

d) Bollgard II®cotton varieties can compensate as well as or better than conventional varieties.

e) A range of activities were co-ordinated with the Cotton Extension Team which helped increase their knowledge of cotton compensation, provided first hand experience with Bollgard II® and provided valuable additional research data. Outcomes from experiments were (i) cotton with early retention levels of 80-85% showed no indication of premature cut-out and treatments to manipulate plant growth to avoid this problem did not increase yield but did cause delay ii) UNR cotton is less able to compensate for early damage than cotton on conventional 1 m beds. 3) In conventional cotton in a cool region (Hillston) later tip damage, at nodes 6 or 8, carries a higher risk of delayed maturity.

f) Cotton growth can be manipulated using mechanical or chemical damage (Prep) but these did not increase yield.

g) Late season damage to younger leaves may have a greater effect on yield than expected and should be investigated further.

h) Jassid damage may affect the yield of cotton. An initial experiment showed a negative linear relationship between jassid density and yield. This should be investigated further.

4. **Detail how your research has addressed the Corporation's three Outputs - Economic, Environmental and Social?**
This project has provided the cotton industry with information to better manage aphids, to select insecticides to more closely match the pest situation and to conserve beneficials, and to better manage compensation in Bollgard II® and to better manage late season pest damage. All of these advances help growers and consultants to manage pest in cotton with greater knowledge and confidence that will allow better decisions. This help address the CRDC three outputs via, better yields (profitability) through improved pest management decisions, by selection of more selective insecticides and by better understanding of pest thresholds and the role of beneficials to reduce insecticide use (and this has been well documented elsewhere), and thereby also help to contribute to a more sustainable cotton industry essential to the well being of small rural communities.

5. **Provide a summary of the project ensuring the following areas are addressed:**

a) **technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.)**

Development of look-up table for establishing if aphids will affect yield loss.
Development of look up charts to understand effects of insecticides on beneficials.
Development of on-line version of the Cotton Pest and Beneficial Guide.

b) **other information developed from research (eg discoveries in methodology, equipment design, etc.)**
Development of methods for mass rearing aphids and manipulation of populations for yield loss experiments
Development of techniques to evaluate the effects of late season damage on aphids
Development of techniques to investigate the effects of aphids on photosynthesis in cotton

c) **are changes to the Intellectual Property register required?**
No.

6. **Detail a plan for the activities or other steps that may be taken:**

(a) **to further develop or to exploit the project technology.**
Most of the findings from this research have been disseminated to industry already via industry conferences, field days, the Cotton Pest Management Guide and Cotton CRC Research Reviews.

(b) **for the future presentation and dissemination of the project outcomes.**
The key opportunity for this project is to finalise, and develop an extension plan for the aphid / yield loss outcomes. This could be via the Australian Cottongrower, Cotton LOGIC, Cotton Tales and interactions with the National Cotton Extension

Team. There is also a great opportunity to involve IDO's and interested consultants in growers in experiments to help understand the effects of late season damage on yield. Simple protocols could be developed, similar to the approach taken previously with early damage.

(c) **for future research.**
This has already been addressed in the development of e new project 'Supporting IPM for Future Cotton Systems'. This project has the specific aims to;
i) Define the economic significance of emerging pests such as jassids and late season thrips.
ii) Determine the non-target effects of new insecticides and new low beneficial impact options and the risk for resurgence of secondary pests
iii) Understand the effect of variety, crop agronomy and predation on development of aphid populations.

7. **List the publications arising from the research project and/or a publication plan. (NB: Where possible, please provide a copy of any publication/s)**

Selected publications are included in this report.

Refereed papers and conference papers

Wilson, L.J., Sadras, V.O., Heimoana, S.C. and Gibb, D. (2003) How to succeed by doing nothing: Cotton compensation after simulated early pest damage. Crop Science 43, 2125-2134

Wilson, L.J., Mensah, R.K. and Fitt, G.P. (2004) IPM in Australian cotton. In: Proceedings of the World Cotton Research Conference III, Cape Town, South Africa, March 2003.

Lei, T.T. and Wilson, L.J. (2004) Recovery of leaf area through accelerated shoot allometry in thrips damaged cotton seedlings. Annals of Botany 94, 179-186.

Reddall, A.A., Sadras, V.O., Wilson, L.J. and Gregg, P.C. (2004) Physiological responses of cotton (*Gossypium hirsutum* L.) to two-spotted mite (*Tetranychus urticae* Koch) damage. Crop Science 44, 835-846

Wilson, L.J., Mensah, R.K. and Fitt, G.P. (2004) Implementing IPM in Australian cotton. In: Novel Approaches to Insect Pest Management in Field and Protected Crops, A. Rami Horowitz and I. Ishaaya (eds), Springer-Verlag, Berlin, pp 97-118.

G.A. Herron, J. Rophail and L. J. Wilson (2004) Chlorfenapyr resistance in two-spotted spider mite (Acari: Tetranychidae) from Australian cotton. Experimental and Applied Acarology. 34:315-321

Fitt, G. P, Wilson, L. J. and Daly, J. (2004) Advances with Integrated Pest Management as a component of sustainable agriculture. Proceeding of the 4th International Crop Science Congress, Brisbane, September 2004

Whitehouse, M.E.A., Wilson, L.J. and Fitt, G.P. (2005) A comparison of arthropod communities in transgenic Bt and conventional cotton in Australia. Environmental Entomology 35: 1224-1241.

Conferences

Lei, T.T., Khan, M. and Wilson, L.J. (2003) Boll damage by sucking pests: tackling an emerging threat. Oral presentation for the World Cotton Research Conference III, Cape Town, South Africa.

G.A. Herron and L.J. Wilson (2004) The management of cotton aphid (Aphis gossypii Glover) in Australian cotton. International Congress of Entomology, Brisbane, August 2004.

TT Lei, B Duggan, M Khan & LJ Wilson (2004) Responses of cotton to actual and simulated green mirid boll damage. International Congress of Entomology, Brisbane, August 2004.

Wilson, L.J., Fitt, G.P. and Pyke, B.A. (2004) Integration of transgenic cotton with IPM – opportunities and challenges. International Congress of Entomology, Brisbane, August 2004.

Wilson, L.J., Lei, T.T. and Takenaka. A. (2004) Compensation for pest damage: Linking pest and damage based thresholds. International Congress of Entomology, Brisbane, August 2004.

Extension materials

Gunning, R., Larsen, D., Pyke, B., Tucker, G. and Wilson, L. (2003) Insecticide resistance management strategy for conventional cotton 2003-04. Cotton Pest Management Guide 2002-2003 Agdex 151/680

Deutscher and Wilson (2003) Pest and Beneficial Guide. WWW tool (http://www.cotton.pi.csiro.au/insects.htm)

Lei , T., Baguley, K., Cameron, D. and Wilson, L. (2003) Can high yield potential crops recover from pest damage. Aust. Cottongrower 24(7) 50-51

Franzmann, B., Smith, L., Trackson, K. and Wilson L. (2004) The silverfly: A predator of cotton aphid. Aust. Cottongrower 25(1): 24-26.

Rossiter, L., Wilson, L., Larsen, D., Pyke, B., Gunning, R., Herron, G., and Kelly, D. (2003) Insecticde resistance. Where are we now? Australian Cotton CRC Information Sheet.

Wilson, Lei and Heimoana (2003) How much tip damage can you stand? CSD Trial results booklet pp 94-96.Farrell, T., Wilson, L., Mensah, R. and Dillon, M. (2004) Key insect and mite pests of Australian cotton. Cotton Pest Management Guide 2004-2005, pp 1 – 9. CRC and NSW DPI Publication.

Wilson, L., Mensah, R., Johnson, A. and Deutscher, S. (2004) Integrated Pest Management (IPM) guidelines for Australian cotton. Cotton Pest Management Guide 2004-2005, pp 16 – 29. CRC and NSW DPI Publication.

Rossiter, L., Gunning, R., Herron, G., Larsen, D., Pyke, B., and Wilson, L. (2004) Insecticide resistance management strategy for conventional cotton 2004-05. Cotton Pest Management Guide 2004-2005, pp 1 – 9. CRC and NSW DPI Publication.

Deutscher, S., Wilson, L. and Mensah, R. Integrated pest management guidelines for cotton production systems in Australia. CRC Publication. pp 78, ISBN: 1 921025 01 8.

Wilson, Lei and Heimoana (2004) Aphid and mites in the Bollgard II® era. CSD Trial results booklet pp 81-83.

Khan, M., Kelly, D., Hickman, M., Mensah, R., Brier, H. and Wilson, L. (2004) Mirid ecology in Australia cotton (Australian Cotton CRC Research Review. No. 14.

Khan, M., Kelly, D., Hickman, M., Mensah, R., Brier, H. and Wilson, L. (2004) Mirid management in Australia cotton (Australian Cotton CRC Research Review. No. 15.

Wilson, L.J., Deutscher, S. and Pyke, B. Cotton Pests. (2005) In, Insects (and allied forms) of Australian field crops and pastures: Cotton. CSIRO Publishing, in press

Farrell, T., Mensah, R., Wilson, L., and Dillon, M. (2005) Key insect and mite pests of Australian cotton. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 1-17

Wilson, L., Deuscher, S., Mensah, R., and Johnson, A. (2005) Integrated pest management (IPM) guidelines for Australian cotton II. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 18-31

Rossiter, L., Farrell, T., Larsen, D., Kauter, G., Downes, S. and Wilson, L. (2005) Insecticide resistance management strategy for 2005-06. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 32-36

Downes, S., Wilson, L., Kauter, G. and Farrell, T. (2005) Preamble to the resistance management plan for Bollgard II® 2005-06. Cotton Pest management Guide 2005/06. NSW DPI Publication. Pp 37-46.

8. Have you developed any online resources and what is the website address?

The project principal researcher was a significant contributor to each of the following on-line resources.

Cotton pest and beneficial guide (http://www.cotton.crc.org.au/insects.htm)

Cotton pest management guide (http://www.agric.nsw.gov.au/reader/cotton-pest-management)

Mirid ecology in Australian cotton
(http://www.cotton.crc.org.au/Assets/PDFFiles/miridec.pdf)

Mirid management in Australian cotton
(http://www.cotton.crc.org.au/Assets/PDFFiles/miridmgt.pdf)

Integrated pest management guidelines for cotton production systems in Australia
(http://www.cotton.crc.org.au/Assets/PDFFiles/IPMGL05/IPMGLFor.pdf)

Insecticide resistance; where are we now?
(http://www.cotton.crc.org.au/Assets/PDFFiles/resist03.pdf)

Impact of insecticides and miticides on predators in cotton. October 2005 update
(http://www.cotton.crc.org.au/Assets/PDFFiles/IPMGL99/IPMSD01.pdf)

Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. Where possible include a statement of the costs and potential benefits to the Australian cotton industry or the Australian community.

The results and conclusions from this project will contribute substantially to improving our understanding of the effects of pests and their damage on cotton yield and maturity, and will improve the use and selection of insecticides. Importantly this project has evolved from earlier projects to address emerging issues, such as aphids and late season damage from jassids and thrips and compensation and effects of high retention in Bollgard II® crops.

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Physiological Responses of Cotton to Two-Spotted Spider Mite Damage

A. Reddall, V. O. Sadras, L. J Wilson,* and P. C. Gregg

ABSTRACT

Spider mites are important pests of cotton (*Gossypium hirsutum* L.), capable of dramatically affecting growth, yield, and fiber quality. This study investigated the physiological response of cotton leaves to feeding damage by the two-spotted spider mite (*Tetranychus urticae* Koch) in two experiments in the field over two seasons. Mite colonies initially established and developed in the basal areas of leaves, where the leaf blade joins the petiole. These infestations caused rapid and severe reductions in photosynthetic rate, stomatal conductance, transpiration, transpiration efficiency (TE), and chlorophyll content. In basal areas, a peak of 68 adult female mites per leaf caused photosynthesis to decline to zero, while undamaged leaves averaged 33 μmol CO_2 m^{-2} s^{-1}. Differences in plant responses to mites occurred between seasons despite similar infestation levels, possibly related to later timing of infestation and harder leaves in the second season. Compensation for mite damage was not apparent at the leaf level, since photosynthesis was reduced on undamaged portions of damaged leaves. The sequence of mite damage events on the undamaged leaf portions was determined to be: first, reduction of stomatal conductance; second, reduction of transpiration; third, reduction of photosynthetic rate; and finally, reduction of transpiration efficiency. At the leaf level, the overall effect of mite damage on photosynthesis was greater than expected because undamaged areas surrounding those visibly damaged were also affected.

THE TWO-SPOTTED SPIDER MITE is an important herbivorous pest worldwide and the most important of the mite pests of cotton in Australia, affecting many aspects of cotton growth (Forrester and Wilson, 1988; Wilson, 1993; Herron et al., 1998). *Tetranychus urticae* feeds on the undersides of leaves, which are the major sites of photosynthesis (Tomczyk and Kropczynska, 1985; Welter, 1989). At the crop level, earlier studies have shown that *T. urticae* infestations can have dramatic effects on plant growth, significantly reducing radiation use efficiency (RUE) and resulting in reduced crop yield, fiber quality, germination success, and oil content of seeds (Wilson et al., 1991; Wilson, 1993; Sadras and Wilson, 1996; Sadras and Wilson, 1997a, 1997b). Greatest effects on development and yield were caused by rapidly increasing mite infestations early in the growing period.

At the leaf level, the effects of mites on photosynthesis have been studied in a range of crops, including cotton. Brito et al. (1986) reported that mite infestation increased leaf resistance to CO_2 uptake and decreased photosynthetic rate in glasshouse-grown cotton plants Bondada et al. (1995) studied *T. urticae* damage to cotton grown in the field and found alterations to the stomatal apparatus and internal damage to the mesophyll cells, which resulted in declining photosynthesis in parallel with declining stomatal conductance and transpiration. However, studies of the relationship between the density of mites on leaves and effects on the photosynthetic rate of cotton leaves in the field are limited. Many other studies on the impact of spider mites on host plants such as peach [*Prunus persicae* (L.) Batsch], almond (*Prunus dulcis* Mill.), apple (*Malus domestic* Borkh), tomato (*Lycopersicon esculentum* Mill.), strawberry (*Fragaria ananassa* Duch.), and peppermint (*Mentha piperita* L.) have recorded both reduced leaf photosynthesis and transpiration rates (Hall and Ferree, 1975; Poskuta et al., 1975; DeAngelis et al., 1983; Youngman et al., 1986; Youngman and Barnes, 1986; Hare and Youngman, 1987; Royalty and Perring, 1989; Mobley and Marini, 1990; Nihoul et al., 1992). Reductions in photosynthesis have been shown to result from decreased stomatal opening and increased mesophyll resistance (Welter, 1989). However, the order in which these changes occur and how this varies with different mite densities and intensity of damage has not been clarified previously.

A further limitation of the above studies was that none considered the possibility of compensation for reductions in leaf photosynthesis because of mite feeding damage. For instance, it is possible that the photosynthetic rate of an undamaged portion of a mite-damaged leaf could increase relative to a leaf in the same position in an uninfested plant, thereby maintaining the total level of photosynthate produced per leaf (Nowak and Caldwell, 1984; Welter, 1989). In cotton, the possibility of compensation in response to mite damage was raised in crop level, rather than leaf level, studies by Sadras and Wilson (1997a). These authors derived estimates of crop RUE from measures of dry matter accumulation and light interception. They found that until mite populations exceeded about 20 adult female mites per leaf, the RUE of mite-infested cotton was maintained at similar levels to those occurring in uninfested cotton. This implied that the photosynthetic rate of leaves infested at this mite density was also being maintained, though portions of leaves were quite heavily damaged. Hence, the possibility of within-leaf compensation was invoked but was not tested because the photosynthetic rate of damaged and undamaged potions of leaves was not measured.

A.A. Reddall and L.J. Wilson, CSIRO Plant Industry and Australian Cotton CRC, Locked Bag 59, Narrabri NSW 2390, Australia; V.O. Sadras, CSIRO Land and Water, Waite Campus, Urrbrae SA 5064, Australia; P.C. Gregg, The University of New England, Armidale NSW 2351, Australia. Received 18 Mar. 2003. *Corresponding author (lewis.wilson@csiro.au).

Published in Crop Sci. 44:835–846 (2004).
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Abbreviations: afm, adult female mites (*Tetranychus urticae* Koch); ai, active ingredient; Bt, *Bacillus thuringiensis*; Ci, intercellular CO_2 concentration; Cry 1Ac, crystal protein 1Ac; DAS, days after sowing; gs, stomatal conductance to water vapor; LPR, leaf penetration resistance; +M, mite treatment (plants artificially infested with mites); −M, control treatment (no mites); PAR, photosynthetically active radiation; Pn, net photosynthesis; RUE, radiation use efficiency; S1, Season 1; S2, Season 2; T, transpiration.

This study had two aims. The first aim was to investigate the relationship between the intensity of *T. urticae* infestation, characterized as the number of adult female mites per leaf (Wilson and Morton, 1993), and leaf physiological responses, including photosynthesis, transpiration, stomatal opening and conductance, transpiration efficiency, intercellular CO_2 concentration, and leaf chlorophyll content. The second aim was to evaluate the possibility of within-leaf compensation for mite damage by assessing photosynthesis on damaged and undamaged portions of leaves.

MATERIALS AND METHODS

The effect of mite damage on leaf photosynthetic rate (Pn), stomatal conductance (gs), transpiration (T), intercellular CO_2 concentration (C_i), and transpiration efficiency (TE also known as physiological water use efficiency) were investigated in cotton crops over two seasons (Season 1, 1996–1997; Season 2, 1997–1998) at the Australian Cotton Research Institute (Narrabri, 30°S, 150°E).

Crop Management

The cotton crops were sown into cracking gray clay soil (Vertisol, Typic Pellustert; Ug5.25) (Northcote, 1979; Constable et al., 1992), in rows 1 m apart, on 9 Oct. 1996 in Season 1 and on 16 Oct. 1997 in Season 2. The plant density was 13 plants per meter in Season 1 and 10 plants per meter in Season 2 because of differences in establishment between years. The cultivar, Deltapine NuCotn 37, was used in both seasons and produces *Bacillus thuringiensis* subsp. *kurstaki* insecticidal proteins (Cry IAc) that provide control of *Helicoverpa* spp. (Lepidoptera, Noctuidae), the main insect pest of cotton in Australia. All insect pests were monitored twice weekly and controlled according to thresholds published in Shaw (1996) by insecticides that had little or no effect on mites directly. Crops were fertilized with anhydrous ammonia at a rate of 100 kg N ha^{-1} 2 mo before sowing and furrow irrigated before sowing. Soil water content was measured weekly with a neutron probe as described in Sadras et al. (1998). Crops were furrow irrigated whenever a soil water deficit of 50 to 60 mm was reached. Weeds were controlled with herbicides and interrow cultivation after crop emergence.

Treatments and Experimental Design

Two mite treatments, (i) −M, control and (ii) +M, plants artificially infested with mites, were included in a randomized block design which was replicated four times within a season. Plots were 8 rows by 18 m in Season 1 and 8 rows by 15 m in Season 2. The crops were mite-free before they were artificially infested with mites 83 d after sowing (DAS) in Season 1 and 91 DAS in Season 2, using the procedures developed by Wilson (1993, 1994a). These procedures included (i) spraying of crops with a broad-spectrum insecticide [thiodicarb (3,7,9,13-tetramethyl-5,11-dioxa-2,8,14-trithia-4,7,9,12-tetra-azapentadeca-3,12-diene-6,10-dione) at 750 g ai ha^{-1}] 2 d before mite infestation to eliminate mite predators and encourage mite establishment, (ii) infestation of the central rows of +M subplots with mite-infested cotton seedlings grown in a glasshouse, (iii) use of 4-m intervening bare soil gaps between plots to reduce the risk of cross infestation between +M and −M plots, and (iv) control of mites in −M plots with acaricides whenever mites exceeded an average of one adult female mite per leaf.

Measurements

Weekly measurements of photosynthetic rate, stomatal conductance, transpiration, intercellular CO_2 concentration, transpiration efficiency, chlorophyll content, leaf damage, and mite abundance were made, beginning 1 wk before the introduction of mite infestations. To avoid possible effects of miticides (see above) on photosynthesis, measurements were not taken within 48 h of an application. Measurements were made on the top most fully expanded mainstem leaf, which was usually four nodes below the terminal; this is also the node most likely to contain the highest mite density within the cotton plant (Wilson and Morton, 1993). This means that the position of the leaf measured remained constant relative to the plant terminal but that it was at a progressively higher node position in relation to the cotyledons as the season progressed. Because the leaf that occupied this position changes from week to week the fate of particular leaves over time was not studied. Each week, two measurements were taken on one leaf on a previously tagged plant in the center row of each plot, one measurement at the basal and one at the distal portion (see below). A new plant was tagged in each plot each week (i.e., four leaves were measured per mite treatment per week, four new leaves the following week, and so on).

To assess within-leaf compensation, all plant measurements were taken from the basal portion of each leaf, where mites initially colonize leaves, and the distal portion of the leaves, which are colonized by mites later as mite populations build and spread (Wilson, 1994b) (i.e., two measurements per leaf, Fig. 1). Mite abundance and leaf area damaged were recorded for the whole leaf.

Gas exchange variables were measured with a LI-COR, LI-6400 (Lincoln, NE, USA) portable photosynthesis system with a clear leaf chamber covering an area of 6 cm^2. Measurements were taken within the period of 3 h either side of solar noon in ambient light when the photosynthetically active radiation (PAR) reaching the adaxial leaf surface of the leaves was greater than 1600 μmol m^{-2} s^{-1}. While measurements were being taken, the leaves were held perpendicular to the sun. Photosynthetic rates were measured approximately 2 min after the chamber was placed over the leaf to allow stabilization of readings. Each measurement was the average of five consecutive readings, taken sequentially at two second intervals. TE

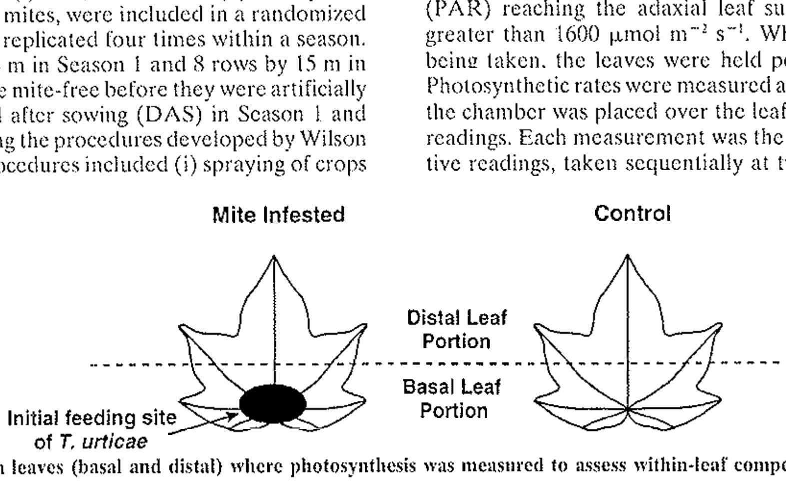

Fig. 1. Positions on cotton leaves (basal and distal) where photosynthesis was measured to assess within-leaf compensation.

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was calculated by dividing the photosynthetic rate by the transpiration rate of the leaf portions (Sinclair et al., 1984).

Leaf chlorophyll content was measured with a SPAD 501 chlorophyll meter (Minolta, Osaka, Japan), which has been tested in a number of plant species, including cotton (Wood et al., 1992). The relationship between actual chlorophyll content and output from the SPAD is nonlinear and was calibrated for analysis by the exponential decay equation (Markwell et al., 1995):

$$\log_{10}C = s^{0.265}$$

where C = chlorophyll content (μmol m^{-2}) and s = SPAD units. Chlorophyll content was measured in basal and distal portions (average of five separate measurements) of the same mite infested and control leaves used for photosynthesis measurements.

The number of adult female mites and feeding damage were recorded for each tagged leaf in both the +M and −M plots. Feeding damage was scored to compare the leaf damage per mite between years and leaf portions and to test the relationship with photosynthetic rate and related components. In Season 1, damage was scored by estimating the percentage of the abaxial leaf area visibly damaged by mites, irrespective of damage intensity, as described in Wilson and Morton (1993). In Season 2, the damage intensity was similarly estimated but classified further as light damage, where the leaf showed the pale yellow mottling typical of a short period of mite feeding or heavy damage, where the leaf showed the dark red-brown scarred areas typical of prolonged mite feeding.

In Season 1, stomatal imprints were taken to (i) relate stomatal conductance to the proportion of open stomata and (ii) assess if mite feeding alters this relationship. Stomatal imprints were taken at solar noon on three dates, 21 Jan. (104 DAS), 10 Feb. (124 DAS), and 19 Feb. (133 DAS), 1997. Imprints were made by painting a thin layer of clear fingernail polish over a 1-cm^2 area of the abaxial surface of the leaf. This was allowed to dry for 1 min. Adhesive tape was then placed over the nail polish and peeled off, removing with it the nail polish with stomatal imprints. The tape with nail polish was then stuck to a 35-mm glass microscope slide. The number of open and closed stomata was counted in a 1-cm by 1-mm area (about 500 stomata) of each imprint with a compound microscope (Nikon, model L-Ke, Nippon Kogaku Inc., Garden City, NY, USA). Measurements were taken at four sites on each leaf, a visibly damaged and an undamaged sample from both the basal and distal portions.

Data for leaf penetration resistance were obtained from Sadras et al. (1998) for Season 1 and unpublished data of Sadras and Wilson in Season 2. Briefly, penetration resistance was measured on attached leaves with a dial tension gauge (Sadras et al., 1998). Three leaves per plot and three positions per leaf near the insertion of the petiole, where mites prefer to feed (Wilson, 1994b), were measured and averaged at approximately weekly intervals.

Calculations and Statistical Analyses

Days after sowing were converted to cumulative degree days after sowing with a base temperature of 12°C, which is close to the threshold for development of both cotton and *T. urticae* (Wilson, 1993).

Linear and nonlinear curves were used to characterize the relationship between leaf response variables, i.e., photosynthesis, stomatal conductance, transpiration, intercellular CO_2 concentration, transpiration efficiency and chlorophyll content, and the number of adult female mites per leaf (SigmaPlot 2000, SPSS Science, Chicago, IL, USA). The nonlinear curves fitted included exponential decay, which allows for a rapid drop in the dependent variable as the independent variable increases, and a negative logistic growth curve, which allows for a delay in the decline of the dependent variable as the independent variable increases. To account for ontogenetic and environmental effects, net photosynthesis and other components for the +M treatments were normalized with respect to controls. This was done by expressing the +M as a percentage of −M for each sample occasion. An analysis of variance including terms for block, mite treatment, leaf portion, and damage status was used when comparing the percentage of stomata open of +M and −M mite treatments (Genstat Version 5, Lawes Agricultural Trust, IACR, Rothamsted, UK). Mite numbers were $\log_e$ transformed and damaged leaf percentages arcsine transformed before analysis to stabilize variances (Wilson, 1993), but untransformed values are shown in figures for easier interpretation. Significant differences were expressed at 95% ($P < 0.05$) confidence unless otherwise stated.

RESULTS

Dynamics of Mite Populations and Leaf Damage

Crops were infested at a similar chronological time in both seasons (83 and 91 DAS, Fig. 2a,b) but at an earlier crop developmental stage in Season 1 than Season 2 (905 and 1320.7 day degrees after sowing, respectively). Once established, mite colonies in infested plots grew at a similar rate of 0.09 adult female mites (afm) per leaf per day degree in both years. There was a dip in the increase of mites in Season 1 because of heavy rainfall. The percentage of leaf area damaged by mites increased linearly with increasing mite population density; the slopes for Seasons 1 and 2 were not significantly different (df = 34, t = −0.23, P = 0.822), so the data were combined (Fig. 3). About 1% of the leaf area was damaged for each adult female mite.

Effects of Mites on Pn, gs, T, and TE

Net photosynthesis, stomatal conductance and transpiration all declined in both basal (Fig. 2c–h) and distal leaf portions (data not shown) as control plants aged over the course of experiments (e.g., Fig. 2c–h). In both years mite damage accelerated these declines and this effect was more pronounced in Season 1 than in Season 2, despite similar mite population rates of increase. Transpiration efficiency increased during the middle of Season 1 and at the start of Season 2 measurement periods (Fig. 2i,j). Mite damage caused a reduction in transpiration efficiency, earlier in Season 1 than 2.

Photosynthetic Compensation

There was no significant evidence for within-leaf photosynthetic compensation for mite damage in either season. At no time was there a significant increase in Pn in either basal or distal leaf sections of the +M leaves relative to the −M leaves (Fig. 4a,b). In contrast, Pn declined rapidly as mite numbers increased in the damaged basal areas and declined even in the undamaged distal portions of damaged leaves.

Relationships between Pn, gs, T, TE, and Mite Density—Basal Portions

Pn, gs, T, and TE showed a nonlinear decline in response to increasing mite density (Fig. 4a-h, Table 1).

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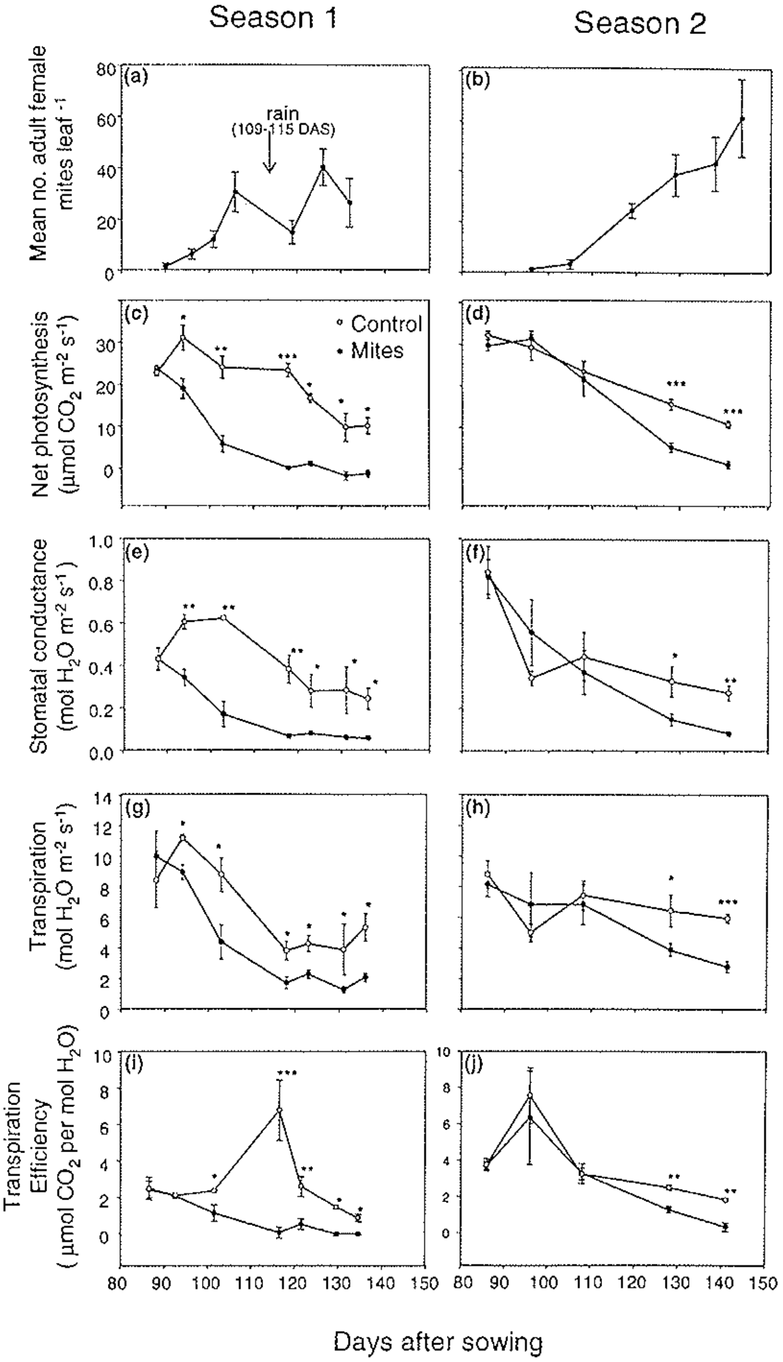

Fig. 2. Development of mite populations in mite infested plots (a,b) and net photosynthetic rate (c,d), stomatal conductance (e,f), transpiration (g,h), and transpiration efficiency (i,j) in the basal portion of mite damaged (+mites) or undamaged (−mites) leaves in Season 1 and 2. Values are mean ± SE (n = 4). Asterisks indicate significant differences between + and −mite treatments within each season at $*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

In the basal areas, all response variables declined as mite populations increased, following an exponential decay curve. The decline in Pn, gs and TE in response to increasing mite density was steeper than for T in both seasons. Declines in all variables with increasing mite density were steeper in Season 1 than Season 2.

Relationships between Pn, gs, T, TE, and Mite Density—Distal Portions

Pn, gs, T, and TE showed nonlinear decreases with increasing mite density even though these areas were not directly damaged by mites until late in the season. In all cases, the relationships were well described by a

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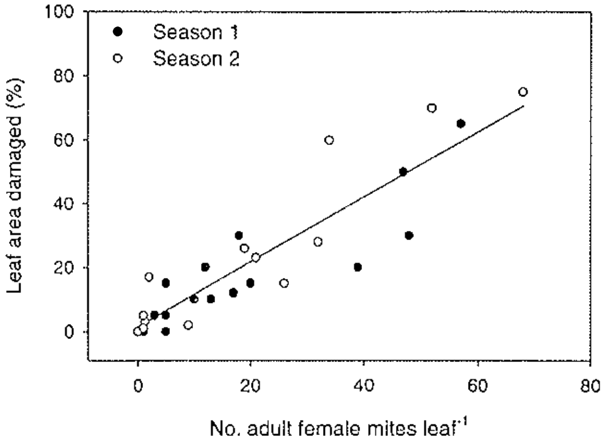

Fig. 3. Relationship between percentage leaf area damaged and number of adult female *T. urticae* per leaf; pooled data from Seasons 1 and 2. The fitted line is $y = 1.35 + 1.02x$, $R^2 = 0.83$; df = 35, F = 167.36, $P < 0.0001$.

negative logistic curve (Fig. 4a–h, Table 1). These curves allow for the initial delay in the decline of the predicted variable as mite numbers increase, which is well illustrated by the decline in Pn in the distal portion in Season 1 compared with Season 2. In Season 1, distal percentage Pn showed rapid reductions as mite numbers increased in the basal area, while in Season 2 a clear biphasic response in distal percentage Pn was apparent, where percentage Pn was maintained at about 100% (relative to −M leaves) until about 20 afm leaf^{-1} after which percentage Pn began to decline rapidly (Fig. 4a,b). Similar general trends were apparent for gs but T declined slightly earlier and TE declined later.

Relative Sensitivity of Pn, gs, T, and TE to Mite Damage

In the basal portions, initial reductions of 10% in Pn, gs, T and TE, in +M compared with −M treatments, all occurred at less than 7 afm leaf^{-1} in both seasons (Table 2). Larger reductions of 50%, in +M compared to −M treatments, followed a more discernable sequence in both seasons with gs affected first at 8 to 11 afm leaf^{-1}, followed by Pn at 8 to 14 afm leaf^{-1}, followed by TE at 11 to 21 afm leaf^{-1}, then T at 20 to 36 afm leaf^{-1}. The more rapid decline in Pn compared with T probably explains why TE declined at a lower afm leaf^{-1} than T.

In the distal portions, effects were observed at higher mite densities than in basal areas and followed a slightly different pattern, with initially T showing a 10% reduction before Pn, especially in Season 2 (Table 2). In Season 1, initial reductions of 10% in Pn, gs, T, and TE, in +M compared with −M treatments, all occurred at less than 6 to 8 afm leaf^{-1}. In Season 2, similar responses of Pn, gs, T, and TE to mites were slower with reductions of 10% in gs and T occurring at similar densities of 14 to 16 afm leaf^{-1}, with reductions in Pn, followed by TE at much higher densities. Reductions of 50% in +M compared with −M plots showed initially a similar pattern to the basal areas with gs and Pn affected at the lowest densities in both seasons. T and TE were not affected until almost double the number of mites, but the order was different between years with TE affected earlier in Season 1 and later in Season 2 where a reduction of 50% was not reached (Table 2).

Relationship between C_i and Mite Density

C_i showed a linear increase with increasing mite density in both seasons, with a greater increase per afm in the basal portions than the distal portions (Fig. 4i,j, Table 1). It is important to note that C_i is calculated from photosynthesis, transpiration, and vapor pressure deficit, thus C_i and Pn are correlated to a degree.

Stomatal Imprints

Stomatal imprints were taken in Season 1 after significant reductions in Pn, gs, and T had occurred in both the basal and distal leaf positions of the +M leaves (Fig. 5). Reductions in the percentage of open stomata were generally found on damaged and undamaged areas in both distal and basal portions of mite infested leaves compared with uninfested control leaves (Fig. 5, 6). On uninfested leaves, the proportion of open stomata ranged 50 to 70%. On damaged leaf areas of mite infested leaves, it ranged between 5 to 30% while on undamaged portions it was higher, ranging between about 20 to 55% but still less than the uninfested leaves. On the final measurement date, there was a similar percentage of open stomata on the undamaged portions of mite-infested leaves and control leaves.

Chlorophyll Content and Relationship with Mites and Pn

In both seasons, mite feeding damage resulted in reduced chlorophyll content of the basal leaf portions, but had little or no effect on the distal leaf portions. The chlorophyll content of the basal leaf portions in +M leaves declined linearly as afm abundance increased (Season 1: df = 18, $F = 9.82$, $P = 0.006$; Season 2: df = 27, $F = 42.11$, $P < 0.0001$) (Fig. 7). No significant relationship was found between percentage chlorophyll content and afm in the distal leaf portions for either season (Fig. 7).

Photosynthesis and chlorophyll content of the basal leaf portions, expressed as a percentage of the −M treatment (Fig. 8), showed a linear relationship in both seasons (basal Pn − Season 1: df = 16, $F = 9.92$, $P = 0.0066$; Season 2: df = 18, $F = 105.53$, $P < 0.0001$). Photosynthesis declined faster than chlorophyll content; for example, chlorophyll content was 60 to 75% of the −M treatment when Pn was less than 10% of the −M treatment. A similar relationship was found for the distal portion in Season 1 but not Season 2.

Leaf Penetration Resistance

Leaf penetration resistance (LPR) provides an indication of leaf hardness. In most cases, mite feeding damage had little effect on LPR in both seasons (df = 23, $F = 0.06$, $P = 0.813$). The mean LPR in Season 1 was 3.7

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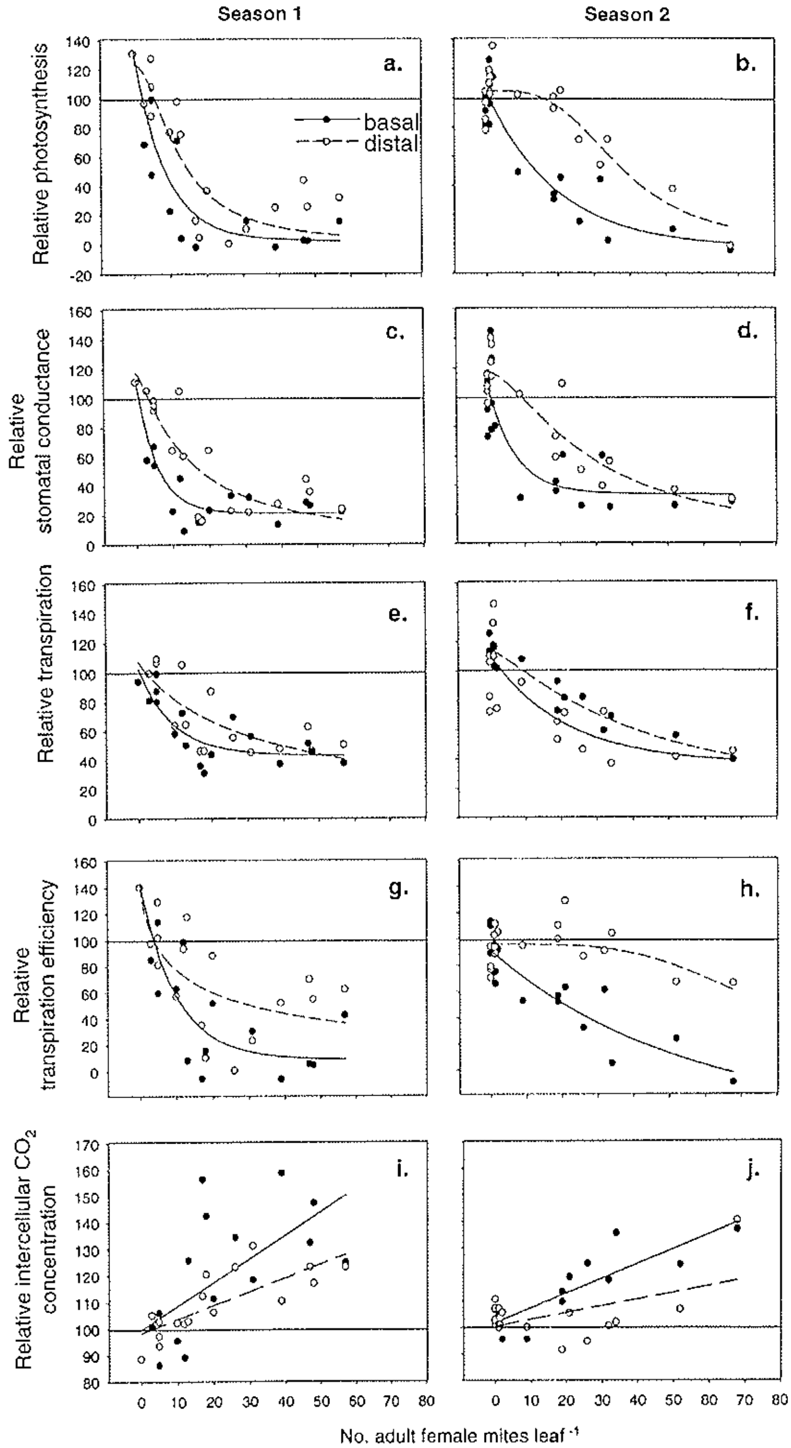

Fig. 4. Relationship between the number of adult female *T. urticae* per leaf and photosynthesis (a,b), stomatal conductance (c,d), transpiration (e,f), transpiration efficiency (g,h), and intercellular CO$_2$ concentration (i,j) of basal (solid lines) and distal (dashed lines) leaf portions in mite infested plants (expressed as a percentage relative to undamaged controls) for both seasons.

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Table 1. Regression equations describing the relationship between photosynthesis (Pn), stomatal conductance (gs), transpiration (T), transpiration efficiency (TE) and intercellular CO_2 concentration (Ci) and the number of adult female *T. urticae* per leaf (x) in the basal and distal leaf portions in Seasons 1 and 2.

Response Variable	Basal leaf portion–exponential decay equations		Distal leaf portion–negative logistic equations	
	Season 1	Season 2	Season 1	Season 2
Pn	$y = 2.4 + 130.5 \times \exp(-0.12 \times x)$ $R^2 = 0.74$, df = 16, $F = 19.6$, $P < 0.0001$	$y = 104.0 \times \exp(-0.05 \times x)$ $R^2 = 0.87$, df = 18, F = 113.9, $P < 0.0001$	$y = 123.9[1 + (x/12.4)^{1.9}]$ $R^2 = 0.79$, df = 16, F = 26.0, $P < 0.0001$	$y = 104.8/[1 + (x/37.4)^{3.5}]$ $R^2 = 0.81$, df = 18, $F = 33.7$, $P < 0.0001$
gs	$y = 21.47 + 90.86 \times \exp(-0.18 \times x)$ $R^2 = 0.75$, df = 16, F = 40.0, $P < 0.0001$	$y = 33.38 + 73.29 \times \exp(-0.13 \times x)$ $R^2 = 0.71$, df = 17, F = 18.7, $P < 0.0001$	$y = 117.55/[1 + (x/13.90)^{1.25}]$ $R^2 = 0.75$, df = 16, F = 20.8, $P < 0.0001$	$y = 117.17/[1 + (x/28.62)^{1.59}]$ $R^2 = 0.82$, df = 16, F = 31.9, $P < 0.0001$
T	$y = 43.15 + 59.14 \times \exp(-0.11 \times x)$ $R^2 = 0.68$, df = 16, F = 15.0, $P = 0.0003$	$y = 36.32 + 74.26 \times \exp(-0.05 \times x)$ $R^2 = 0.62$, df = 17, F = 12.0, $P = 0.0008$	$y = 106.99/[1 + (x/34.35)^{0.95}]$ $R^2 = 0.62$, df = 16, F = 11.5, $P = 0.0011$	$y = 114.46/[1 + (x/43.83)^{1.25}]$ $R^2 = 0.93$, df = 17, F = 207.2, $P < 0.0001$
TE	$y = 8.90 + 133.96 \times \exp(-0.10 \times x)$ $R^2 = 0.69$, df = 16, F = 15.7, $P = 0.0003$	$y = -40.75 + 131.52 \times \exp(-0.02 \times x)$ $R^2 = 0.79$, df = 17, F = 29.1, $P < 0.0001$	$y = 143.03/[1 + (x/12.69)^{0.71}]$ $R^2 = 0.47$, df = 16, F = 6.3, $P = 0.0114$	$y = 95.51/[1 + (x/53.03)^{0.82}]$ $R^2 = 0.75$, df = 17, F = 21.4, $P < 0.0001$
Ci (linear response)	$y = 99.7 + 0.89x$ $R^2 = 0.42$, df = 16, F = 11.0, $P = 0.005$	$y = 101.8 + 0.56x$ $R^2 = 0.78$, df = 17, F = 54.1, $P < 0.001$	$y = 98.4 + 0.52x$ $R^2 = 0.59$, df = 16, F = 21.5, $P < 0.001$	$y = 100.5 + 0.26x$ $R^2 = 0.26$, df = 16, F = 5.4, $P = 0.035$

Table 2. Timing and sensitivity of responses to mite damage.

		Timing of response				Sensitivity (afm leaf^{-1})			
		DAS†		afm leaf^{-1}‡		10% reduced§		50% reduced¶	
Response variable	Leaf portion	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Pn	basal	94	128	6	33	3	3	8	14
	distal	118	NS#	31	NS	8	23	16	38
gs	basal	94	128	6	33	2	2	8	11
	distal	118	141	31	43	6	14	16	34
T	basal	94	128	6	33	1	7	20	36
	distal	123	141	40	43	6	16	39	54
TE	basal	–	–	–	–	5	2	11	21
	distal	–	–	–	–	6	39	30	NS

† DAS when first significant difference occurred between +M and −M leaves.

‡ Number of adult female mites per leaf when first significant difference between +M and −M was detected.

§ Number of adult female mites per leaf required for a 10% reduction in +M responses relative to controls. The values were determined from the fitted functions displayed in Fig. 3 and Table 1.

¶ Number of adult female mites per leaf required for a 50% reduction in +M responses relative to controls. The values were determined from the fitted functions displayed in Fig. 3 and Table 1.

Response not significantly affected ($P > 0.05$).

kPa for the +M and 3.6 kPa for the −M treatments while in Season 2, it was 3.9 kPa in the +M, and 4.0 kPa in the −M treatments. However, there was a significant difference between seasons (df = 23, $F = 6.76$, $P = 0.017$), with a higher LPR in Season 2 than in Season 1.

DISCUSSION

Effects of Season and Time of Mite Infestation on Cotton Leaf Responses

Plant responses to herbivory are strongly influenced by seasonal conditions and timing of infestation (Sadras, 1995). In our study, photosynthetic rate, stomatal conductance, transpiration, transpiration efficiency, and intercellular CO_2 concentration of both basal and distal leaf sections showed a greater response to mite damage in Season 1 than in Season 2 (Fig. 4).

The rate of increase in the mite populations of the +M plots in Seasons 1 and 2 was similar and the relationship between the mite abundance and damage was the same in both seasons (Fig. 3). However, the mites were added to plots about 385 day degrees earlier in Season 1, in terms of cotton development, which may have been a major cause for the difference in response between seasons. This suggestion is supported by Wilson (1993) and Sadras and Wilson (1996) who found that the earlier that mite infestations occur, the greater the potential reductions in cotton yield, fiber quality, seed viability and oil content.

Leaf penetration resistance was higher in Season 2 than in Season 1. The higher penetration resistance in Season 2 probably reflected differences in growing conditions. Jiang and Ridsdill-Smith (1996) found that increased leaf toughness in subterranean clover cotyledons (*Trifolium subterraneum* subsp. *subterraneum* L.), measured with a similar penetrometer to that used in this study, was negatively correlated with damage scores from redlegged earth mite [*Halotydeus destructor* (Tucker)]. Sadras et al. (1998) found that mites feeding on harder-leaved water-stressed cotton caused less marked symptoms of mite damage than those on softer-leaved cotton receiving optimal water despite similar levels of infestation. Given the differences in leaf hardness between Season 1 and 2, it is possible that the intensity of damage, in terms of the number of puncture holes in the leaf, was lower in Season 2, even though the proportion of leaf area damaged per afm was similar. Further, Sadras et al. (1998) showed that penetration resistance was positively correlated with specific leaf weight; that is, leaves with higher penetration resistance were thicker. If leaves were thicker in Season 2, it is possible that a higher proportion of the photosynthetic apparatus was

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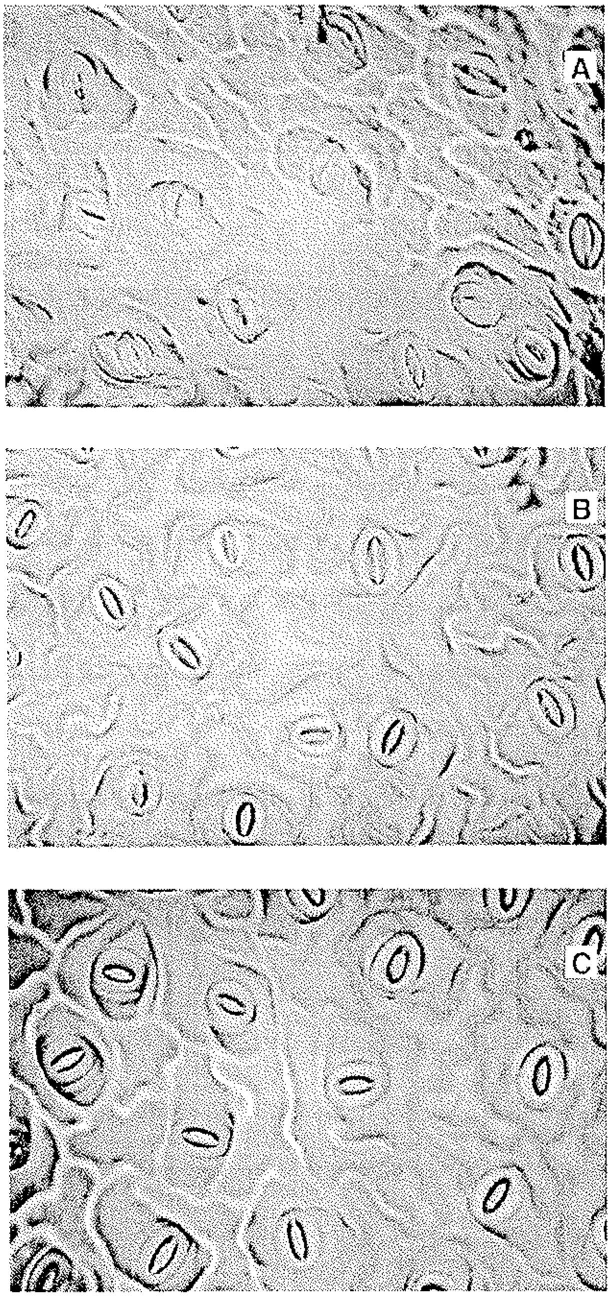

Fig. 5. Stomatal imprints of a mite-infested leaf (A,B) and of an uninfested control (C). The infested leaf had 22 adult female mites. (A) is a visibly damaged basal leaf section and (B) is an undamaged distal area of the leaf.

undamaged, compared with Season 1, because it was beyond the reach of mite stylets (discussed below). Combined with differences in the timing of mite infestation and differences in growing conditions, a difference in leaf hardness could therefore contribute to differences in the severity of damage to cotton leaves and therefore the differences in the response of photosynthesis to mites between seasons.

Leaf Responses to Mite Damage

Both stomatal and nonstomatal components of photosynthesis, chlorophyll for example, were reduced by mite feeding damage and corresponded to reductions in photosynthetic rate. Where the mites caused the most severe damage, particularly the basal leaf portions, the greatest effects on leaf physiology occurred (Fig. 4). In the basal portions of leaves, transpiration, stomatal conductance, photosynthesis, chlorophyll content (Fig. 7), and transpiration efficiency were reduced quickly at low mite densities, while in the distal areas effects occurred at higher mite densities (Table 2).

Leaf transpiration efficiency and photosynthetic rate were reduced by 10% at a similar rate but photosynthetic rate was reduced by 50% more rapidly than leaf transpiration (Table 2). Anisohydric species, such as cotton and sunflower (*Helianthus annuus* L.), tend to keep stomata open and tolerate severe drops in leaf water potential in response to soil water deficit (Tardieu and Simonneau, 1998). Stomatal closure induced by mites (Fig. 5, 6) and consequent heating of the leaf and canopy (Sadras and Wilson, 1997a) therefore contrasts with the trend to maintain high conductance in water-stressed cotton.

The rapid closure of stomata in damaged areas, and resulting decline in gs may be related to the nature of feeding of mites. Their piercing mouthparts (stylets) are about 132 ± 27 μm long. Studies with strawberries as host plants found mites penetrated leaves to a depth of about 117.5 ± 24.9 μm (Sances et al., 1979). Cotton leaves are typically in the order of 255 μm thick (Pettigrew et al., 1993). Assuming mites penetrate the abaxial surface of cotton leaves to a similar depth to strawberry leaves then damage should occur mostly to the spongy mesophyll, and this has been shown by Bondada et al. (1995), though some damage to palisade mesophyll was also observed. Damage to spongy mesophyll has been associated with dehydration and a lack of turgidity of stomatal guard cells, resulting in stomatal closure (Bondada et al., 1995; Sances et al., 1979), which is likely to be one of the first components of photosynthesis to be affected.

There was a strong relationship between chlorophyll content and photosynthetic rate, particularly in the heavily mite damaged areas in basal leaf portions (Fig. 8). However, photosynthesis declined more rapidly than chlorophyll content, suggesting that the initial rapid decline in photosynthesis observed in the basal areas was probably driven primarily by rapid stomatal closure, thereby limiting gas exchange, rather than by loss of chlorophyll. After mite feeding, there are many penetration holes in damaged areas of the leaf surface, which presumably allow water loss independent of the stomata, hence transpiration may appear to be maintained. That *gs* and photosynthetic rate were reduced by 50% more rapidly than transpiration provides some support for this suggestion (Table 2).

In relatively undamaged areas (distal portions), photosynthesis was reduced and cannot be attributed to loss

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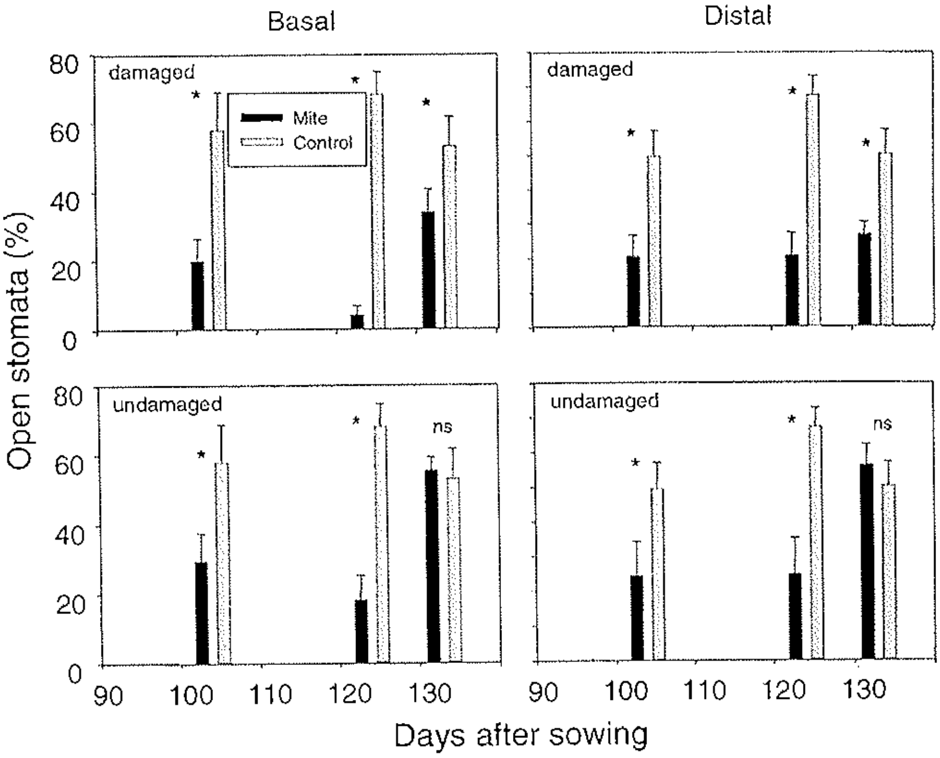

Fig. 6. Percentage of open stomata in both basal and distal leaf portions of mite-infested and uninfested control leaves in Season 1. Values are mean + SE ($n = 4$). Asterisks indicate significant difference at $P < 0.05$ and refer to the significance of the ANOVA comparing mite and control responses.

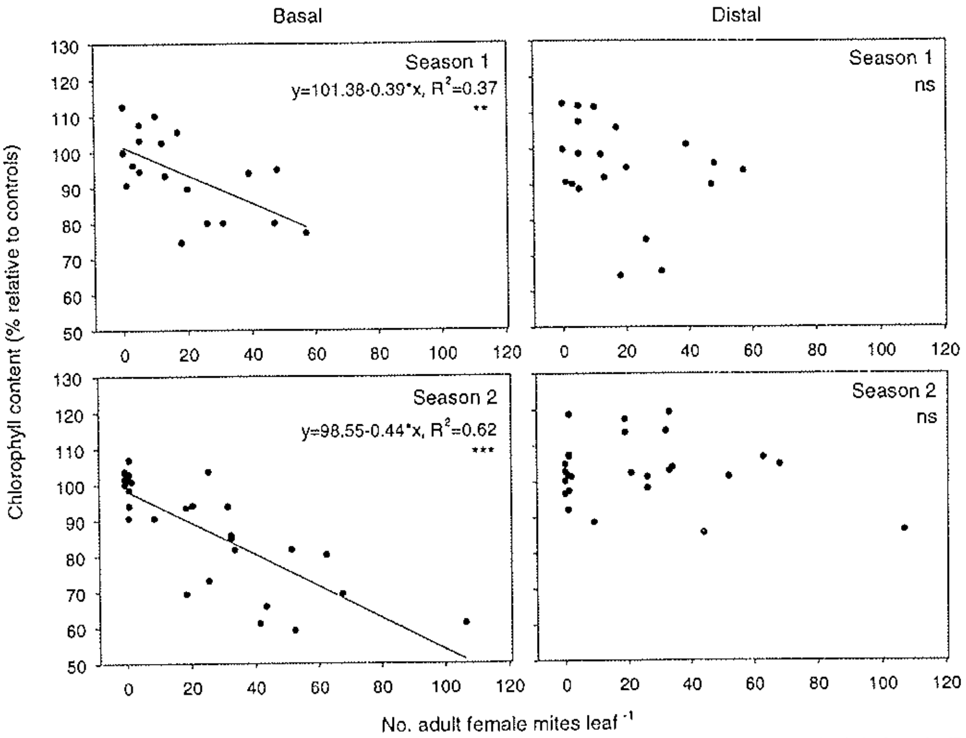

Fig. 7. Relationship between chlorophyll content, expressed as the percent relative to control and number of adult female *T. urticae* per leaf. Asterisks indicate significant differences between + and −mite treatments within each season at $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$ and refer to the significance level of the regression relating chlorophyll content to afm leaf^{-1}.

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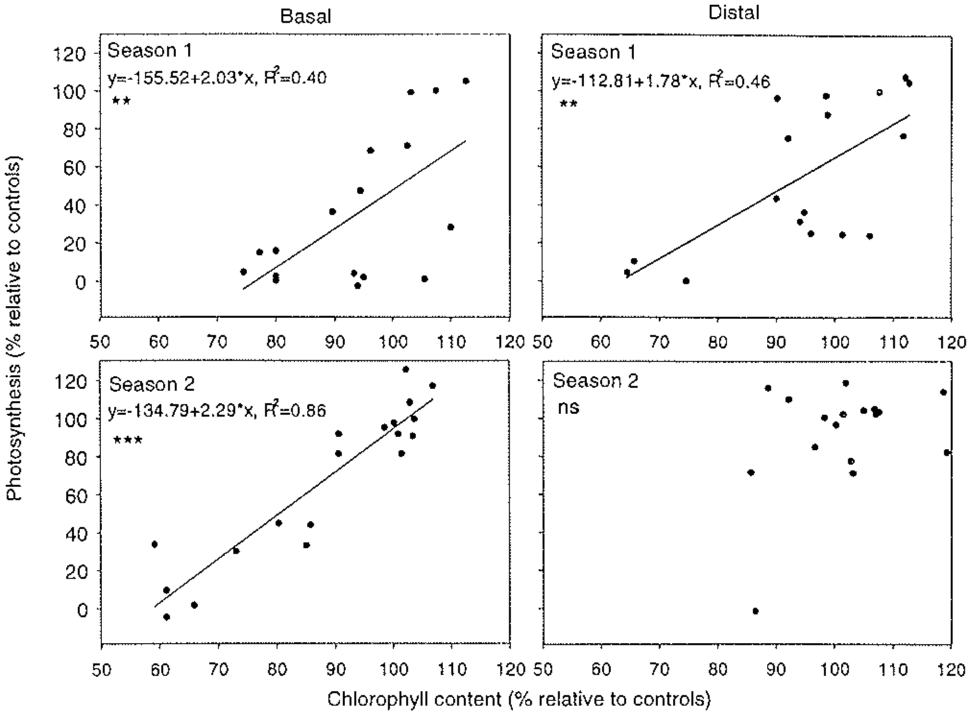

Fig. 8. Relationship between percentage photosynthesis and percentage chlorophyll content of the basal and distal leaf portions of mite infested leaves relative to controls. Asterisks indicate significant differences between + and −mite treatments within each season at $*P < 0.05$, $**P < 0.01$, $***P < 0.001$ and symbols refer to the significance level of the regression analysis relating percentage chlorophyll content and percentage photosynthesis.

of chlorophyll, at least in the initial stages. In these areas, reductions in stomatal conductance occurred even though there was no direct feeding damage. We determined a sequence of events as a result of mite damage in distal areas for Season 2, where first stomatal conductance was reduced, then transpiration, then photosynthetic rate and finally transpiration efficiency (Fig. 9). In Season 1, reductions in physiological processes were too rapid in the distal areas so a sequence of events could not be determined.

Photosynthetic rate was maintained longer than stomatal conductance in the distal leaf portions, which indicated that reductions in stomatal conductance did not initially affect photosynthetic rate (Table 2). Causes for the closure of stomata in undamaged areas cannot be determined in this study. We suggest, however, that a combination of changes to transport within the leaf structure due to mite damage and possibly hormonal responses may be involved. As mite damage initially occurred around the petiole and basal area of the leaves, the transport of nutrients, hormones and water from the rest of the plant to the distal leaf portion may have been inhibited by damage to vascular tissues. This in turn could lead to water stress in undamaged leaf portions and progressive closure of stomata (see Fig. 4d) and ultimately affect photosynthesis. Accumulation of photosynthetic products with impaired transport might also have contributed to reduce photosynthesis (Evans et al., 1993). There may also be a hormonal component as changes in abscisic acid (ABA) concentrations in particular can affect stomatal mechanics and leaf gas exchange; ABA is widely known to regulate stomatal aperture (Franks and Farquhar, 2001). So in contrast to heavily damaged areas, where photosynthesis and

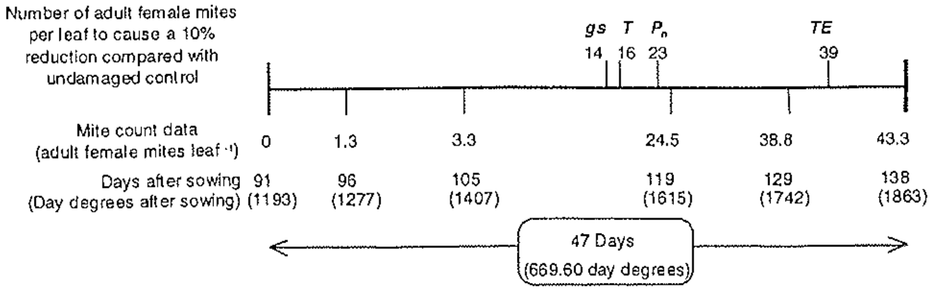

Fig. 9. Sequence of the initial reduction in stomatal conductance (gs), transpiration rate (T), leaf photosynthesis (Pn) and transpiration efficiency (TE) in response to the adult female mite density per leaf of the distal leaf portions in Season 2.

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stomatal conductance declined concurrently, a weaker (hormonal) response signal to the mite damage may have occurred in distal areas, resulting in a more gradual stomatal response. Later, direct mite feeding damage spread to the distal portions (mainly in Season 1), causing additional cellular damage, which probably further reduced photosynthetic rate.

Interestingly, intercellular CO_2 concentration increased with increasing mite density in both basal and distal portions over the two seasons (Fig. 4). In contrast, Wong et al. (1979) showed that under many conditions where photosynthetic capacity and stomatal conductance declined, the ratio of intercellular and ambient CO_2 concentration often remained constant. In order for plants to do this and therefore maximize their efficiency of water use, plants synchronize stomatal opening with the CO_2 requirement of the assimilatory tissue (Farquhar et al., 1978, 2001). In our study, an increase in C_i was found when photosynthesis decreased as a result of mite feeding damage rather than a constant intercellular CO_2 concentration as would be expected. This may be due to puncture holes in the plant (discussed above) caused by mite feeding damage or even possibly damage to some stomata leading to leakage of H_2O, therefore preventing C_i from being maintained.

Within-Leaf Compensation

Two seasons of fieldwork did not show evidence of within-leaf compensation for mite damage. Sadras and Wilson (1997a) in studies of mite-cotton interactions at the crop level found that mite damage caused significant reductions in crop radiation use efficiency (RUE), which is essentially a crop level reflection of effects on photosynthesis. They also reported an initial tolerance of RUE to increasing mite density, indicating possible compensatory photosynthesis. In the study presented here, photosynthesis declined rapidly in response to increasing mite density in basal areas. The only evidence for such a lag in response was for the distal portion in Season 2; however, there was no evidence of elevated rates of photosynthesis that would suggest compensation. Instead, we report for the first time that damage to basal leaf areas also results in reductions in photosynthesis, stomatal conductance, transpiration and transpiration efficiency in the distal, undamaged portions of leaves. This response is delayed compared with the responses in the basal areas, particularly in Season 2, and indicates that damage to basal areas eventually has an effect on undamaged leaf portions.

Herbivores often induce biphasic responses in plants, where at low levels of herbivory an increase in production potential can occur, whereas extreme herbivory causes extreme reduction in productivity (Dyer et al., 1993). No evidence of such a response was found in this study. Furthermore, Welter (1989) noted that photosynthetic compensation has not been recorded as a result of mesophyll or selective tissue feeders such as spider mites. The results from this study agree with Welter (1989) as it would appear that selective tissue feeding of the mesophyll cells by mites has negatively affected the surrounding tissue.

This study does not explain the initial lag in decline of RUE reported by Sadras and Wilson (1997a). It is possible, however, that there could be within plant compensation, i.e., undamaged leaves on mite infested plants could have higher rates of photosynthesis than similar aged leaves on undamaged plants. This possibility is reinforced by the within plant distribution of mites which is initially skewed toward younger leaves, leaving the bulk of the plant's mature leaves undamaged.

CONCLUSIONS

This study shows that mite populations can cause dramatic reductions in photosynthesis and related processes of cotton leaves. This supports the findings of studies of the effects of mites on cotton productivity (Wilson, 1993; Sadras and Wilson, 1997a). Responses varied in magnitude in relation to mite density between years, suggesting that other factors can modulate the effects of mite damage on photosynthesis at the leaf level including leaf hardness and plant growth conditions.

No evidence of within leaf compensation for mite damage was found. In contrast, undamaged portions of damaged leaves showed a decline in photosynthesis compared with similar portions of undamaged leaves.

ACKNOWLEDGMENTS

We thank Vivienne Wheaton for able technical assistance and Greg Constable and Tom Lei (CSIRO) for valuable comments on an early draft of this manuscript. This research formed a portion of a Ph.D. dissertation submitted to the University of New England, Armidale, Australia. The Cotton Research and Development Corporation provided substantial funding for this project (grant no. CSP60C).

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How to Succeed by Doing Nothing: Cotton Compensation after Simulated Early Season Pest Damage

Lewis J. Wilson,* Victor O. Sadras, Simone C. Heimoana, and Dallas Gibb

ABSTRACT

Clarifying the amount of pest damage that can be tolerated without justifying insecticidal control will be useful in reducing insecticide use and in development of integrated pest management (IPM) systems. This study investigated the ability of irrigated, high-yielding cotton (*Gossypium hirsutum* L.) to recover from artificially applied damage simulating that of early season insect pests. Six experiments were done across five cotton-growing seasons. Damage included defoliation, terminal damage, and flower bud removal in a range of timings, combinations, and intensities. Crop yield was unaffected by defoliation applied before first flower buds appeared, even when 100% of true leaves were removed on three occasions (Nodes 2, 4, and 6). Crop maturity was affected by sustained high levels of leaf loss with a peak delay of 10 d after 100% defoliation three times. Up to three light tip damage events or one heavy damage event had no effect on yield and only a slight effect on crop maturity (<5-d delay to harvest). Heavy early fruit loss (100% fruit removal from the first four fruiting branches) did not affect yield but caused a delay in maturity of ≈7 d. Equations describing the relationship between damage type, intensity, and repetition and the yield and maturity of cotton were developed and used in sensitivity analysis to define tentative damage thresholds for IPM systems in cotton.

Cotton is attacked by a range of insect pests, some of which are prevalent through the early portion of the growing cycle, such as tobacco thrips (*Thrips tabaci* Lindeman), tomato thrips [*Frankliniella schultzei* (Trybom)], the native budworm [*Helicoverpa punctigera* (Wallengren)], the cotton bollworm [*H. armigera* (Hübner)], the green mirid [*Creontiades dilutus* (Stål)], and the cotton tip-worm (*Crocidosema plebejana* Zeller) (Pyke and Brown, 1996). Application of insecticides to prevent damage caused by these pests (i) increases the risk of inadvertent environmental pollution, (ii) increases selection pressure for insecticide resistance both in target and nontarget pests, and (iii) often reduces the abundance of beneficials, thereby contributing to secondary pest outbreaks (Wilson et al., 1998). Notably, the pest thrips are also important predators of the eggs of twospotted spider mite (*Tetranychus urticae* Koch), which is a key secondary pest (Wilson et al., 1996). It is therefore critical to accurately assess if pests require control, taking into account the capacity of the plant to recover from some degree of damage.

Accurate estimates of the abundance of some pests are difficult to obtain because, for instance, the small size and fast movement of thrips and the elusive behavior of green mirids. Accurate estimates of *Helicoverpa* spp. can be made, but often plants are found damaged with no *Helicoverpa* spp. being observed. These issues make thresholds based on pest abundance alone less reliable, undermining grower confidence and encouraging use of preventative insecticide applications. Understanding the capacity of cotton to recover or compensate for early season pest damage will enable pest thresholds to be coupled with damage thresholds. This will allow in the development of improved IPM systems for cotton by providing a more rational basis for pest control decisions.

Cotton can recover from a degree of early pest damage, often without loss of yield or delay in crop maturity, a process known as compensation. Compensation in cotton has been reported following damage by thrips (Terry, 1992; Sadras and Wilson, 1998) and by *Helicoverpa* spp. (Brook et al., 1992a) and has been reported in range of other plant species (Trumble et al., 1993). Given the difficulties of manipulating populations of pests in field experiments, manually inflicted or *simulated damage* is often used to help understand the responses of plants to herbivore damage. Simulated damage is different from real pest damage, in part because simulated damage does not involve the saliva of the pests, which may affect plant responses. Nevertheless, because it can be inflicted more uniformly, it provides valuable insights into likely plant responses to damage. Importantly, manual removal of buds and leaves triggers morphological and physiological plant responses that closely mimic major changes induced by actual pest damage (Brook et al., 1992a,b,c; Sadras, 1996a,b).

We investigated the response of cotton to the types of damage similar to that most likely to be inflicted by insect pests early in the season. This includes reduced leaf area (thrips damage); death of the apical meristem, known as *tipping out* (thrips, mirids, tip-worm, or *Helicoverpa* spp.), and damage to and loss of flower buds or *squares* (*Helicoverpa* spp. or mirids). As different pests cause different degrees of terminal damage, we also considered the effects of different severities of tip damage. While a number of studies have investigated the responses of cotton to defoliation, and loss of vegetative and reproductive buds, most reports have dealt with a single type of damage (Evenson, 1969; Bishop et al., 1977; Brook et al., 1992b; Danobrega, 1993; Longer, 1993; Sadras, 1996b). Here, we emphasized a combination of damage types (defoliation, tipping out, fruit loss), as they often coincide in the field and imposed extreme levels of damage to assess their effects on yield and timing of maturity of field-grown cotton.

L.J. Wilson and S.C. Heimoana, CSIRO Division of Plant Industry and Australian Cotton Cooperative Research Centre, and D. Gibb, NSW Agriculture and Australian Cotton Cooperative Research Centre Cotton Research Unit, Locked Bag 59, Narrabri, NSW, Australia, 2390; V.O. Sadras, CSIRO Land and Water, Private Bag No. 2, Glen Osmond, South Australia, 5064. Received 21 Dec. 2002. *Corresponding author (lewis.wilson@csiro.au).

Published in Crop Sci. 43:2125–2134 (2003).
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Abbreviations: DAS, days after sowing; DWT, dry weight; IPM, integrated pest management.

MATERIALS AND METHODS

Six experiments were done across five cotton-growing seasons (Exp. 1, 1994-1995; Exp. 2 and 3, 1996-1997; Exp. 4, 1997-1998; Exp. 5, 1999-2000; and Exp. 6, 2000-2001) to allow for different damage combinations and for differences between seasons. Experiments 1, 2, 4, 5, and 6 were conducted at the Australian Cotton Research Institute (30°13′ S, 149°47′ E), 25 km west of Narrabri in New South Wales. Experiment 3 was done on a commercial cotton property, Redmill, $\approx$120 km northeast of Narrabri, NSW.

All experiments were sown into 1-m beds in early October and grown under conditions of nonlimiting N (120–150 kg N ha^{-1} applied presowing) or water inputs (furrow irrigated at a soil water deficit of $\approx$60 mm below field capacity), in line with commercial practices. To prevent damage from pests, which could confound manually applied damage, systemic insecticides were applied at sowing with the seed [phorate (*O,O*-diethyl *S*-ethylmercaptomethyl dithiophosphate) at 600 g a.i. ha^{-1} in 1994-1995, aldicarb (2-methyl-2-methylsulfenylpropionaldehyde) at 450 g a.i. ha^{-1} for the remainder]. Experiments were also sprayed with insecticides in accordance with standard thresholds to prevent damage from pests not controlled by phorate or aldicarb and to prevent damage after the efficacy of these compounds had declined (4–6 wk after emergence). In Exp. 1, the nontransgenic cultivar Siokra V15 was used, which is an okra-leaf variety. In Exp. 2 to 6, a normal-leaf transgenic cotton cultivar, Sicala V 2*i*, was used, which contains a gene from *Bacillus thuringiensis* that produces the insecticidal protein, Cry1Ac, and provides control of *Helicoverpa* spp.

In each experiment, a randomized block design was used. Five replicates were used in Exp. 1 and four in the remainder. In Exp. 1 to 3, plots were 2 m long and 3 rows wide (3 m). The plots and blocks were laid out contiguously both end-to-end and across-the-rows. The two outer rows of each plot were buffers across the rows, and in each plot the 0.5 m on either end of the central row was a buffer. Only the middle 1 m of cotton in the central row was used for yield and maturity assessments (described below). In Exp. 4, plots were 3 rows wide but were increased in length to 6 m to allow for destructive samples to be taken (described below). As above, 1 m in the central row of each plot, with a buffer of 0.5 m at each end was preserved for yield and maturity assessments. In all experiments, damage treatments were applied to all three rows of each plot. Plant densities were in the range of 10 to 12 plants m^{-1} across all experiments.

Thrips damage was simulated by leaf area removal of true leaves and entailed cutting off the whole leaf at the top of the petiole (100% reduction) or cutting off portions of leaves to simulate different degrees of reduced leaf area. With the exception of Exp. 1, the cotyledons were not damaged, as we noticed they generally suffer little pest damage. Light terminal damage, simulating damage by thrips, mirids, or *Helicoverpa*, involved pinching out the terminal and the surrounding two unfurled leaf primordia with curved forceps. Cotton tipworm bores down through the terminal into the stem cortex, often resulting in the death of the terminal and of one or two nodes below the terminal. Such heavy tip damage was simulated by pinching off the terminal and upper two nodes, as defined by the presence of unfurled leaves. In some experiments, defoliation and tip damage were imposed repeatedly to better simulate the effect of prolonged damage to the plant by a pest population. Where terminal damage was repeated, all of the new dominant terminals were removed, which meant that for some plants, more than one terminal was removed. *Helicoverpa* spp. damage was simulated by removing all of the young squares from the first four sympodial branches. The growth stage of plants was defined each time damage was inflicted by counting the number of main-stem nodes of 20 undamaged plants in an area immediately adjacent to the experiment. Where damage resulted in significantly delayed growth, the timing of repeated damage was delayed as necessary to ensure that sufficient regrowth had occurred for the damage to be imposed accurately.

The effect of damage was assessed in terms of yield of cotton lint and the date of maturity of the crop. Maturity was defined as the date at which 60% of mature fruit (bolls) had matured and dehisced (Snipes and Baskin, 1994). We harvested all of the open bolls each week from each plot, beginning from the date that open bolls were first found in the experiment. Analysis of variance was used to test for differences in yield, lint weight per mature boll, and date of crop maturity between treatments and the undamaged control (Genstat Version 5, Lawes Agricultural Trust, IACR, Rothamsted, UK). When the analysis of variance was significant, Fisher's Protected LSD was used to compare treatment means with the control. The treatments imposed in each experiment and rationale is outlined below.

Experiment 1—Defoliation and Tip Damage

Treatments were (i) defoliation by removing 50% of the area of all leaves, including the cotyledons, (ii) light tip damage (see description under Exp. 5), and (iii) the combination of (i) and (ii). Damage was imposed when plants had $\approx$3, 5, and 8 nodes, either at each node individually (i.e., 3, 5, or 8), or progressively (i.e., 3, 3 plus 5, 3 plus 5 plus 8). There where 16 treatments in total, including an undamaged control (Table 1). On each damage date, the number of main-stem

Table 1. Treatments imposed in each experiment and plant growth measurements taken.

	Nodes tip damage inflicted (T)		Defoliation (D)		Interactions			Measurements	
Exp.	Light	Heavy	Nodes	% removed	Fruit (F)	T × D	T × D × F	Control plants	Dry matter
1	3, 5, 8	–	3, 5, 8	50	No	Yes	No	Yes	No
	3 + 5		3 + 5,	50					
	3 + 5 + 8		3 + 5 + 8	50					
2	2 + 4	–	2 + 4	50, 100	Yes	Yes	Yes	Yes	No
			2 + 4 + 6 + 8	50	No	No	No		
3	2 + 4	–	2 + 4	50, 100	Yes	Yes	Yes	No	No
			2 + 4 + 6 + 8	50	No	No	No		
4	–	–	2 + 4	50, 75, 87.5, 100	No	No	No	Yes	Yes
			2 + 4 + 6	50, 75, 87.5, 100					
5	3	3	–	–	–	–	–	Yes	No
	3 + 4 + 6	3 + 4 + 6							
	3 + 4 + 6 + 10 + 12	3 + 4 + 6 + 10 + 12							
	3 + 4 + 6 + 10 + 12 + 13 + 14								
6	3	3	–	–	–	–	–	Yes	No
	3 + 6 + 9	3 + 6 + 9							
	3 + 6 + 9 + 11 + 12	3 + 6 + 9 + 11 + 12							
	3 + 6 + 9 + 11 + 12 + 14 + 15								

nodes and total leaf area of undamaged plants, measured with a leaf area meter (LI-300, LI-COR Inc., Lincoln, NE), was recorded for four samples of five plants.

Experiments 2 and 3—Defoliation, Tip Damage and Fruit Loss

In these experiments, we investigated the effects of defoliation imposed alone and in combination with light tip damage and/or square removal (Table 1). The treatments were designed to simulate (i) moderate thrips damage: 50% defoliation of each leaf twice (when plants had two and four nodes) or four times (when plants had 2, 4, 6, and 8 nodes); (ii) moderate thrips damage as in (i), followed by square loss, to simulate damage by *Helicoverpa* spp.; (iii) heavy thrips damage: 100% defoliation twice (two and four nodes); (iv) heavy thrips damage as in (iii), with tip damage at the same times; (v) heavy thrips damage with square removal; (vi) heavy thrips damage with tip damage at the same time, followed by square removal; and (vii) square removal alone. There were 10 treatments in total, including the undamaged control (see *x*-axis of Fig. 1). For Exp. 2, we recorded additional details of plant growth status at each damage event by collecting four samples of five undamaged plants from similar cotton adjacent to the experimental area and counting the number of main-stem nodes and fruit for each plant and total leaf area of each group of plants. These data were analyzed separately for Exp. 2, but the yield and maturity data for both experiments were analyzed together for Exp. 2 and 3.

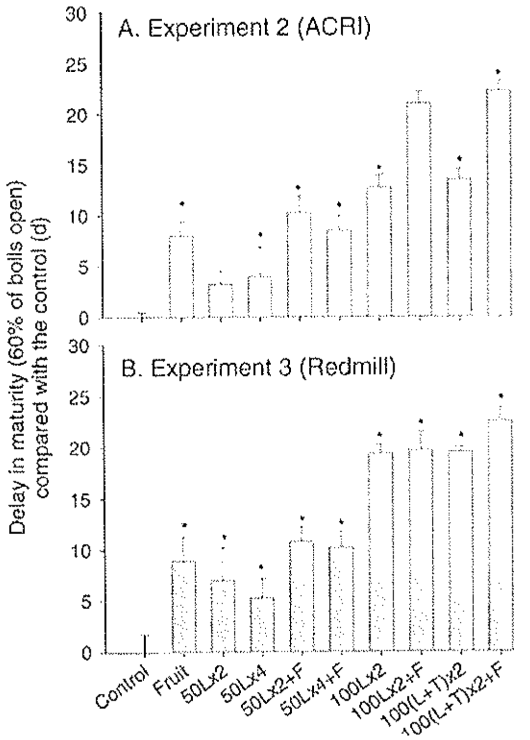

Fig. 1. Effect of defoliation, tip damage, and early fruit loss on maturity of cotton in Exp. 2 and 3. Values are means + SE. Asterisks indicate treatments significantly different from the control at $P = 0.05$. For treatments, F indicates removal of fruit from first four fruiting branches; 50L or 100L are percentages of the leaf tissue removed; number of damage events is indicated by × 2 (twice) or × 4 (four times); and tip damage is indicated by T.

Experiment 4

Experiment 4 investigated in more detail the plant responses to defoliation in terms of yield and maturity, but also in terms of growth and development (Table 1). Defoliation levels of 0, 40, 60, 80, and 100% true leaf damage were imposed. Each damage level was imposed at either Nodes 2 and 4 or at Nodes 2, 4, and 6. There were nine treatments in total.

Destructive harvests of 0.5 m of row were collected to monitor the amount of leaf area actually removed and the recovery of plants in terms of mass (shoot + tap root) and leaf area. Immediately following each damage event (28, 36, and 44 d after sowing, DAS) and at 62 and 104 DAS, 0.5 m of row was harvested from the central row of each plot. The number of plants in each 0.5 m was recorded and the plants partitioned into leaves, squares, green bolls, open bolls, and either stem and stems plus tap-root (first three harvests) or stems and root separately (final two harvests). Total leaf area was determined with a leaf area meter, the samples dried at 80°C and the dry weight (DWT) of each structure type recorded.

Experiments 5 and 6

These experiments investigated the effects of different numbers of events of heavy or light tip damage (Table 1). Light tip damage was repeated weekly three, five, or seven times beginning from Node 2; heavy damage was inflicted one, three, or five times beginning at Node 2. Repeated events of heavy damage were often delayed for up to an extra week to allow time for sufficient regrowth for further damage to be imposed accurately. There were seven treatments in total, including the undamaged control. These two experiments were replicates of the same experimental design and hence were analyzed together.

RESULTS

Experiment 1

Actual timing of damage was close to the nominal treatments of 3, 5, and 8 nodes, that is, 3.5, 5.1, and 8.0 nodes. At these stages, undamaged plants had leaf areas of 97, 222, and 662 cm^2 respectively. Neither 50% defoliation nor tip damage, or the combination of the two, affected the number of harvested bolls per meter (109.6 ± 1.7, mean ± SE; $F = 1.28$; df = 4, 60; $P = 0.24$), mean boll weight (2.2 ± 0.01 g, mean ± SE; $F = 1.75$; df = 4, 60; $P = 0.065$), lint yield (240.8 ± 3.8 g m^{-2}; $F = 0.97$; df = 4, 60; $P = 0.5$) or maturity date (DAS) (179.1 ± 0.5 d; $F = 1.59$; df = 4, 60; $P = 0.1$) of cotton, even when both defoliation and tip damage combined were repeated on three occasions.

Experiments 2 and 3

In Exp. 2, damage was imposed when undamaged plants had 2.1, 3.9, 6.4, and 6.8 nodes and leaf areas of 142, 197, 345, and 374 cm^2, respectively. Square removal was done on 19 Dec. 1996 when control plants had 12.8 nodes, a leaf area of 2536 cm^2, and six squares per plant. An average of 24.9 young squares were removed per meter of row. This value is less than expected (i.e., expect six squares per plant × 10 plants m^{-1} = 60 squares m^{-1} removed) because some of the squares on later fruiting branches and some very small squares were overlooked in the field but were counted on plants partitioned in the laboratory. The 100% defoliation treatments had delayed growth so removal of squares in these plots was delayed until 30 December in the 100% defoliation twice treatments, when 37 squares m^{-1} were removed, and until 7 January for the 100% defoliation twice plus tip damage treatment, when 42 squares m^{-1} were removed.

In Exp. 2, the effect of damage on plant height (cm) was assessed and both leaf damage and tip damage caused significant reductions. After the damage event at Node 4, plants with 50% (9.4 ± 0.4) and 100% (8.2 ± 0.2) defoliation and 100% defoliation plus tip damage (7.3 ± 0.3) were shorter than the control (10.3 ± 0.4) ($F = 12.7$; df = 4, 95; $P < 0.001$). After the final damage event at Node 8, plants with 50% defoliation twice (14.6 ± 0.4) were no different from the control (14.8 ± 0.7), while plants with 50% defoliation four times (13.3 ± 0.3), 100% defoliation twice (10.6 ± 0.4) or 100% defoliation twice plus tip damage (8.8 ± 0.3) were shorter than the control ($F = 36.9$; df = 4, 95; $P < 0.001$).

Yield, yield components, and maturity for Exp. 2 and 3 were analyzed together, with experiment as a treatment in the ANOVA. Neither boll number (92.9 ± 1.1 m^{-2}; $F = 1.64$; df = 9, 63; $P = 0.12$), boll weight (2.12 ± 0.02 g; $F = 1.65$; df = 9, 63; $P = 0.12$) nor lint yield (196.0 ± 2.9 g m^{-2}; $F = 1.49$; df = 9, 63; $P = 0.17$) were affected by early season defoliation, tipping out, or square removal, even in the treatments combining 100% leaf removal and tipping out on two occasions with early square loss.

There was a significant interaction between experiments, defoliation, and square damage ($F = 2.91$; df = 3, 50; $P = 0.044$) (Fig. 1) for crop maturity. On plants with no square damage, moderate defoliation (50% twice or four times) caused a small but significant delay of 3 to 6 d across both experiments. Heavier defoliation (100% twice) caused a significant delay, which was longer in Exp. 2 (19 d) than Exp. 1 (13 d). When square damage was combined with moderate defoliation, delays (8 to 11 d) were similar to that caused by square damage alone (8 to 9 d). This means that square damage increased the delay from moderate defoliation by ≈4 d, indicating that the effect of square damage was less than additive (i.e., extended maturity by 4 d rather than 8 d). When square damage was combined with heavy defoliation, the increase in the delay in maturity was additive for Exp. 1; that is, 13 to 21 d, an increase of 8 d. In Exp. 2, however, addition of square damage caused little additional delay; that is, 19 to 21 d, an increase of 2 d.

Experiment 4

Damage treatments were applied at 2.6, 4.9, and 6.4 nodes, which occurred at 28, 36, and 44 DAS, respectively. As expected leaf area differed between defoliation treatments (leaf removal twice: $F = 142$; df = 4, 27; $P < 0.001$; leaf removal three times: $F = 185$; df = 4, 42; $P < 0.001$) (Fig. 2).

Damage resulted in reductions in total leaf area (true leaves plus cotyledons), total shoot DWT (Fig. 2), and root DWT (Table 2). Data for leaf area and shoot DWT were analyzed on a per-plant basis, as there were strong effects of plant density in earlier sample dates (28, 36, and 44 DAS). Root, square, and boll DWTs were analyzed on a per-square-meter basis, as plant density effects were generally not significant at this stage.

Leaf area and shoot DWT differed among damage treatments and the control for dates following damage (28, 36, and 44 DAS) as expected (leaf area: $F = 21.7$ to 38.2; df = 8, 24; $P < 0.001$; DWT: $F = 3.4$ to 30.1; df = 8, 24; $P = 0.01$ to $P < 0.001$), with the exception of 50% defoliation three times, which was not different from the control at 44 DAS (Fig. 2). At 62 DAS, the 50% defoliation treatments and the 75% defoliation twice treatment were no different from the control, but the higher defoliation treatments were different (leaf area: $F = 8.7$; df = 8, 24; $P < 0.001$; DWT: $F = 10.6$; df = 8, 24; $P < 0.001$). At 104 DAS, no treatments were different to the control (leaf area: $F = 0.55$ to 38.2; df = 8, 24; $P = 0.81$; DWT: $F = 0.9$; df = 8, 24; $P = 0.53$).

The development of cotton with heavier damage treatments was slower than the control. Node production of cotton with 100% defoliation twice (36 DAS: 3.4 ± 0.6; 44 DAS: 4.2 ± 0.2 nodes) or three times (36 DAS, 3.4 ± 0.4; 44 DAS, 4.5 ± 0.3) was behind that of the control (36 DAS: 5.0 ± 0.5; 44 DAS, 6.4 ± 0.3) (36 DAS: $F = 2.37$; df = 8, 24; $P < 0.049$; 44 DAS: $F = 7.1$; df = 8, 24; $P < 0.001$). Other treatments were similar to the control on all dates.

Specific leaf weight [DWT of leaves (g)/leaf area (m^2)] of damaged and undamaged treatments was compared as it could indicate differences in leaf thickness. Specific leaf weight was not different among treatments at 28 or 36 DAS, which was immediately after the first and second damage event, or at 62 or 104 DAS ($F = 1.88$ to 2.35; df = 8, 24; $P = 0.051$ to 0.11). However, the specific leaf weight of all treatments, except 50% defoliation twice, was lower than the control at 44 DAS, indicating that leaves of damaged plants could be thinner than those of the control ($F = 3.69$; df = 8, 24; $P = 0.006$) (Table 2).

Tap-root DWT at 62 DAS was reduced, compared with the control, by most defoliation treatments ($F = 12.0$; df = 8, 23; $P = 0.001$) with the exception of the 50% defoliation twice treatments (Table 2). At 104 DAS, there was no difference in root DWT ($F = 0.9$; df = 8, 24; $P = 0.56$). Square biomass was lower in the more severe damage treatments at 62 DAS, as indicated by square DWT ($F = 6.2$; df = 8, 24; $P < 0.001$) (Table 2). At 104 DAS, most damage treatments had greater square biomass than the controls ($F = 6.4$; df = 8, 24; $P = 0.001$), especially the most severe damage treatment. Boll biomass at 104 DAS was also affected by treatments ($F = 4.3$; df = 8, 24; $P = 0.002$) with boll DWT being lower than the controls in the two 100% defoliation treatments (Table 2). Allometric analysis of reproductive allocation [slope of ln(reproductive DWT) against ln(vegetative DWT)] was lower in many of the heavier damage treatments ($F = 4.1$; df = 8, 24; $P = 0.003$) in the period between 62 and 104 DAS, indicating lower allocation of resources to reproductive tissue in these treatments during this period (Table 2).

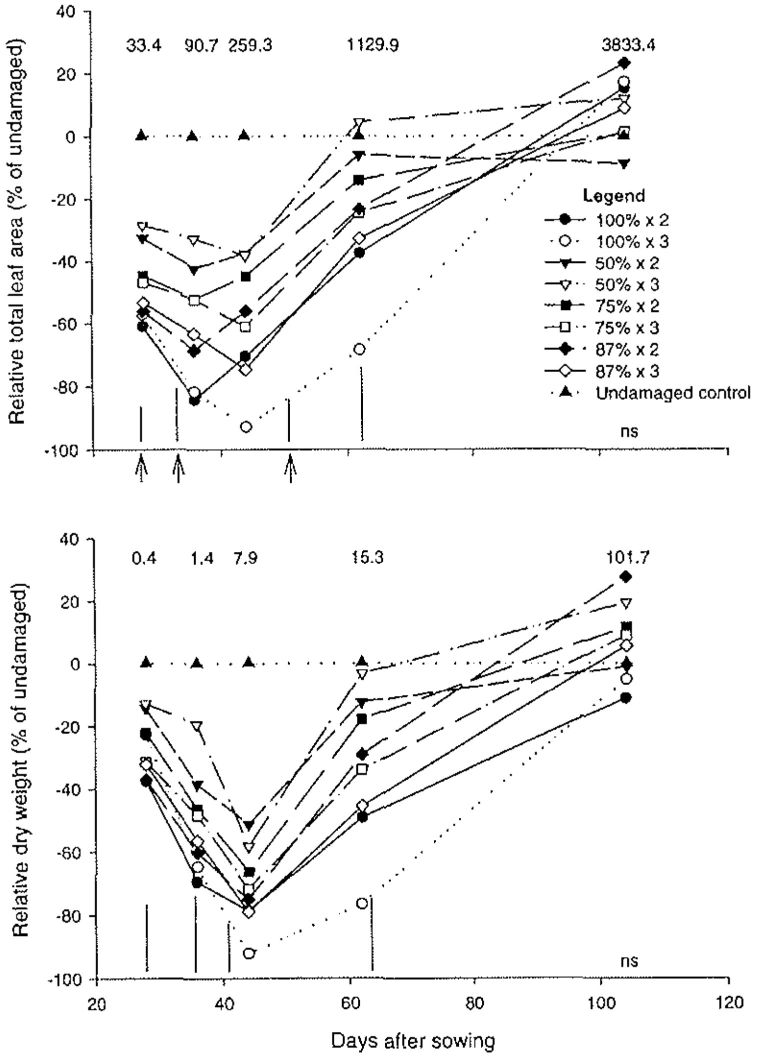

Fig. 2. Relative leaf area and shoot dry weight of cotton in Exp. 4. Bars indicate Fisher's Protected LSD values at $P = 0.05$; arrows indicate the timing of damage treatments; and numbers on each graph indicate the actual leaf area (cm^2) or shoot dry weight (g) of undamaged plants at the time samples were collected. Legend refers to amount of leaf area removed (i.e., 100%) by the number of damage events (i.e., × 2 or × 3).

Defoliation had no significant effect on final boll number (125.8 ± 3.6 m^{-2}, $F = 0.6$; df = 8, 24; $P = 0.73$), mean boll weight (2.3 ± 0.02 g, $F = 0.6$; df = 8, 24; $P = 0.87$) or yield (288.1 ± 7.8 g m^{-2}, $F = 0.4$; df = 8, 24; $P = 0.88$). Only the heavier defoliation treatments affected time of maturity ($F = 9.2$; df = 8, 24; $P < 0.001$) (Fig. 3). Defoliation of 87% twice, 100% twice, or 100% three times caused significant delays of ≈4, 5, or 10 d, respectively.

Experiments 5 and 6

Tip damage was inflicted up to seven times, when the undamaged control had 3.4, 4.3, 6.1, 10.5, 12.2, 13.8, and 14.3 nodes in Exp. 5 or at 2.7, 5.9, 9.5, 11.2, 11.3, 14.9, and 15.2 nodes in Exp. 6.

Boll number did not differ between experiments ($F = 0.33$; df = 1, 3; $P = 0.6$) or among treatments ($F = 0.53$; df = 6, 36; $P = 0.78$) averaging 91.8 ± 2.1 bolls m^{-2} (mean ± SE) at maturity. Boll weight differed between experiments (Exp. 5, 1.86 g; Exp. 6, 2.05 g)($F = 13.3$; df = 1, 3; $P = 0.035$) and among treatments ($F = 3.5$; df = 3, 36; $P = 0.008$). Light damage seven times or heavy damage three or five times reduced boll weight (Table 3). Yield did not differ between experiments ($F = 2.44$; df = 1, 3; $P = 0.21$) but differed among treatments ($F = 3.2$; df = 3, 36; $P = 0.012$). Light damage seven times or heavy damage five times reduced yield compared with the control (Table 3). Maturity date (DAS) differed between experiments (Exp. 5, 176.7 g; Exp. 6, 188.6 d; $F = 739.8$; df = 1, 3; $P < 0.001$) and among treatments ($F = 23.6$; df = 3, 36; $P < 0.001$). Lighter damage treatments, light damage three times or heavy damage once caused minor delays of 2 to 5 d. Intermediate damage, light damage five times or heavy damage three times caused longer delays of 8 to 9 d,

Table 2. Specific leaf weight, root, square, and boll dry weights (DWT) and reproductive allocation [slope of ln(reproductive DWT) against ln(vegetative DWT)], Exp. 4.

Treatment	Node damage imposed	Specific leaf weight at 44 DAS†	Tap root DWT 62 DAS	Tap root DWT 104 DAS	Square DWT 62 DAS	Square DWT 104 DAS	Boll DWT (no. m^{-2}) at 104 DAS	Reproductive allocation 62–104 DAS
		g m^{-2}						
Control	nil	166.0	21.1	116.6	2.92	11.2	369 (203.0)	3.35
Defoliation 50%	2 + 4	128.5	17.7	104.0	2.94	15.9	463 (232.0)	3.07
Defoliation 75%	2 + 4	102.5*	14.8*	95.0	1.82	19.0*	363 (200.4)	2.98
Defoliation 87%	2 + 4	89.6*	14.6*	92.0	2.41	20.7*	413 (214.0)	2.59*
Defoliation 100%	2 + 4	116.9*	10.3*	90.4	0.79*	18.1*	180* (158.4)	2.59*
Defoliation 50%	2 + 4 + 6	83.2*	15.3*	106.8	2.60	18.6*	414 (218.4)	2.90*
Defoliation 75%	2 + 4 + 6	78.3*	12.4*	104.6	1.82	16.5	390 (106.0)	2.70*
Defoliation 87%	2 + 4 + 6	78.4*	10.5*	106.2	1.21*	23.5*	259 (177.4)	2.42*
Defoliation 100%	2 + 4 + 6	110.1*	10.3*	81.2	0.03*	31.9*	158* (111.6)	2.91*
SED		21.1	1.9	16.5	0.57	3.2	74.0	0.20

* Significantly different from the control at $P = 0.05$ with ANOVA, Fisher's Protected LSD.

† DAS, days after sowing.

while the heavier damage treatments, light damage seven times or heavy damage five times caused substantial delays of 13 to 14 d (Table 3).

Relationships between Damage and Crop Maturity or Yield

Regression was used to explore the relationship between the frequency of damage, the severity of damage, and the reduction in yield or delay in maturity of cotton. Data for each treatment in each experiment were compiled into a dataset which included identifiers for the amount of leaf area removed (D_R, 0–100%), the duration of the damage, expressed as the final node at which defoliation was imposed (D_D, control = 0), the number of tip damage events (T_E, 0–7 events), and the severity of tip damage events, expressed as phyllochrons (time between exsertion of leaves) removed, assuming that in the terminal there are four phyllochrons, two visible and two embryonic, (T_S: none = 0; light = 4 phyllochrons; heavy = 6 phyllochrons).

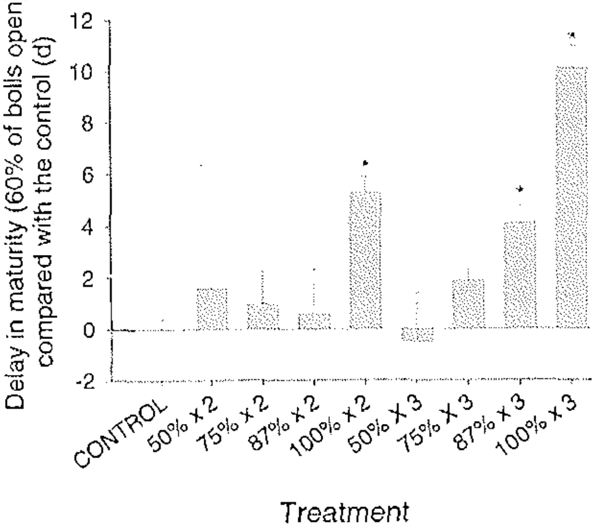

Fig. 3. Effect of defoliation on crop maturity in Exp. 4. Asterisks indicate treatments significantly different from the control at P = 0.05. Values are means ± SE. Treatment labels refer to the amount of leaf area removed (i.e., 100%) by the number of damage events (i.e., × 2 or × 3).

Our expectation was that effects on yield or maturity would be because of the interaction between the severity of the damage and its duration or repetition. Hence, we calculated interaction terms for defoliation (D_RD_D) and tip damage (T_ET_S). These were regressed against the delay in maturity (days) of each treatment compared with the control for each experiment and the crop yield, expressed as the % reduction in yield compared with the control, that is, (treatment yield × 100/control yield) − 100. The interaction terms were fitted additively and also in interaction to test for the possibility of interaction between defoliation and tip damage, that is, $D_RD_D + T_ET_S$, and $D_RD_D \times T_ET_S$. A term denoting each experiment was also fitted to test for differences in responses between experiments.

Crop maturity, expressed as days earlier (−ve) or later (+ve) than the control, was well explained by the equation

$$\text{days delay} = 0.45T_ET_S + 1.198^{e-6}D_R{}^{3.14}D_D + \text{Exp.};\quad r^2 = 0.85, \qquad [1]$$

where Exp. 1 = −2.56, Exp. 2 = 1.82, Exp. 3 = 5.36, Exp. 4 = −2.48, Exp. 5 = −0.94, and Exp. 6 = 1.46. The interaction term $D_RD_D \times T_ET_S$ was not significant ($P = 0.35$), indicating no interaction between defoliation and tip damage in this data. A simplified version excluding the experiment term was also fitted for use in estimating general responses:

$$\text{days delay} = 0.487T_ET_S + 1.3^{e-6}D_R{}^{3.14}D_D;\quad r^2 = 0.66. \qquad [2]$$

Crop yield was less well explained:

$$\%\ \text{yield reduction} = -0.637T_ET_S + -1.67^{e-7}D_R{}^{3.47}D_D + \text{Exp.};\quad r^2 = 0.46, \qquad [3]$$

where Exp. 1 = 7.26, Exp. 2 = 0.78, Exp. 3 = −4.22, Exp. 4 = 2.76, Exp. 5 = 4.78, and Exp. 6 = 3.47. The interaction term $D_RD_D \times T_ET_S$ was not significant (P = 0.13), indicating no interaction between defoliation and tip damage. Similarly, a simplified version excluding the experiment term was also fitted for use in estimating general responses:

Table 3. Number of bolls, boll weight, and yield of treatments in combined Exp. 5 and 6.

Damage type	No. of tip damage events	Boll wt.	Yield	Crop maturity	
				60% open bolls	Difference from control
		g	g m^{-2}	DAS†	d
Control	0	2.12	193.4	175.1	
Light	3	1.99	192.1	179.8*	4.7
Light	5	1.96	178.2	184.3*	9.2
Light	7	1.81*	157.6*	189.6*	14.5
Heavy	1	2.04	195.8	178.0	2.9
Heavy	3	1.93*	176.5	183.2*	8.1
Heavy	5	1.85*	161.4*	188.5*	13.4
SED		0.08	12.15	1.56	

† DAS, days after sowing.

$$\% \text{ yield reduction} = -0.41T_{E}T_{S} + -1.41^{e-7}D_{R}{}^{3.47}D_{D}; \quad r^2 = 0.31. \qquad [4]$$

DISCUSSION

Defoliation

Damage by pests such as thrips often results in reduced leaf area and size of cotton plants which is visually very striking (Sadras and Wilson, 1998). In field experiments involving actual thrips damage, the dynamics of leaf area, expressed as the ratio between crops damaged by thrips and insecticide-protected crops, showed a typical biphasic pattern, including an initial phase when reductions in leaf area reached a maximum of 20 to 50% ≈40 DAS, and a second phase when leaf area in crops damaged by thrips increased faster than in controls (Sadras and Wilson, 1998). A similar biphasic pattern that was displaced by ≈10 d was observed for shoot growth (Sadras and Wilson, 1998). Here, we were able to reproduce very similar patterns of leaf area and shoot dry matter reduction and recovery, summarized in Fig. 2. The overall similarity between the patterns of leaf area, shoot dry matter, crop yield, and maturity found in previous studies involving actual insect damage (i.e., Sadras and Wilson, 1998), and the responses generated with manual leaf removal reinforces the confidence in this technique.

We found that moderate to intense levels of damage, up to 50 to 87.5% loss of true leaf area twice, had transient effects on plant growth. Plants recovered from such damage rapidly with little effect on the onset of fruiting, or ultimately on the yield or maturity of cotton. For example, in Exp. 4, plants with 75% leaf area removed twice had recovered in leaf area and DWT by 62 DAS (34 d after damage). Earlier studies have similarly found that large reductions in leaf area in excess of 75% are required before cotton yield was affected. Lane (1959) simulated loss of 25, 50, 75, or 100% of leaf area at the seedling, squaring, flowering, or boll-filling stages. At the seedling and squaring stages, only the 100% leaf removal treatments consistently reduced yield. Kerby and Keely (1987) also found that manual removal of the first two true leaves had no significant effect on early plant growth.

Longer et al. (1993) and Kerby and Keely (1987) found that severe artificial defoliation damage could reduce the growth rate of cotton. We also found a similar *exponential* response to loss of leaf area in the seedling stages (up to eight true leaves) (Eq. [1] and [2]), i.e., defoliation had little effect on either yield or maturity until high levels, in excess of 90% removal, regardless of how often imposed. For instance, at 44 DAS, plants with 100% true leaf removal three times lagged behind the controls by 1.7 nodes and at 62 DAS their leaf area and leaf DWT were below that of the control. This delay in recovery probably explains the delays in both square and boll production. Recovery of leaf area and plant DWT was complete by 104 DAS, and yield was not affected, though maturity was, as would be expected from the delay in fruit production. These findings suggest that complete, or almost-complete loss of leaf area results in an extreme shortage of assimilate as new leaf area developed during the early stages of recovery is effectively a sink rather than a significant exporter of assimilate. This shortage of assimilate may delay growth, as indicated by delays in node production in Exp. 4, and hence ultimately result in delayed fruit development with eventual delayed crop maturity and reduced yield if the delay pushes boll maturation into unfavorable conditions.

The mechanisms of recovery from such damage are not clear; however, our results provide some support for the hypothesis of Sadras and Wilson (1998), that reduced specific leaf weight may contribute to plants recovering from defoliation. That is, defoliated plants are able to increase their leaf area, and hence light interception, by making leaves thinner. This hypothesis would need to be tested, however, with assessment of the specific leaf weight of individual leaves on damaged vs. undamaged leaves. In this study, the younger average age of leaves on damaged plants may have caused a bias toward lower specific leaf weight that we cannot exclude.

Allometric analysis further indicated that treatments with more severe damage had a reduced allocation of dry matter to reproductive structures, enhancing recovery of vegetative structures and, hence, leaf area index. This enabled plants to recover without loss of yield though with delayed maturity, suggesting that the allometric ratio of heavily damaged plants eventually achieved that of undamaged plants. The postponement of allocation to reproductive structures partially explains the delay in crop maturity of heavily damaged treatments. More frequent dry matter harvests would allow greater discrimination between more and less severe damage treatments in the rate and mechanism of recovery following defoliation.

Tip Damage

Our results show that cotton is able to compensate well for repeated tip damage events up to a point. Cotton tolerated up to seven light tip damage events without affecting yield and up to three without affecting maturity. Lower amounts of heavy tip damage could be tolerated; for example, three events did not reduce yield and one event caused only a minor delay in maturity. Others have similarly reported a high tolerance of cotton for terminal damage. Brook et al. (1992b) reported that tip damage applied at four or six true leaves or at first-square did not reduce yield and caused delays of 1 to 4 d. They found in one experiment that early (Node 4) or late (first square) damage resulted in a significant yield increase.

The main effect of tip damage is to cause production of vegetative branches (monopodia), which in turn produce fruiting branches (sympodia). Tip damage could therefore be expected to cause an initial delay in the development of fruiting branches, but thereafter a higher number of vegetative branches would potentially lead to a faster rate of production of fruiting branches and therefore fruiting sites (Lei and Gaff, 2003). The delay in reestablishment of vegetative branch growth and hence fruiting could be expected to be related to the severity and repetition of damage, as our results show. Light tip damage could be expected to delay the onset of fruiting less than heavy damage of a similar frequency. The delay in fruiting caused by tip damage would be expected to have a greater effect on maturity than yield, because provided growing conditions are adequate the plant should have time to mature a similar fruit load, and our results support this assertion. At some point, extensive tip damage could be expected to result in yield loss as well as delayed maturity, as a plant's growth is delayed sufficiently to push the fruit maturation period into less favorable growing conditions at the end of the season or because of the plant's capacity to develop a full canopy is curtailed, thereby reducing light interception and the plant's assimilate supply and hence yield potential. Intraspecific variation in cotton responses to tip damage has been identified and also needs to be considered, as the recovery of some varieties is faster following tip damage than others (Sadras and Fitt, 1997).

Interaction between Damage Types

There was no significant interaction between defoliation, tip damage, and fruit damage. The effects of each type of damage were additive (see Eq. [1] and [2]). Tip damage might be expected to promote recovery from other forms of damage by increasing branching and, hence, leaf area and fruiting sites. However, others have similarly found that tip damage interacts additively with other types of damage, such as fruit loss. For instance, Brook et al. (1992b) found that early tip damage in the variety Siokra 1-1 increased yield by 211 kg lint ha^{-1} compared with undamaged cotton, whereas heavy early fruit loss resulted in a loss of 63 kg lint ha^{-1}. The combination of these treatments resulted in a gain of 100 kg lint ha^{-1}, hence Brook et al. (1992b) found that tip and fruit damage were statistically additive. Nevertheless, in Exp. 2 and 3 there was a nonsignificant trend for plants with both defoliation and tip damage to have higher yields than plants with defoliation alone, suggesting that further investigation of the interactions between tip damage and other types of damage may be justified.

Evenness of Damage

In our studies, plants within a treatment were uniformly damaged; that is, all plants were damaged. However, pest distributions in cotton fields are rarely uniform, often showing patchy or aggregated distributions (Wilson and Room, 1983; Wilson and Morton, 1993). It is therefore likely that the distribution of damage is less uniform than in our experiments. Our studies examine the capacity of plants suffering a simulated level of damage to recover, that is, plant level responses. Sadras (1996d), however, showed that the uneven distribution of damage allows for population level compensation; that is, when "herbivore attack on one individual allows another to grow more rapidly" (Crawley, 1983). Sadras (1996d) compared crops that were uniformly tip damaged, uniformly undamaged, or unevenly damaged, where every second plant was tip damaged, and found evidence of strong plant–plant interactions. It is likely that damage from thrips is uneven and this should be considered in future research.

Implications for Pest Management

The results presented here therefore confirm the conclusion of Sadras and Wilson (1998), that early season pest damage is often largely cosmetic, with little effect on crop yield or maturity, despite its highly visual and dramatic appearance. These experiments were all done in fully irrigated, well-fertilized crops in the lower Namoi Valley, which is a *full season* region. Season length, as limited by temperature or water availability, and nutrient availability could constrain the potential ability of plants to compensate for herbivory (Oesterheld and McNaughton, 1991; Sadras, 1996c). Weather could also affect recovery; for instance, in cooler regions there may not be sufficient time for recovery before crop growth is limited by temperature. In some of the cooler regions in the more north-easterly cotton production zones of the USA, thrips damage has often been shown to stunt growth, delay maturity, and reduce yield (Hawkins et al., 1966; Johnson et al., 1988). Similarly, soil type could also be important; for instance, poorer soils with low water-holding capacity may not support as vigorous growth or recovery compared with the soils in this study. Our results therefore cannot be reliably extrapolated to dryland crops, or to cooler or shorter season regions, which require further research.

Improvements in IPM in Australian cotton need to take into account the early season compensatory capac-

Table 4. Effect of defoliation of true leaves and of tip damage on maturity of cotton, from Eq. [2]. Underscoring indicates damage combinations resulting in a delay of 5 d or less.

Defoliation		Tip damage events							
			Light tip damage (4 phyllochrons)				Heavy tip damage (6 phyllochrons)		
Duration (node of final damage)	Removed	None	1	2	3	4	1	2	3
	%	days of delay							
0	0	0.0	*1.9*	*3.8*	5.8	7.7	2.9	5.8	8.6
6	40	0.8	*2.8*	4.7	6.6	8.5	*3.7*	6.6	9.5
6	50	1.7	*3.6*	5.5	7.4	9.4	4.6	7.4	10.3
6	60	3.0	4.9	6.8	8.7	10.7	5.9	8.7	11.6
6	70	4.8	6.8	8.7	10.6	12.5	7.7	10.6	13.5
3	80	3.7	5.6	7.5	9.4	11.4	6.6	9.4	12.3
3	85	4.5	6.4	8.3	10.2	12.1	7.3	10.2	13.1
3	90	5.3	7.3	9.2	11.1	13.0	8.2	11.1	14.0
3	100	7.4	9.4	11.3	13.2	15.1	10.3	13.2	16.1

ity of cotton. This period is critically important in Australia, as it corresponds with the movements of beneficial populations into cotton from other hosts. Disruption of these populations by broad-spectrum insecticides can increase the risk of outbreaks of secondary pests such as spider mites (Wilson et al., 1998) or aphids (Wilson et al., 1999), as well as reducing the effect of beneficials on primary pests such as *Helicoverpa* spp. In terms of IPM, therefore, the results suggest that reasonably high levels of defoliation and/or tipping-out can be tolerated without the need to spray, thereby reducing costs, environmental pollution, and helping to conserve beneficial insect populations. Significantly, amongst the pests often targeted early season, the phytophagous thrips are also important predators of mite eggs (Wilson et al., 1996).

A limitation of many current pest thresholds is that they are developed assuming an average level of damage from given pest density. However, a given pest density can be associated with a range of levels of plant damage, depending on earlier pest numbers and on plant growing conditions. Thresholds that took into account both pest abundance and plant damage levels would allow for the possibility that a pest may exceed an abundance threshold but plant damage does not exceed a damage threshold: therefore, control could be avoided or delayed.

Simple sensitivity analyses were done with Eq. [2] and [4] to help derive potential thresholds for management of defoliation or tip damage (Tables 4, 5). As an indication of a link between damage and commercial practice, we assumed that delay was significant if it was longer than 5 d, which is the level that normally begins to cause concern for cotton growers. We assumed yield loss was economically important if it was >4%. This was based on a grower wanting to do more than cover the cost of control, that is, double his money, assuming that the crop is valued at \$2800 U.S. ha^{-1} (7 bales, 227 kg per bale, \$400 per bale) and control costs of \$50 ha^{-1} (\$40 insecticide + \$10 application), hence a yield loss of ≈2% is required just to recoup control costs. Both crop yield and maturity are relatively insensitive to defoliation, because of the *power* nature of their response to the proportion of leaf area removed. This can be seen for crop maturity in Fig. 3. Defoliation up to 70% continuing as late as six true leaves has no economic effect on yield or maturity. Single terminal damage events had no effect on maturity or yield but multiple events affected both. For instance, three light damage events or two heavy damage events caused a delay of >5 d or yield loss exceeding 5%. In the field, plants are often exposed to combinations of both tip damage and defoliation, and it is possible to derive estimates of delay or yield loss combining both types of damage (Tables 4, 5).

The values shown in Tables 4 and 5 can serve as tentative thresholds for plant damage that can be used in conjunction with pest abundance thresholds to allow better decisions. This is provided the growing conditions, soil types, crop nutrition, and irrigation are similar to those in these experiments. As an example, modified thresholds for thrips and *Helicoverpa* spp. in Australia

Table 5. Effect of defoliation of true leaves and of tip damage on yield of cotton, expressed as yield relative to undamaged cotton, from Eq. [4]. Underscoring indicates damage combinations resulting in yield reduction of 4% or less.

Defoliation		Tip damage events							
			Light tip damage (4 phyllochrons)				Heavy tip damage (6 phyllochrons)		
Duration (node of final damage)	*Removed*	*None*	1	2	3	4	1	2	3
		%							
0	0	100	*98*	*97*	95	93	*98*	95	93
6	40	100	*98*	96	95	93	*97*	95	92
6	50	99	*98*	96	94	93	*97*	94	92
6	60	99	*97*	95	94	92	*96*	94	91
6	70	98	*96*	95	93	91	*95*	93	91
3	80	98	*97*	95	93	92	96	93	91
3	85	98	*96*	95	93	91	95	93	91
3	90	97	96	94	93	91	95	93	90
3	100	96	95	93	91	90	94	91	89

now incorporate assessment of both pest abundance and plant damage and emphasize that both must be over threshold before pest control is justified (Deutscher and Wilson, 1999; Mensah and Wilson, 1999). The actual damage thresholds used are based on the studies reported here as well as results of *real* pest damage studies (Brook et al., 1992a; Sadras and Wilson, 1998). In the future, the information obtained in Exp. 4, where the recovery of damaged plants was monitored, may be used to link the effects of reduced leaf area from pests such as thrips with crop simulation models via their effects on plant growth.

ACKNOWLEDGMENTS

We thank Dee Hamilton, Mark Laird, Allison Wales, Sally Kennedy, Lesley Burke, Deanne Johnson, Deirdre Lally, Les Bauer, Lyn Gett, Trudy Staines, Kelly Scott, Mike Mennell, and Kym Bush for technical assistance under trying conditions. Thanks to Greg Constable, Stephen Milroy, and Tom Lei (CSIRO Plant Industry) for critical review of the manuscript. This research was funded by the Cotton Research and Development Corporation (Grants CSP46C, CSP74C).

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Annals of Botany **94**: 179–186, 2004
doi:10.1093/aob/mch125, available online at www.aob.oupjournals.org

Recovery of Leaf Area through Accelerated Shoot Ontogeny in Thrips-damaged Cotton Seedlings

TOM T. LEI* and LEWIS J. WILSON

Cotton Research Unit, CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW 2390, Australia

Received: 13 October 2003 Returned for revision: 4 December 2003 Accepted: 24 March 2004 Published electronically: 21 May 2004

• *Background and Aims* Leaf area of cotton seedlings (*Gossypium hirsutum*) can be reduced by as much as 50 % by early season thrips infestations, but it is well documented that plants can regain the difference in leaf area once infestation ceases. The processes involved in the recovery have not been identified. Hypotheses include enhancement of the photosynthetic rate of the damaged leaves, more efficient leaf construction (i.e. more leaf area per unit of dry matter invested in new leaves), and more branching.
• *Methods* This 2-year field study examined these hypotheses and found that thrips-affected plants recovered from a 30 % reduction in total leaf area. During the recovery period, repeated measurements of gas exchange, leaf morphology and individual leaf areas at all nodes were made to assess their contribution to the recovery.
• *Key Results* Recovery was not achieved through the previously proposed mechanisms. The pattern of nodal development indicated that the duration of leaf expansion of the smaller deformed leaves was shorter than that of control leaves, possibly because they had fewer cells. The production and expansion of healthy upper node leaves in thrips-affected plants could, therefore, begin sooner, about 1–2·5 nodes in advance of control plants. The proposed process of recovery was evident but weaker in the second year where thrips numbers were higher.
• *Conclusions* It is concluded that thrips-affected plants overcame the leaf area disparity through an accelerated ontogeny of main stem leaves. By completing the expansion of smaller but normally functioning lower node leaves earlier, resources were made available to the unfolding of larger upper node leaves in advance of control plants. The generality of this mode of plant resistance in pest damage remains to be determined.

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Key words: *Gossypium hirsutum*, cotton, leaf ontogeny, thrips damage, defoliation, leaf area recovery.

INTRODUCTION

Recovery from herbivory, or compensation, is an important process in plant–herbivore interactions in natural systems (Belsky *et al.*, 1993). It is also a key component of integrated pest-management systems (IPM) for crops such as cotton, permitting the reduction of insecticide use (Fitt, 1994). In many cotton-producing regions, thrips are common pests (Hawkins *et al.*, 1966; Quisenberry and Rummel, 1979; Wilson and Bauer, 1993; Atakan *et al.*, 1996), and most crops receive some protection against thrips by seed treatment, insecticide application at planting, or foliar sprays. Once established, populations of thrips normally build up rapidly early in the growing season (Watts, 1937) leading to infestations that cause visually dramatic deformation of seedling leaves (Quisenberry and Rummel, 1979). The characteristically crinkled leaves are significantly smaller than normal leaves, and lower canopy leaf areas continue until thrips numbers drop, generally within 3–4 weeks of the initial increase (Sadras and Wilson, 1998). Affected plants then resume the production of normal leaves but development is accelerated so that plant leaf area equals that of unaffected plants within weeks (Hawkins *et al.*, 1966; Sadras and Wilson, 1998). As is common in other crop species, cotton plants can often recovery fully from this type of early season defoliation without any economic consequences (Harp and Turner, 1976; Hay and Walker, 1989; Sadras and Wilson, 1998).

It is known that cotton seedlings can recover fully after losing as much as 70 % of total leaf area (Wilson *et al.*, 2003), but the mechanism by which this is achieved has not been identified. Sadras and Wilson (1998) proposed four possible mechanisms for leaf area recovery: (1) increased photosynthetic capacity; (2) increased leaf area to mass ratio; (3) improved branching (Watts, 1937); and (4) the production of additional leaves. The first three mechanisms involve physiological or morphological adjustments, whereas the last requires an acceleration of shoot development. As there has been no evaluation of these potential mechanisms of recovery, the present study was carried out to examine the processes by which cotton plants could recover from reduced leaf area. Beyond quantifying the response of cotton to thrips, the findings from this study may have broader implications in understanding the physiological basis of aspects of plant tolerance to herbivory (Belsky *et al.*, 1993).

MATERIALS AND METHODS

This study was conducted over two seasons (2001–2002 and 2002–2003) at the Australian Cotton Research Institute in

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* For correspondence. Department of Environmental Solution Technology, Faculty of Science and Technology, Ryukoku University, 1-5 Yokoba, Seta-Oe, Otsu 520-2194, Japan.
E-mail tomlei@rins.ryukoku.ac.jp

Narrabri, NSW Australia (30·4°S, 149·8°E). Cotton (*Gossypium hirsutum* L. 'Siokra V-16i', transgenic cotton containing the Monsanto Cry 1Ac gene) was sown on 17 Oct. 2001 (year 1) and on 30 Sept. 2002 (year 2) at 10–12 plants per m^2. Two treatments were imposed: a control where the systemic insecticide aldicarb (Temik, Aventis) was applied at sowing at 450 g ai ha^{-1} to protect seedlings against thrips species, and a thrips-damaged treatment where no aldicarb was used, allowing thrips to establish during early season growth. Plots (10 m × 4 rows at 1 m between rows) were laid out in a randomized block design with four replicates.

Thrips populations were monitored by weekly sampling of control and treatment plants from each plot. On each occasion, five plants were collected randomly from each treatment plot, placed in a ziplock bag and immediately brought back to the laboratory. The plants were thoroughly washed by adding water to the bags and agitating them vigorously for 1 min. The water containing dislodged thrips was poured through a fine mesh sieve. This process was repeated. The thrips retained in the sieve were then flushed on to a filter paper, which was placed in a Petri dish and stored frozen until they were counted using a stereomicroscope. Thrips populations were expressed as total numbers per plant in year 1, combining adults and larvae, but in year 2 larvae were separated from adults. The species identified were *Thrips tabaci* Lindeman and *Frankliniella schultzei* (Trybom). Wilson and Bauer (1993) also observed the predominance of *T. tabaci* in cotton at this time of the season at this location. The mean area of cotyledons and leaves at each node of the five plants was measured using a leaf area meter (LiCor, Nebraska, USA). Leaves and cotyledons were then placed in separate bags for each node and dried to constant mass at 70 °C, and the mean leaf mass to area ratio (LMA) was determined. Since leaf areas at individual nodes were recorded, it was possible to detect the change in nodal and whole plant leaf area during the phases of damage and recovery.

Gas exchange of individual leaves was measured in the field four times each year at 27, 35, 44 and 56 d after sowing (year 1) and at 31, 38, 46 and 56 d after sowing (year 2), using a portable photosynthesis system (Li-Cor 6400). The same parameter settings were used at all measurement dates: photon flux density 2000 μmol m^{-2} s^{-1} (Li-Cor light source); chamber block temperature 30 °C; vapour pressure deficit of the leaf maintained at less than 3 by adjusting the flow through the desiccant; and reference CO_2 concentration 370 μmol m^{-2} s^{-1} (using a CO_2 mixer). All measurements were made between 0830 and 1130 h Eastern Standard Time. The gas exchange of leaves at all nodes (including cotyledons) was measured for six plants of each treatment (3 plants × 2 replicates in year 1 and 2 plants × 3 replicates in year 2). If the leaf area was <6 cm^2 (the leaf chamber opening), then the leaf was labelled and its area later determined using a leaf area meter. Gas exchange parameters were then recalculated using the correct leaf area. Given the small size of the cotton seedlings (<20 cm in length) and the spacing between seedlings (10 cm along row, 1 m between rows) during the measurement period, all leaves on both control and thrips infested plants were exposed to full sunlight for most of each day.

Plots were supplied with furrow irrigation as required but no additional pesticides were applied throughout the season. At the end of the season, all bolls were harvested from four randomly selected 1 m length rows of plants in each plot. Total boll numbers and seed cotton mass per metre were recorded.

As no block effect was detected using ANOVA (PROC GLM; SAS Institute, 1988) for any of the measured parameters, differences between control and thrips treatments were compared using a *t*-test (SAS Institute, 1988).

RESULTS AND DISCUSSION

Thrips-infested plants produced main stem leaves that were deformed (commonly circular in shape) and cupped (Fig. 1).

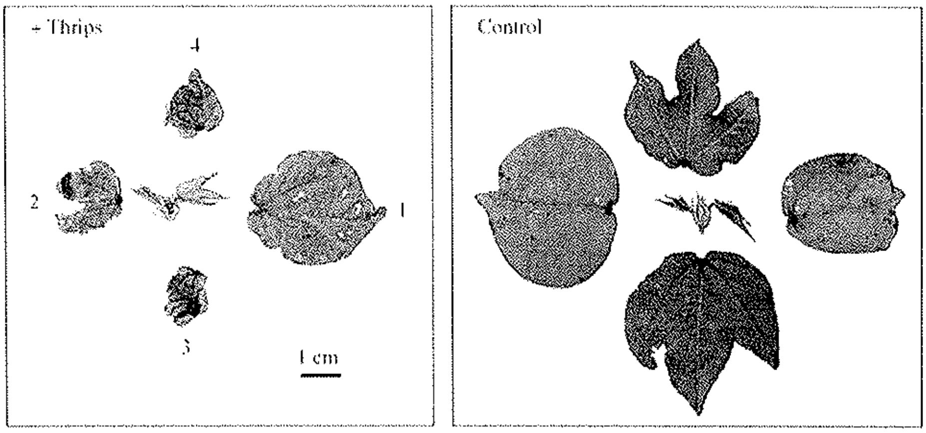


FIG. 1. An example of the difference in leaf development between control (undamaged) and thrips-damaged plants. The photograph was taken at the four-node stage (i.e. when the 4th main stem leaves began to unfold) showing main stem leaves (numbers indicate the node) and the terminal bud at centre.

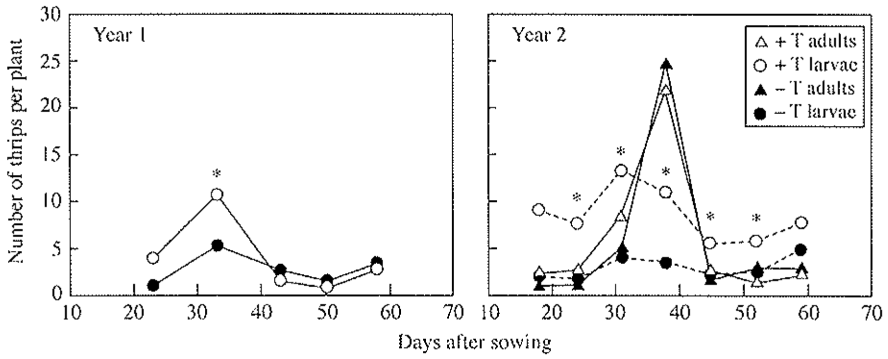


FIG. 2. Mean number of thrips per plant for control (aldicarb-protected) and thrips-infested plants in two seasons. The year 1 panel shows only the total numbers of thrips per plant (adults + larvae) in the control (solid circles) and thrips infested (open circles) plots. Year 2 panel shows thrips numbers of adults and larvae per plant separately in the control (−T) and thrips infested (+T) plots. * Differences that are significant at $P < 0.05$.

Since the infestation occurred after the expansion of the cotyledons, and the thrips were concentrated in the shoot meristem, the cotyledons remained largely unaffected, as noted by Sadras and Wilson (1998). Thrips began to infest the seedlings shortly after germination and, in both years, thrips numbers in plots unprotected by aldicarb at sowing began to exceed those of controlled plots within 3 weeks after sowing. In year 1, by 33 d after sowing (DAS), the populations were 10·6 per plant, double those of control plants ($P < 0.05$, Fig. 2). In year 2, numbers of larvae were significantly higher on unprotected plants from 22 to 52 DAS, but numbers of adults did not differ between treatments. The reason for the peak in adult numbers at 38 DAS, observed in both control and unprotected plots, is almost certainly due to repeated immigration of adults. In a similar experiment, Sadras and Wilson (1998) found that immigrating adults fed enough to be killed by the Temik in protected plants but did little damage. On the basis of observations of control and unprotected plants during this period (Fig. 2), it was concluded that the influx of adults did not play a significant role in damaging leaves. Total numbers of thrips in year 2 were about twice the numbers in year 1; they declined naturally to a similar level in all treatment plots in each year but more quickly in year 1. The duration of infestation was about 20 d in year 1 and 40 d in year 2.

The reduction in leaf area caused by thrips began at about 3 weeks after sowing (Fig. 3), in close correspondence with the increase in thrips numbers (Fig. 2). Summing all leaves (including the cotyledons), the total reduction in leaf area of thrips-affected plants reached a maximum of 30 % relative to the control between 40 and 60 DAS in each year (Fig. 3). The more rapid reduction in leaf area in year 2 is attributed to the higher populations of thrips early in the infestation (Fig. 2). Sadras and Wilson (1998) found a comparable degree of leaf area reduction associated with peak populations of 10–30 thrips (larvae + adults) per plant. The total duration of leaf area reduction observed here, about 50 d (20–70 DAS), is similar to the 40 d (generally between 20 and 60 DAS) reported by Sadras and Wilson (1998). The recovery in leaf area per plant began at 50–60 DAS, reaching 89 and 83 % of the control by 68 and 67 DAS for the two years, respectively. The subsequent decline (after 70 DAS) in leaf area in year 2 was largely associated with the greater recruitment of non-main stem leaves located on vegetative and fruiting branches in control plants (Fig. 4B). Although Sadras and Wilson (1998) found a full recovery in leaf area after 60–80 d in most investigations, some showed a dip in leaf area, similar to that found here, about 80 d after sowing.

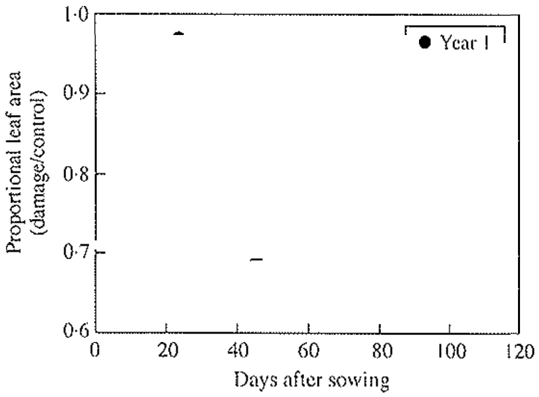


FIG. 3. Relative leaf areas per plant for thrips-infested and control plants during the damage and recovery period for the 2 years. Total leaf area was calculated by summing the mean leaf area at each node, including cotyledons.

Study of the progression of leaf area development at each node (Fig. 4) shows that a significant reduction in the area of infested plants had begun by 23–24 DAS in each year, and it continued through to node 8 (68 DAS, year 1) and node 9 (67 DAS, year 2). Leaf area recovery began by 45 and 50 DAS, with the area of leaves of upper nodes beginning to exceed that of corresponding leaves in control plants. No vegetative branch growth was detected in either treatment during the measurement period (up to 68 DAS) in year 1. Some vegetative branch growth was observed in year 2 in both control and infested plants with additional leaf area on

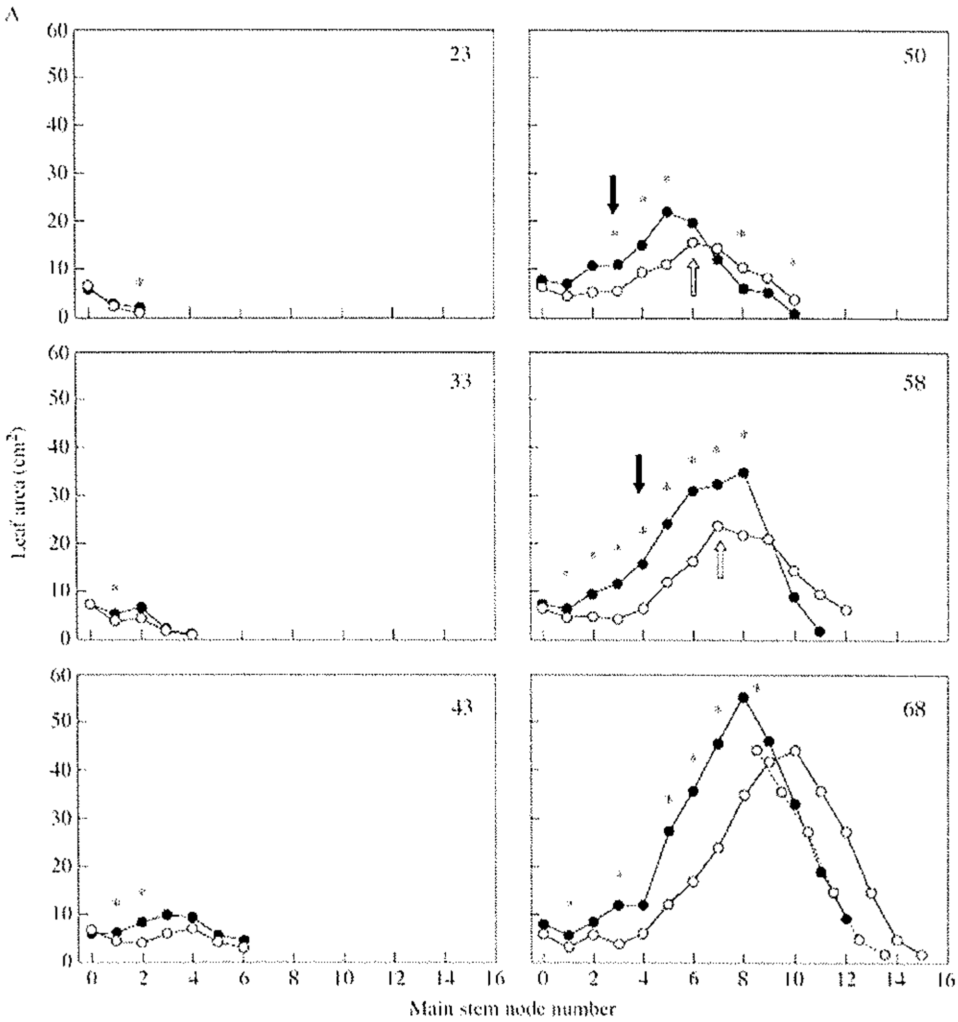
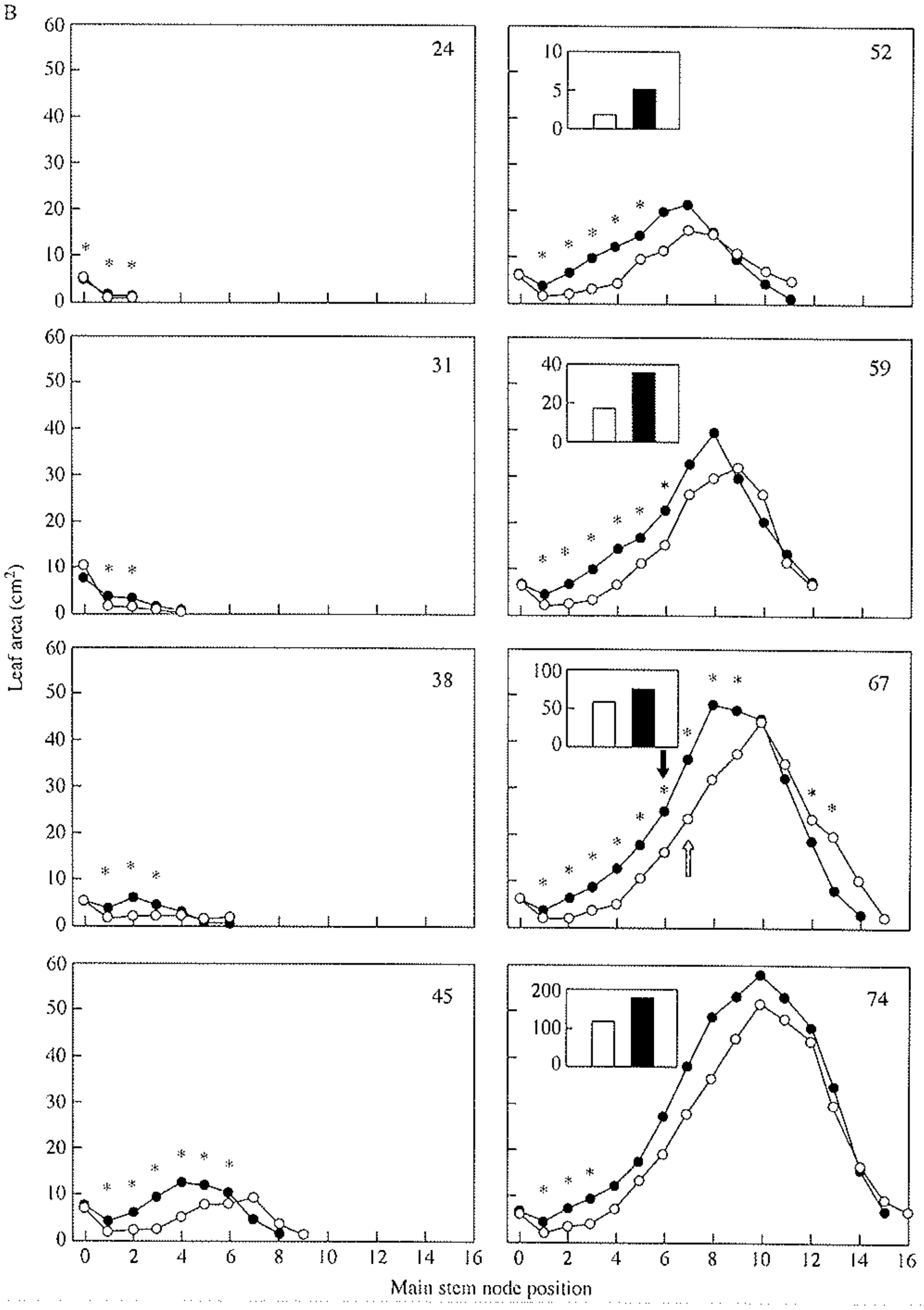


FIG. 4. Leaf area development at individual main stem nodes (cotyledon = node 0) through the thrips infestation and recovery periods for control (solid circles) and thrips-infested (open circles) plants in year 1 (A) and year 2 (B). The number in each panel represents the date of sampling (in days after sowing). Values represent mean of four plots at five plants per plot. * Differences in leaf area between control and infested plants that were significant at $P < 0·05$. Arrows indicate the uppermost fully expanded leaf in control (solid arrows) and infested (open arrows) plants. The line formed by the grey circles in Fig. 4A at 68 DAS shows the correspondence in leaf area between treatment and control when nodal leaf area of infested plants was shifted 2·5 nodes to the left. Insets in Fig. 4B represent the total area of non-main stem leaves per plant of control (solid bar) and infested (open bar) plants. There was no significant difference in non-main stem leaf area between treatments at each date.

these branches contributing, respectively, 9 and 14 % to total leaf area on 59 DAS and 24 and 29 % to total leaf area on 74 DAS (insets of Fig. 4B). At the latter date, leaves from fruiting branches were also included. The additional leaf area contributed by non-main stem leaves was not significantly different ($P > 0·05$) between treatments at all sampling dates and therefore did not play a role in the recovery process.

One of the suggested mechanisms facilitating leaf area recovery (Sadras and Wilson, 1998) is an increased photosynthetic rate of damaged leaves: higher rates of assimilation might provide the necessary resource for the acceleration in leaf area expansion. The rate of net photosynthesis (A) of individual leaves (including cotyledons), measured at four dates spanning the infestation and recovery phases, revealed no significant enhancement in thrips-affected leaves (Table 1). In fact, there were several occasions where A was higher in the control than in damaged plants in year 2. Although A varied among nodes in accordance with the stage of leaf maturity, the pattern was the same for control and unprotected plants. Given that main stem leaves were smaller in unprotected plants, the similarity in A translates to a reduction in total carbon gain per plant comparable with that of leaf area (i.e. by up to 30 % between 40 and 60 DAS). It can, therefore, be concluded that compensatory photosynthesis is unlikely to contribute



to recovery. It is, however, possible that damaged plants could have allocated their smaller pools of carbon preferentially to above-ground growth, reducing the supply to the root system. Under the conditions of the present experiments, soil moisture was maintained at non-stress levels, reduced root growth might have had no consequences for plant growth. This assumption requires further investigation.

Increased branching has also been suggested as a mechanism of recovery from thrips damage (Watts, 1937). Thrips damage to the apical meristem of cotton is known to promote vegetative branch growth (Sadras and Fitt, 1997; Jones and Wells, 1998; Lei and Gaff, 2003), but this occurs only at very high levels of infestation (L. J. Wilson, unpublished data). The type of damage found in the present study caused only deformation of the small unfolding leaves

TABLE 1. *Rate of net photosynthesis (measured at PFD = 2000 μmol m^{-2} s^{-1}) of cotyledons (leaf node = 0) and main stem leaves (μmol m^{-2} s^{-1}) measured during thrips infestation and the subsequent recovery phase*

	27 DAS		35 DAS		44 DAS		56 DAS	
Leaf node	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips
Year 1								
6							30·4	30·3
5							27·4	29·1
4					16·6	13·0	26·5	23·1
3			13·1		15·0	16·0	24·8	18·8
2	11·6	13·4	17·2	18·0	16·4	17·6	19·9	19·8
1	14·8	14·3	17·3	15·8	12·0	16·4	20·5	23·9
0	10·7	9·3	13·3	11·7	10·5	10·3	15·0	13·9
Year 2								
8							30·7	35·3
7							35·8	35·1
6					37·1	39·3	36·4	33·5
5					39·2	36·2	34·7	31·7
4			15·9	20·5	40·2*	31·8*	32·1	26·1
3			28·7	28·9	36·3	31·3	26·2	26·2
2	20·2	16·2	30·9	34·1	31·9*	25·9*	24·3	20·0
1	26·2	25·6	33·6	28·6	32·5*	24·5*	22·9*	17·0*
0	20·7	22·9	26·1	20·5	27·0*	22·9*	18·9	17·6

* Differences between control and infested plants significant at $P < 0·05$.

surrounding the meristem. A survey in year 1 found very low levels of tip damage in control (2·6 %) and thrips-affected plants (4·0 %). It can, therefore, be concluded that branching did not play a role in leaf area recovery; the degree of thrips damage resulted in leaf damage only and was insufficient to initiate lateral branch growth.

Wilson *et al.* (2003) have shown that it is possible for cotton crops to recover from up to 70 % loss of leaf area without affecting the yield of lint. This indicates that the supply of carbohydrate required to maintain normal shoot development during the recovery phase is relatively small; the 30 % reduction in leaf area found in this study may not have been sufficient to affect this requirement. Within 1–2 d after leaf unfolding, immature cotton leaves have already reached a positive carbon balance (i.e. carbon assimilation exceeds dark respiration; Constable and Rawson, 1980*a*, *b*). This means that the rate of leaf development in control plants was not carbon limited, but to achieve maximum A (at 75–90 % of final leaf area; Constable and Rawson, 1980*a*), an expanding leaf will require continued nitrogen imports for the maturation of chloroplasts. It is possible that the more rapid cessation in nutrient demand of damaged leaves on damaged plants contributed to the accelerated development of new leaves.

Decreased leaf mass to area ratio (LMA) has also been suggested as a mechanism of recovery. With a lower LMA, the damaged plant would need to invest less dry matter for a given leaf area. Table 2 shows little variation in LMA in corresponding upper node leaves between treatments; in fact, some damaged leaves (lower nodes) had significantly higher LMA than the control, particularly in year 2.

The remaining hypothesis is that leaf area recovery is achieved simply through a more rapid ontogeny. Although Sadras and Wilson (1998) suggested that the addition of new leaves can 'partially compensate' for the loss of leaf area, the present work suggests a mechanism by which this occurs. Initially, thrips feed in the apical bud region by piercing leaf primordia repeatedly before leaf unfolding. It is likely that clusters of laminal cells are destroyed in the process, leading to a reduction in cell number per leaf. The patchy destruction of cells throughout the lamina of the leaf primordia would also explain the cupped appearance of affected leaves (Fig. 1). Furthermore, deformed leaves have normal petiole development, suggesting that the turgor pressure required for normal cell expansion was not disrupted and that the remaining laminal cells are of normal size.

If thrips-affected leaves had fewer cells, then the duration of their expansion would be shorter, thus making resources available sooner for the production of upper leaves. Evidence for this is shown in Fig. 4A where by 50 DAS in year 1, all damaged leaves up to node 6 had reached full expansion (open arrow) while nodes 4–6 of control plants (solid arrow) were still expanding. By 58 DAS, thrips-affected node 7 had expanded fully compared with node 4 in control plants. A similar pattern was seen in year 2 where, on 67 DAS, node 6 and 7 were the uppermost fully expanded leaves for thrips-affected and control plants, respectively.

Since the leaf area of a plant is determined by the rate of leaf production/unfolding and the rate and duration of leaf expansion (Hay and Walker, 1989), results of this study indicate that the leaf area of infested plants recovered by both a shorter duration of the expansion of lower node leaves and a faster rate of unfolding of larger upper node leaves. The more rapid unfolding of upper node leaves is

TABLE 2. *Leaf mass to area ratio (mg cm^{-2}) of cotyledons (leaf node = 0) and main stem leaves measured during thrips infestation and during the subsequent recovery phase (VB in year 2 represents the mean value of all non-main stem leaves)*

Year 1

	27 DAS		35 DAS		44 DAS		56 DAS		68 DAS	
Leaf node	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips
14									–	12·4
13									–	8·5
12									11·3	8·6
11									9·0	8·9
10									7·9*	9·2*
9									8·7	9·6
8									9·2	8·9
7									9·1*	10·6*
6							9·4	9·5	8·7	10·2
5							9·0	9·3	9·9	11·5
4					8·2	8·0	9·2	9·5	9·9	11·5
3			7·4	–	9·7	9·0	9·8	10·3	10·3	13·1
2	6·7	6·6	8·7*	9·9*	10·1	10·3	9·2	11·4	10·5	12·9
1	8·0	7·8	9·5	9·8	10·1	10·5	9·7*	11·5*	10·7	14·7
0	8·9	8·2	10·2	10·1	10·5	10·9	10·6	11·3	20·2	16·7

Year 2

	24 DAS		31 DAS		38 DAS		45 DAS		52 DAS		59 DAS		67 DAS		74 DAS	
Leaf node	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips	Control	Thrips
VB									6·1	6·8	5·6	5·7	6·1	6·3	6·5	6·8
16															–	8·8
15															10·5	12·5
14											–	9·0	11·4	7·6	7·5	7·8
13											–	6·5	8·5	7·1	7·6	7·3
12											7·3	9·1	7·1	7·2	7·8	7·9
11											6·0	6·7	6·8	7·4	8·2	8·8
10									10·6	7·7	7·1	6·4	7·2	7·9	8·7	9·0
9									7·9	7·1	6·3	7·0	7·5	8·4	9·1	9·3
8									6·8	7·4	6·8	7·6	8·0	8·9	9·5	9·2
7							8·0	5·7	7·0	7·4	7·3	8·1	8·5	9·1	10·0	9·6
6							6·9	7·5	7·8	8·6	8·0	8·6	9·2	9·4	9·6	10·0
5					12·9	10·4	7·1*	8·2*	8·5	8·9	8·1	8·6	9·4	9·4	10·0	10·1
4					8·7	8·8	8·4*	10·1*	9·0	9·4	8·6	9·8	9·8*	10·9*	10·7	11·2
3			10·7	15·2	8·2	9·4	9·0*	10·9*	9·2*	10·6*	9·0*	10·9*	10·6	11·4	11·3	13·1
2	6·8*	11·2*	9·9*	14·5*	8·9	11·1	9·4*	12·3*	9·5*	12·5*	9·1*	12·9*	10·1*	14·9*	11·3	12·5
1	7·5*	11·8*	9·8*	13·1*	11·0	12·6	10·0*	12·3*	10·6*	13·5*	9·3*	12·8*	10·8	16·4	12·4	15·6
0	8·6	8·8	10·2	10·1	10·8*	10·3*	10·6	11·2	10·9	11·5	10·2*	11·7*	12·1	13·1	12·8	13·3

* Differences between control and infested plants significant at $P < 0·05$.

illustrated by the 2·5 node gain in infested plants over control plants (Fig. 4A, 68 DAS). The size of cotton leaves, as in other species (Hay and Walker, 1989), increases with each successive node, reaching a maximum at node 8–10 (Constable and Rawson, 1980*a*; Fig. 4). Thus, the recovery in leaf area of infested plants was mainly achieved through the earlier unfolding of larger leaves of the upper, unaffected nodes.

There was no residual effect of the early season damage on lint yield. At harvest, when all plots had reached >80 % open bolls, there was no significant difference ($P > 0·05$) between control and unprotected plants in total number of bolls and in seed cotton mass in each year (Fig. 5). Similar results were reported by Rummel and Quisenberry (1979) where a reduction in leaf area of up to 19 % had no effect on yield, but loss of 51 % of leaf area resulted in a yield loss of 9 %. In the same cropping area as this study, Sadras and Wilson (1998) reported a significant yield loss in only one of ten thrips-infested trials. The affected crop showed a relapse in leaf area recovery 60 d after sowing (i.e. at the beginning of fruit production), a pattern similar to that observed in year 2 of this study (Fig. 3). It is possible that higher infestations could delay the recovery of leaf area until after the start of fruit production. If the ontogenetic recovery in leaf area is incomplete at the initiation of fruiting branches, lower leaf area could be maintained, resulting in smaller plants with a lower assimilation capacity and reduced yields.

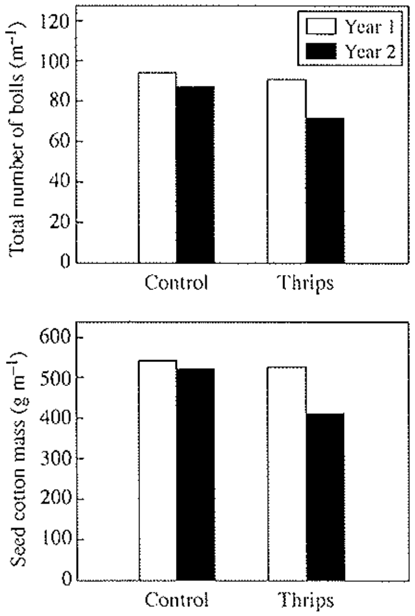


FIG. 5. Comparisons of yield components [total numbers of bolls per metre and total seed cotton mass (g) per metre] of control and thrips-affected plants for the 2 years. There were no significant differences at $P > 0{\cdot}05$ in either year.

CONCLUSIONS

Within a very short time period (<3 weeks), thrips feeding on leaf primordia led to a significant loss of leaf area at main stem nodes 1–8. Since the residency time of thrips was short, the affected cotton plants were able to recover completely. The transient loss and subsequent recovery of leaf area resulting from thrips feeding, at the densities experienced, was not achieved through physiological responses such as an improved carbon assimilation or increased allocation of biomass to leaf construction, but through changes in the pattern of development. This involved the earlier completion of expansion of lower, thrips-affected, main stem leaves which shortened the period during which these leaves competed for resources (Constable and Rawson, 1980*b*), making resources available for the earlier unfolding of upper, undamaged leaves. Since the upper node leaves are successively larger ontogenetically, their earlier unfolding accounted for the recovery in leaf area of thrips-affected plants.

ACKNOWLEDGEMENTS

The technical assistance of Kellie Baguley, Deon Cameron, Simone Heimoana and Dee Hamilton is greatly appreciated. Our thanks to the farm staff at the Australian Cotton Research Institute for their help in establishing and maintaining the experimental fields. This study was supported in part by an Australian Cotton Research and Development Coorporation (CRDC) grants CSP124C and CSP103C.

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A. R. Horowitz
I. Ishaaya
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Agricultural Research Organization
The Volcani Center
Bet Dagan 50250
Israel

ISBN 3-540-20755-4 Springer-Verlag Berlin Heidelberg New York

Library of Congress Cataloging-in-Publication Data
Insect pest management : field and protected crops / A. Rami Horowitz, Isaac Ishaaya (eds.).
p. cm.
Includes bibliographical references.
ISBN 3-540-20755-4 (alk. paper)
1. Insect pests – Integrated control. I. Horowitz, A. Rami, 1942- II. Ishaaya, I.

SB931.I43 2004
632.7 – dc22

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Printed in Germany

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Cover Design: Design & Production, Heidelberg
Typesetting: Mitterweger & Partner GmbH, Plankstadt
31/3150WI – 5 4 3 2 1 0 – Printed on acid-free paper

In the middle of the twentieth century, new insecticides were being constantly developed and it seemed that pesticides would be able to control insect pests indefinitely. In fact, from the 1950s to the 1980s, pest control was mostly based on conventional insecticides such as organochlorines, organophosphates, carbamates and pyrethroids. However, the severe adverse effects of pesticides on the environment, the resistance problems reaching crisis proportions and public protests led to stricter regulations and legislation aimed at reducing the use of pesticides. Consequently, other ways to manage insects have been suggested, such as the use of biorational pesticides with minimal adverse effects on the environment, biological control, host–plant resistance to pests, mating disruption with pheromones, and cultural and physical control. The ideas behind "integrated control" were published at the end of the 1950s by groups of entomologists from California, and served as a basis for initiating integrated pest management (IPM) in the 1970s. Since the 1980s, insecticide resistant management (IRM) programs have been introduced as a result of increasing problems of resistance to pesticides. IPM programs were strengthened as the awareness of environmental fragility intensified. Since the late 1990s, advanced approaches to manage insect pests have been developed. One of the novel and exciting innovations in the study of plant resistance to pests has been the introduction of genetically engineered or transgenic plants. This technology is still in its initial phase; perhaps, after improvement, standardization, and overcoming some obstacles, transgenic crops that are resistant to pests will be widespread and serve as important components in pest management in the twenty-first century. This volume has been written to address the demand for safer, environmentally friendly approaches to pest management, and new strategies to reduce resistance problems.

The authors of the various chapters have a wealth of experience and are considered world leaders specializing in various aspects of control programs. The book consists of chapters relating to general topics in pest management, i.e., the efficacy and selectivity of new biorational insecticides such as insect growth regulators (IGRs), avermectins, and the neonicotinoid insecticides, and the ecology of insect pests and relevance to pest management along with new insights into cultural and physical control in greenhouses and field crops. Other chapters deal with transgenic crops, their usefulness and the problems which have emerged during their implementation. Advances in pest

Implementing Integrated Pest Management in Australian Cotton

L.J. Wilson[1] · R.K. Mensah[2] · G.P. Fitt[3]

1
Introduction

The Australian cotton industry faces a number of challenges in pest management. These include damage due to a number of key pests [*Helicoverpa armigera* and *H. punctigera*, spider mites (*Tetranychus urticae*), aphids (*Aphis gossypii*) and mirids (*Creontiades dilutus*)], insecticide resistance in the primary pest (*H. armigera*) and two secondary pests (mites and aphids), escalating **costs of production** and environmental concerns over off-farm movement of insecticides. To 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. As with IPM systems in other cotton-producing countries and in other crops, the Australian cotton IPM system emphasises the use of a range of tools to manage pest populations, with insecticides seen as a last resort. What is unique about the approach taken in Australia is a higher emphasis placed on the role of beneficial insects in IPM, 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 role of IPM groups, where neighbouring growers agree on a common set of IPM goals, communicate regularly and support one another to achieve group goals. This participatory action research approach provides a framework for ensuring the cotton industry is fully engaged with the research effort (Dent 1995), claims ownership of the research, and becomes a driver of the IPM program (Ooi 2003).

Pest management in the 1960s involved regular applications of broad-spectrum organochlorine and organophosphate insecticides on an essentially prescriptive cycle. In the late 1970s, the SIRATAC computerised decision support system revolutionised this approach and provided the first step toward a more integrated approach (Hearn et al. 1985). SIRATAC emphasised regular

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[1] Australian Cotton Cooperative Research Centre, CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW 2390, Australia
[2] Australian Cotton Cooperative Research Centre, NSW Agriculture, Locked Bag 59, Narrabri, NSW 2390, Australia
[3] Australian Cotton Cooperative Research Centre, CSIRO Entomology, Locked Bag 59, Narrabri, NSW 2390, Australia

crop scouting for pests, plant monitoring for fruit production and damage, the use of pest models linked with a crop model to forecast impacts of pest infestation on yield and the use of plant compensatory capacity to 'dynamically' adjust thresholds and the preferential selection of the more selective insecticides amongst the limited range available at that time. The value of the SIRATAC approach was quickly realised and led to an almost universal adoption of crop scouting and application of thresholds, even though use of the program itself peaked at around 25% of the cotton area (Hearn and Bange 2002). This approach, incorporating basic elements of most IPM systems, persisted in industry long after SIRATAC Ltd ceased operation in 1993.

The SIRATAC approach, though undeniably leading to significant improvements in pest management practices in Australian cotton, was limited in the range of IPM strategies it supported. SIRATAC was replaced in the early 1990s by EntomoLOGIC, a PC-based decision support system that embodied the same philosophy as its parent (Hearn and Bange 2002). At the same time, new IPM components were being developed and extended to the cotton industry. These included 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 nurseries for beneficial insects (Mensah 1999), use of food sprays to attract and hold beneficials in crops (Mensah 1997) and cultivation of cotton crop residues to kill diapausing 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, essentially remained undefined, and there was no clearly and consistently elucidated system presented to industry.

Through the 1980s and into the mid-1990s, resistance levels in *H. armigera* to the pyrethroids, endosulfan (Forrester et al. 1993) and carbamates rose to levels where field control was seriously compromised. Low densities of beneficial insects, due to reliance on broad-spectrum insecticide groups, had little impact on *Helicoverpa* survival and often resulted in outbreaks of secondary pests such as mites and attendant resistance problems with these pests (Herron et al. 1998, 2001). In addition, there were problems with off-farm movement of insecticides, particularly the cyclodiene endosulfan which when detected in cattle, affected export markets and resulted in several highly publicised fish kills in rivers. These problems peaked in the 1998/99 cotton season, when heavy rains through winter promoted abundant growth of weeds and interfered with weed control strategies, leading to poor on-farm weed management. This led to an abundance of hosts for pest species and heavy pest pressure in the following cotton season. Insecticide use and costs escalated dramatically in this season highlighting the need for improved IPM systems to reduce insecticide use. These incidents were also the genesis of the industry Best Management Practice program which now encapsulates IPM as best practice for pest management (Williams and Williams 2000).

Here, we outline efforts to develop a workable IPM system for Australian cotton, detailing the components of IPM, the delivery of IPM to industry, and uptake and success achieved to date.

2
Developing the Integrated Pest Management Framework

To address the pest management challenges confronting the cotton industry the IPM system needed to:

1. Reduce insecticide use
2. Maintain crop yield and earliness of maturity (i.e. avoid delayed harvest)
3. Maintain the susceptibility of pests to new selective insecticides
4. Be practical and workable in the context of the whole farming system, and
5. Be effective both for conventional cotton and transgenic (Bt) varieties.

In addition, growers and consultants needed to accept a number of assumptions to better understand the concept of IPM principles (Mitchell 1984; Mensah and Madden 1993). These assumptions are:

1. IPM rejects the belief that the mere presence of a pest species justifies action for control, and that IPM is a containment, not an eradication strategy
2. No single control measure can be applied to all pest complexes
3. Growers should accept a certain level of damage or loss to the crop
4. IPM does not discriminate against the use of pesticides as a control measure, but aims to reduce the use of pesticides for pest control to the lowest practical levels and
5. IPM utilises a diverse array of control options where pesticides are used as the last resort

Knowledge of these IPM concepts enabled growers to understand IPM in its true sense and minimise grower panic in the course of pest infestation. This is important for growers moving from exclusive dependence on synthetic insecticides, which often offer quick control of pests, to an IPM program where there is emphasis on using a range of management or control options.

Most cotton growers in Australia aimed at earliness of crop maturity to avoid higher pest infestations during the late cotton season that are usually linked to higher synthetic insecticide use, hence higher cost of pest control.

However, it is worth noting that earliness of crop maturity is a controversial topic. Early crop maturity has often been linked with stringent early season pest control, which makes little allowance for the capacity of cotton to compensate for early season damage without loss of yield or delay in maturity (Sadras and Wilson 1998; Wilson et al. 2003). Further, recent research has shown that there is a significant trade-off between yield and maturity (Fig. 1; Milroy et al. 2002).

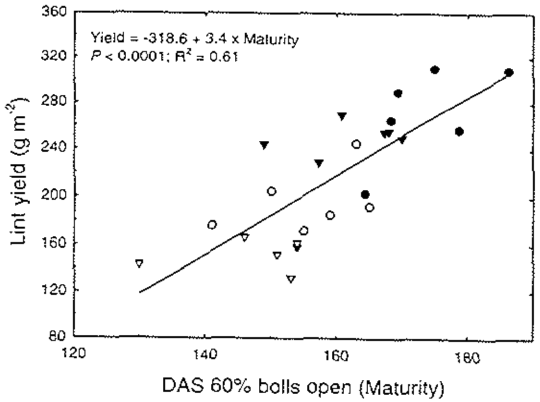

Fig. 1. Relationship between crop maturity expressed as days after sowing (*DAS*) that 60% of bolls were open and crop yield. (Milroy et al. 2002)

Our approach to address these goals promoted four key principles: firstly the conservation and utilisation of beneficial insects; secondly, the preferential use of selective insecticides; thirdly, emphasis on both profitability and sustainability, ensuring that both input costs and yield are considered, rather than the traditional emphasis on maximising yield; and finally, integration of all farm management activities, both through the cotton season and the "off" season, so that they contribute toward the goal of reduced insecticide use. This approach was captured in the *Guidelines for Integrated Pest Management in Australian Cotton* (Mensah and Wilson 1999).

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, following the difficult 1998/99 season. It quickly became apparent that the more 'entomology centric' approach of researchers put IPM as a process that occurred 'on top' of the farming system, whereas the growers and consultants saw it as a component of the farming system (Fig. 2). The extensive interaction between cotton growers, pest management consultants, and government researchers ensured the final result was practical and workable, included current research outcomes, and encouraged a farming systems approach to IPM.

From this meeting a draft document was developed and circulated widely amongst all sectors of industry, including growers, consultants, extension and research staff and members of 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 Cooperative Research Centre Website. This process provided a clear foundation on which both industry and researchers could engage in discussion and communication about issues relating to IPM, particularly to identify new research directions. It also provided a clear framework for implementing new technologies that may be components of IPM or may influence other parts of the farming system that indirectly influence pest management.

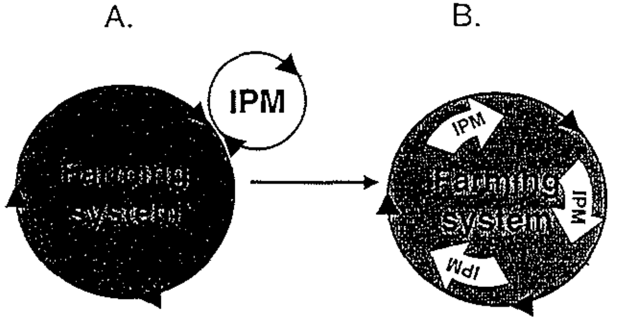

Fig. 2. IPM is often seen as an amalgamation of pest-related activities essentially independent of the farming system (A) rather than the integration of all farm and pest management activities through the cotton season so they contribute toward the goal of reduced insecticide use (B)

This IPM strategy 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; and 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. Inclusion of the winter period was essential, as many of the actions taken through this period have important implications for the success of IPM in the following growing season. In each of these phases we identified key non-insecticidal tools that can be used to manage pests or to enhance the abundance of beneficial species. Through the growing season, we have also identified the situations in which pests may need control and the options to control them, beginning with those least disruptive to beneficial insects.

A critical aspect of the non-insecticidal tools is the incorporation of a range of agronomic, varietal and physiological factors that are part of the farming system, but are not normally thought of as IPM tools. These include optimising fertilizer rates and irrigation strategies, the timing of the last irrigation, and the time to defoliate the crop. These factors can all be manipulated to contribute toward the goals of IPM. They also illustrate the farming system and agronomic context into which IPM must fit.

The Australian cotton IPM guidelines (http://www.cotton.pi.csiro.au/Assets/PDFFiles/IPMGL99/IPMGL99.pdf) follow the chronology of the crop and farming system through the year. This highlights issues relevant to that particular time period or actions needed to have a tool ready for a later period. A number of the tools are common to the three key periods during crop growth. For simplicity, the key tools and the rationale behind them are briefly explained below for the growing season as a whole, and for the whole winter period. More detail can be found in Mensah and Wilson (1999).

3
Integrated Pest Management Strategies Through the Growing Season

Key strategies throughout the growing season are discussed in the following sections.

3.1
Use of Spring Chickpea Trap Crops to Capture Eggs from *H. armigera* Moths That Emerge from Over-Wintering Diapause (Ferguson et al. 2000)

These moths are potential carriers of genes for pesticide resistance from one season to the next. Larvae resulting from eggs laid on the trap crop can be controlled using biopesticides such as nuclear polyhedrosis virus (NPV) or by destruction of the trap crop. Hence, trap crops are a means to concentrate *H. armigera* populations into a limited area of attractive trap crops where they can be destroyed, thereby reducing the carry-over of resistance genes and overall population size. In the cooler central and southern cotton growing regions, chickpea trap crops must be planted at a time to ensure that they are flowering and attractive to *H. armigera* in spring when the moths emerge from diapause (see Sect. 4.1) from early October (in most regions). In the warmer central Queensland regions, few *H. armigera* diapause. In these areas the chickpea trap crops are used as a sink for *H. armigera* populations that have developed through winter on other crops and weeds. This is complemented by use of a late summer pigeon pea trap crop, to concentrate and control *H. armigera* emerging from the soil beneath finishing cotton crops (Sequeira 1998).

3.2
Use of Spring Lucerne Trap Crops to Capture *Creontiades dilutus* (Green Mirid) Adults and Avoid Infestation in Cotton (Mensah and Khan 1997)

Green mirids are important pests in cotton, often causing plants to shed squares (flower buds) or young bolls and damaging maturing bolls, causing yield loss. Damage to growing tips may also result in significant delays in growth and maturity of the plant. Green mirids prefer lucerne (new growths or shoots) to cotton. Lucerne crops adjacent to, or as strips within, cotton crops act as a sink for green mirids. By alternatively slashing half of the lucerne at 4-weekly intervals, new regrowth of lucerne can be maintained and the green mirids can be maintained in the lucerne without moving into the cotton (Mensah and Khan 1997).

3.3
Planting the Cotton Crop at the Optimal Time, Which for Most Australian Regions Is Early–Mid-October

Early soil preparation to optimise soil structure and seedbed tilth will facilitate early planting. Planting outside this optimal time period adversely affects yield potential and is counter-productive to IPM. Very early planting (mid-September) in cool districts increases the risk of damage due to severe cold, slow early growth and greater susceptibility to diseases and herbicide and early pest damage, especially from thrips. Late planted cotton decreases yield potential and increases the risk of late infestations of *H. armigera*, mites and aphids that are difficult and expensive to control.

3.4
Regular Crop Checking for Pests, Plant Damage and Beneficial Insects (Deutscher and Wilson 1999a)

Sampling all fields, at least once every 3 days, is necessary to track pest and beneficial populations. This short interval means that decisions to delay control can be monitored and action taken if the situation changes, while the pest population is still small enough to be effectively controlled with selective insecticides. Sampling plant damage provides a measure of how the plant is responding to the environment in which it is growing as well as pest damage. Extensive research has developed damage thresholds for reduced leaf area (thrips damage) or tip damage (*Helicoverpa* spp.; Wilson et al. 2003). On seedling cotton, control is only recommended if greater than 80% reduction in leaf area occurs. Tip damage is scored as the number of events per plant and control is recommended only if more than 100% of plants have been damaged once. Once fruit production (squaring) begins, the retention of first position fruit is scored. These are the fruit produced at the first fruiting site on each of the fruiting branches that are produced at nodes from the main stem from about the sixth to eighth node onwards. A target of 50–60% of first position fruit retention at first flower is suggested. Yields can be reduced at retention values significantly above or below these levels (Gibb 1999). Unless clearly attributable to other factors such as water stress, low retention (<30%) will trigger action to protect plants from further pest damage until retention returns to desirable levels. Further into the fruiting cycle a fruiting factor (number of fruit per fruiting branch) is used to assess if the plant has retained sufficient fruit in all positions to ensure a profitable yield (Gibb 1999). Values outside the fruiting factor range of 1.1–1.3 may trigger extra protection against pest damage if too low, or careful attention to irrigation and nutrition if too high. Current thresholds include both pest and damage thresholds (see below).

3.5
Integration of Predators into Decisions Using a Predator/Pest Ratio

This is based on extensive field research and ensures that the value of predators is used pro-actively when deciding if a pest population requires control (Mensah 2002a). Frequent sampling ensures rapid feedback on the impact of the beneficial population on pests. If predator/pest ratios are lower than 0.5 (1 predator to 2 pests, mainly *Helicoverpa* spp.), a series of augmentations is progressively recommended, beginning with the use of food sprays (see below) and strip cutting of lucerne plots grown as nurseries for beneficial species, then biological insecticides (Bt and NPV) and finally use of more selective synthetic insecticides (Mensah 2002b).

3.6
Use of Beneficial Nurseries and Attractant Food Sprays to Enhance Predator Numbers

In the semi-arid environments in which the bulk of the Australian cotton crop is grown, there are essentially no perennial crops or horticulture. Beneficial insects must originate from areas of native vegetation or pasture or from within the cotton farm itself. In dry years the growth of native vegetation and pasture is often dramatically reduced, a problem exacerbated by grazing stock. Provision of perennial lucerne crops as on-farm nurseries for beneficial insects, particularly predators, provides some buffer against the unpredictability of natural populations. Positioning nursery crops adjacent to, or as strips within, cotton crops increases the likelihood of beneficials foraging and establishing in cotton crops (Mensah 2002b). When it becomes necessary to increase predator numbers within cotton crops to re-establish a more suitable predator/pest ratio (i.e. a ratio greater than 0.5), for instance following insecticide use, attractant food sprays may be applied to the cotton to manipulate predator populations.

3.7
Use of Combined Pest and Damage Thresholds

Thresholds are used to ensure that insecticides are only applied if economic loss is reasonably expected to occur. However, thresholds based on pest numbers alone assume that all cotton crops will respond in a similar way to a given pest density. Other factors such as crop vigour, disease, temperature and nutrition, may mediate the response of the plant. Wilson et al. (2003) established guidelines for the amount of damage that plants can tolerate without loss of yield or delay. Incorporation of this information into thresholds (Deutscher and Wilson 1999b) identifies situations where a pest is over the threshold, but crop growth indicates it will recover without loss, thereby avoiding use of an insecticide to prevent non-economic damage.

3.8
Strategic Use of Plant Growth Regulators

Optimal irrigation scheduling and rates of nitrogen fertilizer will generally control vegetative growth. However, in some seasons excessive vegetative growth may result in rank crops that remain attractive to pests and mature late, thereby increasing the need to control pests and undermining the IPM system. Appropriate use of growth regulators can help to reduce the severity of this problem. As the response of varieties to growth regulators varies, their use should comply with guidelines published by local seed companies (e.g. Cotton Seed Distributors, Deltapine Australia).

3.9
Optimal Water Management to Avoid Extended Late Season Growth

Irrigation decisions should be based on crop need and the recognised soil water deficit for that particular soil. Objective assessment of water use and deficit through the use of neutron probes or similar equipment is necessary. A critical decision is the timing of the final irrigation. Water applied to a crop that does not require it may produce no additional yield, but could impose considerable cost due to extra late season growth. This will extend the period of attractiveness to pests, and potentially require control measures for a longer period. This undermines the IPM system and could exacerbate insecticide resistance problems.

3.10
Preferential Use of Selective Insecticides

Over the past 6 years new insecticides have become available that are more selective than the older organophosphate, carbamate and pyrethroid chemistries that have been the mainstay of pest control in Australian cotton. The new compounds include spinosad, emamectin, indoxacarb, pymetrozine, diafethiuron and methoxyfenozide. These products are powerful IPM tools as they provide pest control, with less risk to beneficial populations and greater likelihood of maintaining an effective IPM system. These products are used as a last resort, when everything else fails to control the pests and economic loss is likely. The use of the new insecticides in these situations provides flexibility and a safety net for growers to maintain crop yield and continue to adopt IPM. Independent information on the efficacy and non-target effects of all current insecticides has been obtained locally (Wilson et al. 2002). Understanding the particular characteristics of insecticides is important. For example, spinosad (Tracer) has a low impact on predatory Coleoptera and Hemiptera, but is very disruptive of micro-Hymenoptera (including Trichogramma), ants and thrips, which eat mite eggs (Wilson et al. 1996).

3.11
'Site-Specific' Pest Management

Historically cotton growers often treated the farm as a unit and sprayed the whole farm if a pest was over threshold in several fields. This reduced application costs and provided some streamlining of farm operations, but also meant that when broad-spectrum insecticide was used beneficial populations were reduced over the bulk of the farm. By treating only those fields that are over threshold with selective insecticides, unsprayed fields serve as a refuge for beneficials to recolonise sprayed fields. 'Site-specific management' is in a broad sense a type of precision agriculture. Recent research on the issue with Colorado potato beetle showed that site-specific management significantly also decreased resistance selection and increased beneficial numbers (Midgarden et al. 1997).

3.12
Use of Genetically Engineered Ingard Cottons Expressing the Delta-Endotoxin Genes from *Bacillus thuringiensis* subsp. *kurstaki* (Bt)

Fitt and Wilson (2000) demonstrate that insect resistant transgenic plants, such as Ingard cottons, are a good platform for IPM. They reduce the need to control *Helicoverpa* spp., the primary early-season cotton pest in Australia, thereby reducing disruption to beneficial insects caused by insecticide use, and conserving and maximising beneficial insect activity. Genetically engineered cotton is an important tool for IPM because it helps growers to realise the benefits of IPM more easily. Some pest risks, however, may increase such as aphids and mirids, and this is addressed below.

3.13
An Effective Resistance Management Strategy

Resistance to the range of insecticide groups (synthetic pyrethroids, cyclodienes, carbamates) has haunted the Australian cotton industry since the late 1960s (Forrester et al. 1993). Our IPM system encourages preferential use of selective insecticides. However, this places selective insecticides at risk in terms of resistance. Furthermore, the nature of insecticide discovery, development and registration has meant that new selective insecticides have become available sequentially. As a result, several of the newer insecticide groups have each had a period of popularity and have unfortunately been over-used to the point that resistance has already been detected. Rising resistance to spinosad (Tracer) is an unfortunate example (Gunning 2002). Australia's Insecticide Resistance Management Strategy (IRMS) has been developed by the industry sanctioned Transgenic and Insecticide Management Strategies (TIMS) committee. It is based around rotation of chemical groups, use of 'windows' (of use and non-use) and limitations on the number of applications (Gunning et al. 2002). Increasingly, the positioning of new insecticides within the IRMS is being influenced by the desire of growers for effective selective insecticides to control key pests at all times of the season. Similarly, a proactive strategy has been developed by the TIMS committee to minimise the risk of resistance to the Cry1Ac protein in Ingard cotton and to also embrace IPM principles. The strategy hinges around growing refuge crops to produce Bt naïve *H. armigera* moths to mate with any resistant individuals emerging from Ingard crops, thereby massively diluting any resistance. This is coupled with a planting window, defined size of refuge crops, mandatory destruction of crop residues to remove diapausing *Helicoverpa* pupae under the Ingard crops, and defined spray thresholds on Ingard crops to control survivors (Fitt and Wilson 2000). Compliance with this strategy by growers of Bt-cotton is a legal requirement and is audited; hence some IPM components (planting window, pupae destruction) are compulsory.

4
Integrated Pest Management Strategies Through the Winter

Key strategies in the winter or "off" season are discussed in the following sections.

4.1
Destruction of Diapausing Pupae of *H. armigera* that Are a Potential Reservoir of Resistance Genes (Fitt and Daly 1990)

This is a core non-insecticidal component of both the IRM and IPM strategies. Growers are advised to sample cotton stubble for pupae, using published guidelines, to determine which fields require control and to prioritise those that do. The degree of cultivation required to disturb the emergence tunnels of diapausing pupae and to expose them to predation from spiders and birds has been established. The effectiveness of a range of implements, including those used to sow winter crops, has been assessed. This information is available in extension packages such as MACHINEpak. Growers are advised to avoid cultivating under conditions that create other problems such as compaction, i.e. wet soil. For dryland growers seeking to conserve soil moisture pupae cultivation is a problem. This is being addressed by use of modelling to predict likely pupae densities and the need to cultivate, development of sowing equipment for winter crops that provides adequate disturbance and late-season and/or post-picking inter-row cultivation. In the warmer central Queensland region, few *H. armigera* diapause, so cultivation of pupae is ineffective (Sequeira 1998). Instead a strategy using a late summer and early spring trap crop sequence has been developed (see Sect. 3.1).

4.2
Selection of Rotation Crops to Reduce Pest Carry-Over

Rotation crops may be planted for several reasons including favourable prices, improving soil structure and soil nitrogen enrichment (legumes). The selection of a rotation crop also has implications for pest management. Some rotation crops provide an over-winter host for pests. Examples include faba beans (mites, aphids), safflower (mites, mirids), chickpeas (*H. armigera*) or cereals (*H. armigera* and thrips). Some may also affect carryover of cotton diseases, such as some legume crops. The choice of rotation crop should take these issues into account. Options for the management of pests in rotation crops should also be considered. For instance, use of broad-spectrum insecticides, such as pyrethroids or organophosphates to manage *Helicoverpa* or aphids in rotation crops may have a serious detrimental effect on beneficial insect populations and could diminish the number of predators later moving into cotton crops. Similarly, control of mirids in safflower crops often results in outbreaks of mites, which move into adjacent cotton crops. Retention of stubble from rotation cereal crops is being used to help control erosion from cotton fields and has also shown some benefits in terms of reduced *Helicoverpa* abundance on seedling cotton sown into the stnbble (Waters and Kelly 2001).

4.3
Management of Weeds and Cotton Regrowth that Are Over-Winter Pest Hosts

Weeds and cotton regrowth following harvest can provide over-winter hosts for a number of pests including *Helicoverpa*, mites (Wilson 1994a), mirids, aphids, tipworm, cutworm, armyworm and whitefly. Poor in-field hygiene is particularly a problem with spider mites, aphids and mirids as these pests can move off the weeds and onto cotton seedlings in the following season.

4.4
Optimisation of Fertilizer Strategies to Avoid Excessive Plant Growth

The amount of nitrogen available to the crop affects pest management as well as potential yield and maturity. Too little nitrogen will decrease yield. Excessive nitrogen often creates excessive end-of-season plant growth. This makes the crop more attractive to *Helicoverpa*, requiring additional inputs of expensive insecticides for control, can delay crop maturity by 1–2 weeks and can make crops harder to defoliate (Rochester et al. 2001). Growers are advised to manage nitrogen on a field-by-field basis based on soil tests (Constable and Rochester 1988). NutriLOGIC and NUTRIpak are decision support systems (DSS) available to help growers select appropriate fertilizer rates (Deutscher and Bange 2003).

4.5
Matching of Cotton Variety to Region and Pest Complex

The variety should be matched to the region and likely pests and diseases. Seed companies provide guides to suitable varieties. 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. These problems are exacerbated if wet weather delays ground preparation and sowing. Varieties also differ in susceptibility to pests. Okra leaf varieties have a degree of resistance to both *Helicoverpa* spp. and spider mites (Wilson 1994b), potentially reducing sprays for each pest by about one per season (Thomson 1994). Penetration of insecticides into the crop canopy is also better with okra leaf cultivars, and can contribute to better control with insecticides (Jones et al. 1986).

4.6
Development of a Spray Drift Management Plan

Growers should discuss their IPM strategy and the significance of drift management with the insecticide applicator as well as neighbours. With the applicator, an important issue is the hygiene of spray equipment, including ground rigs and aeroplanes. Residues of broad-spectrum insecticides in the tanks or sumps of spray equipment could contaminate selective products causing undesirable and unintended detrimental effects on beneficial insects. The grower should discuss with neighbour(s) the risk of drift of insecticides and how this may impinge on each farm. The possibility of joining them as part of an IPM group could also be discussed (see below). The management of drift also has implications for reducing off-farm effects such as contamination of rivers and impacts on native vegetation that may be reservoirs for beneficial insects.

4.7
Seed Bed Preparation

A feature often mentioned by leading cotton growers in achieving an early crop is a good seed-bed, typified by friable, non-cloddy soil and firm, high, well shaped beds. This helps to achieve vigorous healthy growth resulting in plants that are more able to tolerate seedling diseases and achieve high yields and early crop maturity.

4.8
Selection of Appropriate Seed Insecticide Treatments

By definition, the use of 'at planting' insecticides, applied in the soil (such as aldicarb or phorate) or applied directly to the seed as a seed treatment (such as imidocloprid, thiodicarb and fipronil), is 'prophylactic'. Though the main target of these insecti~~cides is thrips, which are predators~~ of mite eggs, they are reasonably selective against many other beneficial groups (Wilson et al. 2002). Their selectivity is based on the fact that they do not contaminate the foliage, but are absorbed by the plants. Since most beneficial insects do not directly feed on cotton, but feed on the pests, beneficial insects are unaffected by the seed insecticide treatments or in furrow application of these insecticides. Therefore, in situations where there is a reasonable expectation of an economic benefit from control of thrips, the use of 'at planting' insecticides may be a better choice than the conventional approach of treating at pest threshold.

5

Extension and Implementation

Defining and formalising our IPM system by publishing the IPM guidelines has been critical in allowing a consistent and coherent model of IPM to be delivered throughout the cotton industry. The guidelines also serve as a critical resource for a focused extension effort by the National Cotton Extension Team. This team has progressively expanded over the last 10 years with 'Industry Development Officers' (IDOs) 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. Support from the latter institution, in particular, has been critical to success in delivery of IPM by bringing together researchers and extension personal from different federal, state and University departments to work together in development and implementation of IPM. 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). These included field days to discuss IPM issues relevant at the time or about to become important as well as demonstration experiments for growers. For example, co-ordinated experiments to investigate cotton recovery from early season damage were conducted across several regions. These experiments were critical in giving growers confidence, when faced with early pest damage, to delay spraying and allow establishment and development of beneficial insect populations. Extension staff in each region also produced a local extension update, known as 'Cotton Tales', on a regular (weekly or fortnightly) basis. These are faxed or emailed to all growers and consultants in the region and usually draw on components of the IPM guidelines that are relevant at the time, as well as providing research updates.

Further support is provided in the form of ENTOpak, a compendium of pest management information that includes the IPM guidelines, a pest and beneficial identification guide, and supporting documents providing detailed information on pest thresholds, sampling, pupae control, selectivity of insecticides, crop damage monitoring and planning of last irrigation. The supporting documents are cross-~~referenced 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 resources are continually updated and effectively disseminated to the industry through the Australian Cotton Cooperative Research Centre's Technology Resource Centre and website (www.cotton.crc.org.au).

As part of a drive to enhance environmental management of cotton farms, the industry has implemented a Best Management Practice (BMP) approach (Williams and Williams 2000). This provides a framework for growers to evaluate their management performance against the best standards in the industry, for identifying areas of improvement, and documenting this in an auditable fashion. The core principles of the IPM guidelines form one 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. Because these groups are initiated by growers and consultants, the groups have provided the peer support and communication necessary to build confidence in IPM. IDOs have played a crucial role in supporting these groups by organising meetings, coordinating visits by researchers and assembling information. IPM groups have allowed growers and consultants to address pest problems more effectively than if each grower worked alone. Examples of IPM group aims include delaying the use of disruptive chemistry to conserve beneficial populations, the co-ordinated planting of trap crops and sharing of information through regular meetings. The concept of area wide management (AWM) has also been trailed in some regions. In the mixed cropping regions of the Darling Downs region of southern Queensland, an area-wide strategy was established to manage *H. armigera* populations (Ferguson and Miles 2002). This species is a pest of many crops, however, poor communication between growers of different crops meant that there was no coordinated effort to manage it across crop types. The AWM approach provided a framework in which efforts were co-ordinated to manage the pest across the region by using understanding of the pests ecology to reduce abundance, for instance by concentrating spring generations onto trap crops where they could be controlled by crop destruction (Ferguson et al. 2000).

The pioneering work of these IPM and AWM groups is a good example of the participatory research approach outlined by Dent (1995). The IPM groups also allow growers to learn from each other. The old ideology of one "learning from his or her mistakes" is slowly being eroded in cotton pest management as a result of the IPM groups. The grower participatory IPM has increased from the development of the IPM guidelines to the formation of the IPM groups. Each IPM group has experimented with the IPM guidelines and adopted it in their own way so that the growers have become owners of the technology and as such it is grower driven. Thus, the basis for the success of the IPM program in Australia is that it is grower driven and growers feel they own the technology.

Since the inception of the SIRATAC system, computer- based decision support systems (DSS) have been a feature of the Australian cotton industry. The CottonLOGIC suite of DSS incorporates Entomologic, which supports the key elements of IPM and provides a benchmark against which decisions can be compared (Deutscher and Bange 2003). The CottonLOGIC DSS (now also available in hand-held form as CottonLOGIC on the Palm OS) provides a disciplined and objective sampling process, together with access to a *Helicoverpa* development model which forecasts population changes 3 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 collection of predator numbers and estimation of the predator/pest ratio. Data can be entered in the office at a PC or collected in the field using the 'CottonLOGIC for the Palm' software, based on the Palm OS (Deutscher and Bange 2003). Users of CottonLOGIC can later incorporate insect and crop performance data to analyse 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 (Deutscher and Bange 2003).

Another critical factor in gaining support for IPM systems has come from favourable economic analyses of IPM versus traditional approaches. Records of pest abundance, insecticides used, and crop yield for one of the most advanced IPM groups (the Boggabilla group) was analysed by Hoque et al. (2000). The analysis was based on information available in Wilson et al. (2002) to rank each insecticide in terms of its impact on beneficial insect 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 insect 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. Data were separated into fields with a high BDI score, designated "hard" fields, and those with a lower BDI score, designated "soft" fields. Economic analysis showed that the soft, IPM approach generally had equal or higher gross margins than the harder approach (Fig. 3). The difference was attributed to higher beneficial insect populations in the fields managed with more selective insecticides. This analysis was critical in providing 'economic' credibility for the IPM approach. Such studies have now been extended to other regions with similar findings.

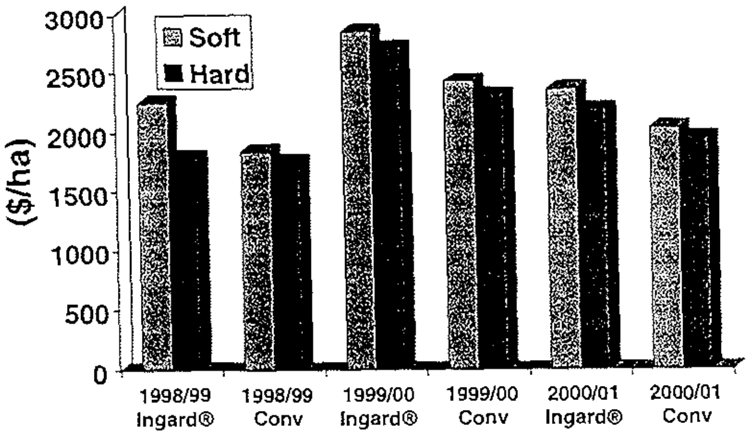

Fig. 3. Gross margins of cotton field grown using more selective insecticide (*soft*) versus those using more broad-spectrum insecticides (*hard*) for conventional cotton (*Conv*) and *Ingard* cotton containing the Cry1Ac protein. (Hoque et al. 2000)

The problem associated with the "soft" option approach is growers believing that the use of the selective new synthetic insecticides is IPM. As a result, there is a general overuse of the new insecticides that are classified as "soft" resulting in the risk of increased resistance to these products. However, there has been increased focus on grower education to improve their knowledge in beneficial insect conservation and utilisation using IPM compatible tools such as food sprays, nursery crops, biopesticides and plant compensation. The education of the growers is conducted through IPM short courses similar to Farmer Field schools (FFS) introduced by FAO and CABI to small-scale resource poor farmers in developing countries (Ooi 2003). Separate courses are organised for farmers and growers. The consultant courses are similar to the 'train the trainers' courses for the plant protection technicians in the developing countries. These courses are co-ordinated by the extension team with inputs from the research officers within the cotton industry.

6
Has This Approach Been Effective?

Adoption of an IPM approach, incorporating many of the elements above, has had a dramatic uptake over the past 4 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 findings suggest

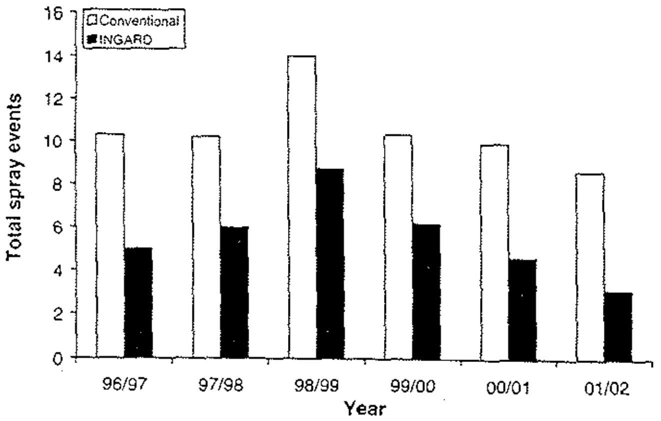

Fig. 4. Average number of insecticide application to *conventional* and *INGARD* cotton crops in Australia, 1996–2002. (Graph prepared using data collected by Cotton Consultants Australia as part of the annual Cotton Research and Development Corporations report on performance of Ingard cotton in Australia)

that grower attitudes and practices have been significantly altered over the past 5 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 current use now at 51% of the crop area and increasing demand for IPM-related software tools (Deutscher and Bange 2003).

Data on insecticide use are also encouraging. Since the publication of the IPM guidelines in 1999 and the initiation of the extension effort to promote IPM, there has been a downward trend in the number of insecticide spray applications, especially in Ingard cotton (Fig. 4), and an increasing trend 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 (Fig. 5) due in part to reduced insecticide use in total, reduced use of older products which required higher levels of a.i. for efficacy (endosulfan, organophosphates and carbamates), and possibly lighter pest pressure. Care must be taken in interpretation of these results since insecticide use is linked to pest abundance, and the cotton seasons since 1998/1999 have been regarded as having lighter than average pest abundance. However, consultants are noting that in fields managed with selective insecticides, *Helicoverpa* egg densities and survival of eggs and larvae remain low through the season, whereas fields where more disruptive insecticides are used tend to have higher egg numbers and higher survival of eggs and larvae.

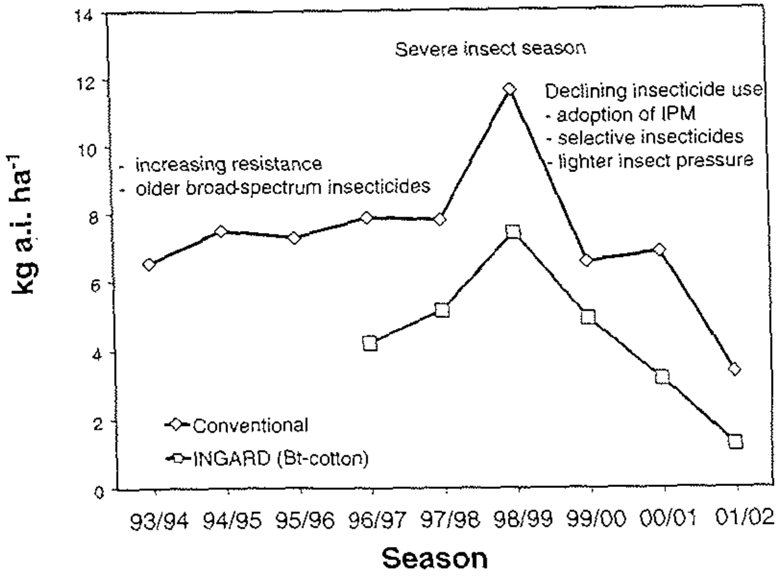

Fig. 5. Average amount of active ingredient (a.i.) of insecticide per hectare for conventional and Ingard cotton crops in Australia, 1993–2002. Reductions are due to reduced insecticide use due to adoption of IPM, a change in insecticide use away from broad spectrum insecticides toward more selective insecticides (including biological that do not contribute to a.i.) and to some extent lower insect pressure. (Graph prepared using data collected by Cotton Consultants Australia as part of the annual Cotton Research and Development Corporations report on performance of Ingard cotton in Australia)

7
Conclusions

The increased commitment to IPM in Australian cotton bodes well for the future sustainability of production. However, as the system changes the pest complex also changes, and sucking pests, formerly suppressed by *Helicoverpa* sprays, are emerging as new challenges that need to be incorporated into 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. Ongoing improvement of transgenic Bt cottons with the commercial release of Bollgard II varieties with two Bt genes should continue to support adoption of IPM approaches. In taking a farming systems and participatory approach, our IPM framework will maintain effective engagement between research, extension services and industry to ensure the continued evolution and implementation of our IPM.

Acknowledgements. We thank Bruce Pyke (Cotton Research and Development Corporation) for access to insecticide use data, Ingrid Christiansen (Australian Cotton Cooperative Research Centre and QDPI) for access to IPM surveys and valuable suggestions, Mike Bange (CSIRO) for valuable comments on the manuscript, David Larsen (NSW Agriculture), Martin Dillon and Steve Milroy (CSIRO) for access to graphs and images, the many colleagues, extension staff, consultants and growers who contributed to the concepts expressed here and the Cotton Research and Development Corporation and Australian Cotton Cooperative Research Centre for funding.

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Area-Wide Management of Insects Infesting Cotton

D.D. Hardee[1] · T.J. Henneberry[2]

1
Introduction

Since 1992 insects have consistently cost cotton, *Gossypium hirsutum L.*, producers US$ 0.8–1.6 billion annually in direct management costs and associated yield losses (Beltwide Cotton Conference Reports, National Cotton Council, Memphis, TN). In the mid-1980s and continuing to the present, cotton entomologists and producer organizations realized the difficulty in managing all of the major complex and persistent cotton insect problems on a local basis (Henneberry and Phillips 1996). In an attempt to overcome these challenges, management programs were organized on an area-wide concept rather than on an individual field basis. These programs were inspired by the amazing success of eradicating the screwworm fly, *Cochliomyia hominivorax* (Coquerel) (Diptera: Calliphoridae) from the southeastern United States (Knipling 1960a). In addition, the propensity for development of insecticide resistance in several cotton insects, especially boll weevil, *Anthonomus grandis grandis* Boheman (Roussel and Clower 1955; Walker et al. 1956; Fye et al. 1957; Smith 1998), tobacco budworm (TBW), *Heliothis virescens* F. (Elzen et al. 1992; Elzen and Hardee 2003), tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois) (Snodgrass and Elzen 1995; Snodgrass 1996) and sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Prabhaker et al. 1996) created an urgency for development of improved management techniques for cotton insects. We report herein, case histories of attempts to manage six cotton insects in an area-wide system.

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[1] Research Leader (retired), USDA-ARS, Southern Insect Management Research Unit, P.O. Box 346, Stoneville, Mississippi 38776, USA

[2] Laboratory Director, USDA-ARS, Western Cotton Research Laboratory, 4135 E. Broadway, Phoenix, Arizona 85040, USA

IPM Guidelines Support Document 1

Impact of insecticides and miticides on predators in cotton October 2005 update

Prepared by Lewis Wilson[1], Robert Mensah[2], Martin Dillon[4], Mark Wade[5], Nat Parker 3, Brad Scholz[3], David Murray[3], Viliami Heimoana[2] and Richard Lloyd[3]

CSIRO[1] - NSW DPI[2]. Queensland Department of Primary Industries & Fisheries[3] - Formerly CSIRO[4]
- Formerly Queensland Department of Primary Industries & Fisheries[5]

Insecticides (in increasing rank order of impact on beneficials)	Rate (g ai / ha)	Target Pest(s)						Overall Ranking[10]	Beneficials															Pest resurgence [12]			Toxicity to bees[14]
		Helicoverpa	Mites	Mirids	Aphids	Thrips	Persistence[8]		Predatory beetles: Total[1]	Red & Blue beetle	Minute 2-spt lady beetle	Other lady beetles	Predatory bugs: Total[2]	Damsel bugs	Big-eyed Bugs	Other Predatory bugs	Apple Dimpling	Lacewing adults	Spiders	Hymenoptera: Total (wasps)	Trichogramma	Ants	Thrips	Mite	Aphid	Helicoverpa	
Bt[11]		✓					very short	very low	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL				VL
NP Virus		✓					very short	very low	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL				VL
Pirimicarb	250				✓		short	very low	VL	VL	VL	VL	L	L	M	VL	VL	VL	VL	VL	M	VL	L				VL
PSO (Canopy)[16]	2%	✓			✓		short	very low	VL	L	L	VL	VL	VL	VL	VL	VL	VL	L	VL	VL	H	VL				VL
Methoxyfenozide	400	✓					medium-long	very low	L	VL	VL	L	L	L	L	VL	VL	VL	VL	VL	VL	VL	VL				VL
Etoxazole	38.5		✓				short	low	VL	VL	.	L	VL	VL	VL	VL	VL	VL	M	L	VL	VL	L				VL
Dicofol[3]	960		✓				long	low	L	.	.	.	L	.	.	.	L	-	L	-	-	-	VL				VL
Amorphous silica[17]	2500	✓					short	low	L	L	.	M	M	.	VL	.	L	L	L	L	-	M	VL				-
Spinosad	96	✓					medium	low	VL	M	L	VL	M	L	H	VL	L	VL	VL	M	H	H	H	+ve			H[15]
Diafenthiuron	350		✓		✓		medium	low	M	H	VL	M	L	M	VL	L	H	VL	L	L	VL	H	L			+ve	M
Pymetrozine	150				✓		short	low	M	M	M	M	L	L	L	VL	H	M	L	L	L	M	VL				VL
Indoxacarb[13]	127.5	✓		✓			medium	low	H[14]	L	VH	VH	L	L	L	L	VH	L	VL	L	VL	VH	VL		+ve		H[15]
Abamectin	5.4	✓[6]	✓				medium	moderate	L	M	H	VL	M	L	M	M	H	VL	M	M	M	H	M				H
Emamectin	8.4	✓					medium	moderate	L	VL	M	VL	H	H	H	H	H	L	M	M	M	VL	M				H
Endosulfan (low)	367.5	✓		✓	✓	✓	medium	moderate	M	VL	VH	M	M	M	M	L	H	L	M	VL	-	VH	H				M[15]
Propargite	1500		✓				medium	moderate	M	H	H	M	M	H	VL	VL	L	VL	M	M	H	H	M		+ve	+ve	L
Acetamiprid	22.5				✓		medium	moderate	M	M	VH	H	M	M	H	M	VH	L	VL	L	H	VH	VH				M[15]
Amitraz	400	✓	✓[9]				medium	moderate	H	M	VH	H	L	.	.	.	H	VL	M	M	L	H	M				L
Fipronil (low)	12.5			✓		✓	medium	moderate	L	VL	H	L	L	H	L	L	VH	VL	M	M	M	VH	VH		+ve	+ve	VH
Chlorfenapyr (low)	200	✓	✓				medium	moderate	M	L	VH	VL	M	VL	H	H	VH	L	L	M	VH	H	M				H
Thiamethoxam	100				✓		medium	moderate	H	H	H	H	M	M	M	H	H	M	VL	M	H	VH	H	+ve		+ve	H
Endosulfan (high)	735	✓		✓	✓	✓	medium	moderate	M	VL	VH	M	M	M	M	M	H	L	M	L	VH	VH	H				M[15]
Fipronil (high)	25			✓		✓	medium	moderate	L	VL	H	L	M	H	H	L	VH	VL	M	M	M	VH	VH	+ve		+ve	VH
Imidacloprid	49			✓	✓		medium	moderate	H	L	VH	H	H	M	H	L	VH	L	L	L	M	H	H	+ve		+ve	M
Methomyl	169	✓					very short	high	H	L	VH	VH	M	L	VH	L	VH	M	M	M	H	H	H	+ve			H[15]
Thiodicarb	750	✓					long	high	VH	M	VH	VH	M	M	L	L	VH	VL	M	M	M	M	H	+ve	+ve		M[15]
Chlorfenapyr (high)	400	✓	✓				medium	high	H	M	VH	L	H	H	H	H	VH	L	M	M	VH	VH	M		+ve		H
OP's[5]		✓	✓	✓	✓	✓	short-medium	high	H	M	H	H	H	M	H	H	VH	L	M	H	H	VH	H	+ve			H
Carbaryl[3]							short	high	H	.	.	.	H	.	.	.	.	-	-	-	-	-	H	-	-	-	H
Pyrethroids[4]		✓	✓[7]	✓[7]			long	very high	VH	.	.	.	VH	.	.	.	VH	VH	VH	VH	VH	VH	VH	+ve	+ve	+ve	H

Foototes to Impact of insecticides and miticides on predators in cotton table October 2005 update table.

1. Total predatory beetles – ladybeetles, red and blue beetles, other predatory beetles
2. Total predatory bugs – big-eyed bugs, minute pirate bugs, brown smudge bugs, glossy shield bug, predatory shield bug, damsel bug, assassin bug, apple dimpling bug
3. Information; Citrus pests and their natural enemies, edited by Dan Smith; University of California Statewide IPM project, Cotton, Selectivity and persistence of key cotton insecticides and miticides.
4. Pyrethroids; alpha-cypermethrin, cypermethrin,beta-cyfluthrin, cyfluthrin, bifenthrin, fenvalerate, esfenvalerate, deltamethrin, lambda-cyhalothrin,
5. Organophosphates; dimethoate, omethoate, monocrotophos, profenofos, chlorpyrifos, chlorpyrifos-methyl, azinophos ethyl, methidathion, parathion-methyl, thiometon
6. Helicoverpa punctigera only.
7. Bifenthrin is registered for mite control; alpha-cypermethrin, beta-cyfluthrin, bifenthrin, deltamethrin and lambda-cyhalothrin are registered for control of mirids
8. Persistence of pest control; short, less than 3 days; medium, 3-7 days, long, greater than 10 days.
9. Suppression of mites only.
10. Impact rating (% reduction in beneficials following application, based on scores for the major beneficial groups); VL (very low), less than 10%; L (low), 10-20%; M (moderate), 20-40%; H (high), 40-60%; VH (very high), $> 60\%$. A '-' indicates no data available for specific local species.
11. Bacillus thuringiensis
12. Pest resurgence is +ve if repeated applications of a particular product are likely to increase the risk of pest outbreaks or resurgence. Similarly sequential applications of products with a high pest resurgence rating will increase the risk of outbreaks or resurgence of the particular pest species.
13. Very high impact on minute two-spotted ladybeetle and other ladybeetles for wet spray, moderate impact for dried spray.
14. Data Source: British Crop Protection Council. 2003. The Pesticide Manual: A World Compendium (Thirteenth Edition),. Where LD50 data is not available impacts are based on comments and descriptions. Where LD50 data is available impacts are based on the following scale: very low = LD50 (48h) $>$ 100 ug/bee, low = LD50 (48h) $<$ 100 ug/bee, moderate = LD50 (48h) $<$ 10 ug/bee, high = LD50 (48h) $<$ 1 ug/bee, very high = LD50 (48h) $<$ 0.1 ug/bee. Refer to the Protecting Bees section in this booklet.
15. Wet residue of these products is toxic to bees, however, applying the products in the early evening when bees are not foraging will allow spray to dry, reducing risk to bees the following day.
16. May reduce survival of ladybeetle larvae – rating of moderate for this group.
17. May be detrimental to eggs and early stages of many insects, generally low toxicity to adults and later stages.

DISCLAIMER Information provided is based on the current best information available from research data. Users of these products should check the label for further details of rate, pest spectrum, safe handling and application. Further information on the products can be obtained from the manufacturer.

Table 2 :Impact of insecticides applied at planting or as seed treatments on key beneficial groups in cotton (high =more disruptive)

		Main Target Pest(s)							Beneficial group				
Insecticides	**Rate (g ai / ha)**	**WW**	**Mite**	**Mir.**	**Aph.**	**Th.**[5]	**Persistance**[6]	**Overall**[7]	**Predatory beetles**[1]	**Predatory bugs** [2]	**Spiders**	**Wasps & Ants**	**Thrips**
At Planting													
Aldicarb	**450**		✓	✓	✓	✓	medium -long	**very low**[3]	v low	v low	v low	v low	v high
Phorate	**600**	✓	✓	✓	✓	✓	medium -long	**very low**[3,4]	No data	No data	No data	No data	v high
Carbosulfan	**750-1000**	✓		✓		✓	medium -long	**very low**[3,4]	No data	No data	No data	No data	v high
Chlorpyrifos	**250-750**	✓					medium	**very low**[4]	No data	No data	No data	No data	No data
Seed Treatments													
Thiodicarb	**500 g ai / 100kg seed**					✓	short	**very low**[3]	v low	v low	v low	v low	high
Thiodicarb + Fipronil	**259 + 12 g ai / 100kg seed**	✓				✓	short-medium	**very low**[3,4]	No data	No data	No data	No data	high
Imidocloprid	**525 g ai / 100kg seed**	✓			✓	✓	medium	**very low**[3]	[redacted]	[redacted]	[redacted]	[redacted]	v high
Imidocloprid	**700 g ai / 100kg seed**	✓			✓	✓	medium	**very low**[3,4]	No data	No data	No data	No data	v high
Thiomethoxam	**280 g ai / 100kg seed**	✓			✓	✓	medium	**very low**[3,4]	No data	No data	No data	No data	v high

1. Predatory beetles – ladybeetles, red and blue beetles, other predatory beetles
2. Predatory bugs – Big-eyed bugs, minute pirate bugs,brown smudge bugs, glossy shield bug, predatory shield bug, damsel bug, assassin bug, apple dimpling bug
3. Except for effects on thrips which are predators of mites. Note that aldicarb and phorate will also control mites.
4. Based on observations with other soil or seed applied insecticides.
5. WW., wireworm; Mir, mirids; aph, aphids; th., thrips
6. Persistence; short, 2- 3 weeks; medium, 3-4weeks, long, 4-6 weeks
7. Impact rating (% reduction in beneficials following application); very low, less than 10%; low, 10-20%; moderate, 20-40%; high, 40-60%; very high, > 60%

DISCLAIMER Information provided is based on the current best information available from research data. Users of these products should check the label for further details of rate, pest spectrum, safe handling and application. Further information on the products can be obtained from the manufacturer.

Important Use of Pesticides

Pesticides must only be used for the purpose for which they are registered and must not be used in any other situation or in any manner contrary to the directions on the label.

Some chemical products have more than one retail name. All retail products containing the same chemical may not be registered for use on the same crops. Registration may also vary between States. Check carefully that the label on the retail product carries information on the crop to be sprayed.

This publication is only a guide to the use of pesticides. The correct choice of chemical, selection of rate, and method of application is the responsibility of the user.

Pesticides may contaminate the environment. When spraying, care must be taken to avoid spray drift on to adjoining land or waterways. Residues may accumulate in animals fed any crop product, including crop residues, which have been sprayed with pesticides. In the absence of any specified grazing withholding period(s), grazing of any treated crop is at the owner's risk.

Australian Cotton
Cooperative Research Centre

COTTON information sheet

INSECTICIDE RESISTANCE

Where are we now ? Dec 2003

Louise Rossiter[1], Lewis Wilson[2], David Larsen[1], Bruce Pyke[3], Robin Gunning[1], Grant Herron[1], David Kelly[4].

Introduction

In recent years the chemical use pattern for *Helicoverpa* spp. control has changed. More reliance is put on new IPM friendly insecticides that help preserve beneficials. Increased use places these new insecticides at risk from resistance development.

Continued exposure of successive generations of insects to these new chemistries will select for resistance. Previous experience indicates pro-active resistance management is essential and we must address emerging resistance problems quickly. The on-going success of IPM depends on access to IPM friendly chemistries so the industry must be vigilant and decisive in dealing with resistance.

This document is an introduction to the principles behind the Australian cotton insecticide resistance management strategy and highlights issues forming the shape of future strategies.

Core principles of the Insecticide Resistance Management Strategy.

The Insecticide Resistance Management Strategy (IRMS) Incorporates:

- **Rotation of chemistries**, to avoid excessive selection with one group of insecticides with the same mechanism for killing pests and therefore the same potential mechanisms of resistance. It also allows for reversion of a population (in the absence of selection pressure resistance may be lost) or immigration of susceptible insects to dilute resistance.
- **Restriction in time**, e.g. the use of windows of use or preclusion.
- **Restriction in number**, to avoid overuse of any one insecticide.
- **Pupae Busting** - a non selective cultural control technique.

The IRMS is also Pro-active and Adaptive

Pro-active. The strategy is designed to prevent resistance development, while managing existing resistance resistance. Limiting the number of applications permitted for new insecticides is an example of pro-active management.

Adaptive. The IRMS is responsive to changes between seasons as new information becomes available from resistance monitoring. However, every season is different and the weather and insect patterns of the previous season should not overly influence the long-term aim of resistance management.

Other Strategies that should be Applied as a Principle

- IPM - softer chemistry use is encouraged with harder more disruptive chemistry restricted to later in the season
- IPM/beneficial conservation & use of plant compensation for damage

Beneficials eat or parasitise resistant as well as susceptible pests.

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RESEARCH REVIEW

Australian Cotton Cooperative Research Centre

Mirid Management in Australian Cotton

Outcomes from the Mirid Management Workshop, 15 July 2004

Compiled by: Moazzem Khan[1], Dave Kelly[2], Mark Hickman[1], Robert Mensah,
Hugh Brier[1] and Lewis Wilson[4]

Australian Cotton CRC [redacted]
Number 15 November 2004

Insects

Introduction:

This is a companion document to Mirid Ecology in Cotton and covers sampling and control measures for mirids in Australian cotton.

Mirid Sampling

Mirids are very mobile pests and populations can fluctuate rapidly, so sampling needs to take place every 3 days.

Using 'beat sheets' is the quickest and most consistent method of sampling these highly mobile insects. When plants have less than 9 nodes, beat sheets and visual checks give approximately the same estimates of mirid numbers. However, as plants grow beyond 9 nodes the beat sheets become more effective for sampling mirids and the ratio of mirids in visual counts to beat sheet counts is about 1:3. If using beat sheets the numbers should be adjusted accordingly as the thresholds are based on visual sampling. Sampling should occur 2-3 times per week, becoming more frequent when approaching a control decision.

Figure 1: Sampling for mirids using the beat sheet (Photo M. Dillon)

The number of beat sheet samples per management unit should be no less than what would have been done by visual sampling. Research is continuing to determine the number of beat sheet samples required per field. Research is also currently being undertaken to calibrate 'sweep nets' as a method of monitoring mirid populations.

Thresholds

Pest thresholds

Thresholds for mirids vary between warm and cool season areas due to the cotton plant's ability to compensate for damage. Thresholds early in the season are quite well established (Table 1). Thresholds mid-season are still being developed. At present during the mid-season the thresholds for early-season can be used as a trigger to look more closely for mirid damage. The need to control should be based on a combination of:

(i) evidence of mirid numbers (i.e. Table 1) and
(ii) evidence of damage exceeding guideline levels (below).

Control decisions for mirids should use a combination of plant damage and insect population data. For example, if early-season fruit retention is very low (<40 %) then mirid thresholds may need to be lowered to prevent further loss. Alternatively, in crops with very high retention (>80 %), thresholds may be lifted.

The use of thresholds, based on mirid numbers, is complicated by the ability of mirids to feed on both plant and prey. Although no work has been done in Australia, research in the US and Israel on similar species shows that the presence of prey can result in reduced levels of plant feeding by mirids. If this is so for the green and brown mirids in Australian crops, then it may explain why in some sea-

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RESEARCH REVIEW

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Insects

Mirid Ecology in Australian Cotton

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Australian Cotton CRC
Number 14 November 2004

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been considered a significant pest of Australian cotton because of their great mobility and ability to cause very rapid damage. A related species, the brown mirid (*Creontiades pacificus*), is also sometimes found in cotton, but in cotton is generally less abundant than the green mirid. Brown mirids are quite common in pulse crops.

Traditionally, under a conventional insecticide system, mirids were only considered a pest early in the cotton season. Towards the mid to late part of the season the use of broad-spectrum insecticides for *Helicoverpa* spp. gave incidental control of mirids. With the broad scale adoption of cotton varieties that contain the Bollgard II genes (Cry1Ac and Cry IIAb) that offer protection against *Helicoverpa* spp., and the shift towards integrated pest management practices, there has been a marked reduction in insecticide applications and change toward use of more selective insecticides on Australian cotton crops. These changes allow mirids to survive and build up through the season, when before they would have been coincidentally controlled by insecticides applied for other pests early in the season.

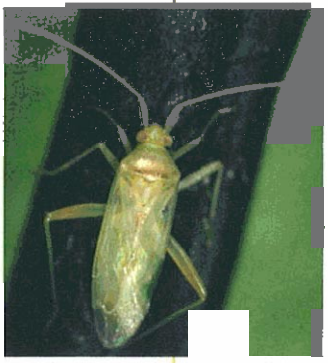

Figure 1: Green mirid (Creontiades dilutus) Note striped antennae,
(Photo J.Wessels)

Figure 2: Brown mirid (*Creontiades pacificus*)
(Photo J.Wessels)

polyphagous insects, meaning they feed and develop on a wide range of host plants, including sunflowers, safflower, lucerne and many legume, and weed species including wild turnips, verbena, common joy weeds and thistles. During the winter months they are often difficult to locate, overwintering as adults or eggs on wild plants in low numbers. However, as temperatures begin to rise in August, their populations increase.

The primary movement of mirids into cotton crops occurs during November as alternative host plants within the vicinity of cotton crops tend to dry off and insects seek a fresh food source. There is also evidence of long distance migration, possibly from inland areas, associated with weather fronts, although this is not well understood. This may be the cause of some of the widespread and repeated influxes of mirids sometimes observed in cotton growing regions early in the season.

Within a crop, mirids lay eggs singly, preferentially on the leaf petiole. The egg is inserted into the plant tissue with an oval egg cap projecting above the leaf or petiole surface. Eggs hatch after 7-10 days depending on temperature; at 30-32 °C (average temperature) eggs

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