



*CSIRO Plant Industry  
Cotton Research Unit  
and  
Australian Cotton CRC*

**FINAL REPORT**

**Project title:** Management of early season damage and secondary pests in cotton.

**Project code:** CSP103C

**Research organisation:** CSIRO Plant Industry

**Principal researcher:** Dr Lewis Wilson - 65%  
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)



*A final report prepared for the Cotton Research and Development Corporation*

The information, advice and/or procedures contained in this publication are provided for the sole purpose of disseminating information relating to scientific and technical matters in accordance with the functions of CSIRO under the Science and Industry Act 1949. To the extent permitted by law CSIRO shall not be held liable in relation to any loss or damage incurred by the use/or reliance upon any information advice and/or procedures contained in this publication.



January, August &amp; Final Reports

**Part 1 - Summary Details****REPORT****S**

Please use your TAB key to complete part 1 &amp; 2.

**CRDC Project Number: CSP103C**

**January Report:**  Due 29-Jan-01  
**August Report:**  Due 03-Aug-01  
**Final Report:**  Due within 3 months of project completion

**Project Title:** *Management of early season damage and secondary pests in cotton.***Project Commencement Date:** 1 July 1999 **Project Completion Date:** 30 June 2002**Research Program:** Insect Management**Part 2 – Contact Details**

**Administrator:** Administration Manager  
**Organisation:** CSIRO Plant Industry  
**Postal Address:** Locked Bag 59, Narrabri, NSW, 2390  
**Ph:** 02-67991500 **Fx:** 02-67991503 **E-mail:**

**Principal Researcher:** Dr Lewis Wilson (Principal Research Scientist)  
**Organisation:** CSIRO Plant Industry  
**Postal Address:** Locked Bag 59, Narrabri, NSW, 2390  
**Ph:** 02-67991550 **Fx:** 02-67991503 **E-mail:**  
 Lewis.Wilson@csiro.au

**Supervisor:** Dr Greg Constable (Senior Principal Research Scientist)  
**Organisation:** CSIRO Plant Industry  
**Postal Address:** Locked Bag 59, Narrabri, NSW, 2390  
**Ph:** 02-67991522 **Fx:** 02-67991503 **E-mail:**  
 Greg.Constable@csiro.au

**Researcher 2** (Name & position of additional researcher or supervisor).

**Organisation:**  
**Postal Address:**  
**Ph:** **Fx:** **E-mail:**

**Signature of Research Provider Representative:**

## Management of early season damage and secondary pests in cotton.

**Project Number:** CSP103C

**Organisation:** CSIRO Division of Plant Industry  
**Address:** Cotton Research Unit  
PO Box 59, Narrabri, NSW, 2390

**Research Staff:** Dr L.J. Wilson (Principal Research Scientist)

**Support Staff:** Ms S. Heimoana (Senior Technical Officer)  
Ms D. Hamilton (Technical Assistant)  
Mr M. Strahle (Technical Assistant to Sep 2001)  
Mr N. Mor (Technical Assistant Dec 2001 – Jun 2002)

**Collaborators:** Dr V. Sadras (formerly CSIRO Plant Industry)  
Dr Tom Lei (CSIRO Plant Industry)  
Dr Grant Herron (NSW Agriculture)  
Dr Gary Fitt (CSIRO Entomology)  
Dr Neil Forrester (formerly NSW Agriculture)  
Dr Jonathan Holloway (formerly NSW Agriculture)  
Mr Dallas Gibb (NSW Agriculture)  
Mr Bernie Franzmann (QDPI)

### **Aims:**

- Further define the effect of early season pest damage to cotton in terms of growth, development, yield, crop maturity and fibre quality, considering effects of pests alone and in combination, and interactions with crop agronomy.
- Investigate effects of early damage on Bt production in transgenic cotton
- To extend research on early pest damage into a range of cotton regions through collaboration with the CRC Cotton Extension Team
- To investigate the effect of aphids on the yield, maturity and fibre quality of cotton
- To investigate the ecology of aphids in cotton regions and the role of beneficial insects in influencing aphid population dynamics
- To investigate the efficacy of new insecticides/acaricides, particularly against aphids and mites, and their effect on non-target insects (predators/parasitoids).

## Plain English Summary

This project investigated three topics of significance to developing IPM systems in cotton (i) responses of cotton to early damage (ii) effects of aphids on cotton development and yield and (iii) efficacy and non target effects of new insecticides.

### (i) Responses of cotton to early damage and interactions with agronomic factors.

- a. Sowing date - We found that cotton compensated for early damage even when crops were late due to delays in sowing. However, the degree of compensation varied between years with almost complete compensation in some years but less complete compensation in others. The results suggest that there was no interaction between damage and sowing date in terms of yield, but that there were differences between experiments, probably due to differences in growing conditions.
- b. Irrigation stress and plant stand – Water stress accelerated maturity as expected. Addition of damage delayed maturity more in irrigated cotton (6-10 d) than non-irrigated solid planted cotton (5 d) regardless of plant stand (5 or 10 plants/m<sup>2</sup>). Plant density and irrigation treatment interacted to affect yield. Irrigated cotton had higher yields. In irrigated cotton recovery following damage was complete at the high plant stand, but incomplete at the low plant stand (- 20 g lint m<sup>-1</sup>). This pattern was reversed in the non-irrigated cotton where recovery was complete at the lower plant stand but not at the high plant stand (-27 to -45 kg lint m<sup>-1</sup>). Better recovery from damage is likely to be achieved by planting at close to the optimum of 10 plants m<sup>2</sup> in irrigated cotton, while if the cotton is non-irrigated solid planted it is better to plant at a lower density.
- c. Impact of heavy and light tip damage - Cotton tolerated up to 7 light tip damage events (removal of terminal only) without affecting yield and up to 3 without affecting maturity. Lower amounts of heavy tip damage (removal of terminal plus top two nodes) could be tolerated, e.g. 3 events did not reduce yield and 1 event caused only a minor delay in maturity. The main effect of tip damage is to promote production of vegetative branches, which in turn produce fruiting branches. 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 in press). 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.
- d. Plant and crop level compensation for damage - The interaction between neighbouring plants affects the ability of the crop as a whole to recover from damage. We looked at 0, 25, 50, 75 and 100% of plants damaged. For the plants that were damaged we removed all leaves (100%) or 75% of each leaf on 3 dates (2, 4 and 6 nodes). In all but the heaviest damage treatment yield was similar to the control indicating complete compensation for yield. The results show that there are strong neighbour effects on the yield of individual plants due to reduced leaf area early in the season, even if yield of the crop as a whole is unaffected. Damaged plants are stunted if neighbouring plants are undamaged. However, undamaged neighbours usually compensate for the reduced yield of undamaged plants.
- e. Damage and efficacy of Ingard cotton - Simple experiments were done to investigate the effect of early season damage on Bt production. We found simulated thrips damage (leaf removal) generally resulted in elevated levels of Bt in plants for a period then a return to similar levels as undamaged plants. The results suggest that tolerating some early damage from thrips is unlikely to reduce the efficacy of Bt-cotton – an important issue for IPM.
- f. Cotton responses to damage in different regions – collaboration with IDOs. A simple experimental design was developed with IDOs to investigate cotton recovery from damage

in on-farm experiments with growers and thirty-eight experiments have been completed. In the hot Emerald region single tip damage caused about a 9% loss of yield, though this was not consistent. In the warm regions cotton recovered without loss from tip damage at 4 or 10 nodes and a slight penalty (8 %) from the combination of the two. In the cool regions yield was not affected by single tip damage but was significantly reduced by tip damages at nodes 4 and 10, by about 16% in about 50% of cases. The combination of tip damage at 4 and 10 true leaves caused a more significant loss of 19%. Overall maturity was not significantly affected by tip damage with most delays being less than 2 days and the longest of 4 days for the combined node 4 and 10 damage at Emerald. The experiments were invaluable in getting the message across industry about compensation and giving growers confidence to tolerate some early damage.

### **(ii) Effects of aphids on cotton development and yield**

Aphids have emerged as an increasing problem in cotton due to a range of factors including changes in pesticide use patterns, the advent of cotton bunchy top disease, for which cotton aphid is a vector, and insecticide resistance. We initiated a series of large-scale experiments to investigate the effects of aphids on the development and yield of cotton. The peak populations in the 2000-01 experiment in particular were very high and significantly affected plant development as shown by dramatic effects on dry weight. Simple plots of cumulative aphid days against relative yield (yield normalised against the control plots in each experiment) have shown a reasonably good relationship, which can probably be improved if the time at which aphid populations began to increase is also included. This relationship can then be used to derive thresholds for aphid control at different stages of the season.

### **(iii) Efficacy and non target effects of new insecticides**

This research has continued from that of earlier projects and has been completed on time. Detailed summaries from each experiment are provided in Appendix 2. Data for the past ten years have been collated into a new colour coded summary document which has been made available to industry via printed copy and the CRC website. This document includes all currently registered insecticides and identifies their target pests, their impact on a wide range of beneficial groups and the potential to cause resurgence of secondary pests.

## **Conclusions**

The outcomes of much of this work have been reported to industry and published in scientific journals and have strongly supported the development of IPM systems in cotton. The results on compensation in particular emphasise that cotton has a strong capacity to recover from early pest damage across most regions, even if sown late, sown at a low plant stand, water stressed, or if damage occurs unevenly. Furthermore, damage does not reduce the efficacy of Ingard cotton and may actually enhance it.

New research has been developed, with funding from CRDC, to follow-up on several important compensation and IPM issues. These include (i) a better understanding of the underlying mechanism of compensation for early defoliation so that models can be improved (ii) finalisation of the relationship between aphid density and yield loss in cotton (iii) continuation of experiments to broaden understanding of the non-target effects of insecticides (iv) investigation of the ecology of aphids in cotton regions and of the role of beneficial insects in their control (v) investigation of the distribution of aphids in cotton field to improve sampling protocols (vi) initiation of a project to determine the cause of cotton bunchy top and develop management strategies.

## Detailed report of Results

The development of IPM systems in cotton hinges on the availability of information on a wide range of issues. Included among these is the response of plants to pest damage, the impact of specific pests on yield and the effects of insecticides on pests and beneficials. Each of these factors has the potential; to influence when and with what a crop is sprayed with and hence to strongly influence the costs associated with insecticide use, the conservation of beneficial insects, resistance selection against pest species and environmental pollution. This research project has focussed on (1) plant responses to early season damage with emphasis on interactions with agronomic factors that may influence the degree to which plants compensate (2) the effect of aphids on cotton yield and initial studies of their ecology and (3) the effect of insecticides on target and non-target species, with particular emphasis on beneficial species so that growers and consultants have more information on which to base insecticide choice decisions. A summary of the research, methodology, results and outcomes for these main themes is given below for each of the main objectives of the project.

### **A) Further define the effect of early season pest damage to cotton in terms of growth, development, yield, crop maturity and fibre quality, considering effects of pests alone and in combination, and interactions with crop agronomy.**

Three sets of experiments were done to consider interactions between damage and agronomy. These included (1) interaction between damage and sowing date (2) interaction between damage, plant stand and water stress and (3) comparison of the effects of light and heavy tip damage. These are discussed individually below;

#### *(1) Interaction between damage and sowing date*

Earlier experiments showed that tip damage had little effect on either yield or maturity date and that defoliation only affected yield or maturity if it was severe and prolonged. However, the data was limited to crops where sowing date was optimal (first or second week in October). Growers have asked if cotton planted later would respond to damage in the same way as found for the optimal planting date.

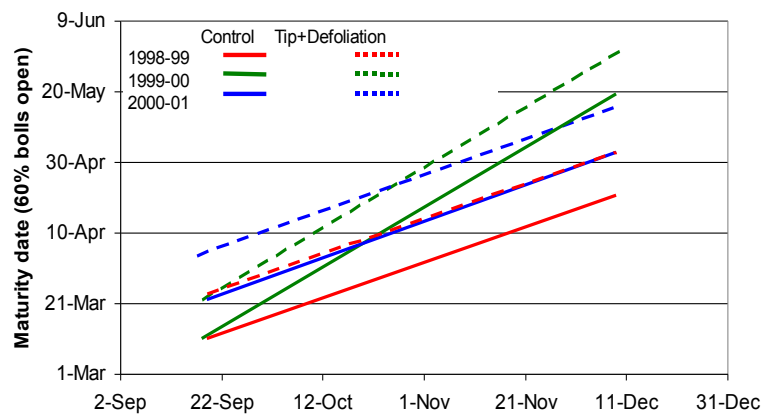
We investigated this interaction between planting date and damage in experiments which included 3 planting dates (optimal, late and very late) and 4 damage levels (undamaged, 100% tip damage, 100% defoliation and 100% defoliation plus tip damage, in the first experiment the 100% tip damage was replaced with 75% defoliation). We had bigger plots for two treatments – the undamaged control and the 100% leaf damage so that we could partition samples of plants to understand how they are responding to damage in terms of dry weight allocation.

As each experiment had a slightly different range of sowing dates a regression analysis was used to investigate the major responses to damage across the experiments. For treatment in each experiment the time of sowing was calculated as the days from the 1<sup>st</sup> July and the time of 60% open bolls, estimated from sequential harvests, similarly expressed. Maturity date and yield for each treatment in each experiment were regressed against sowing date, with terms added for defoliation, tip damage and experiment. All combinations of interactions were also included and a reduced model developed.

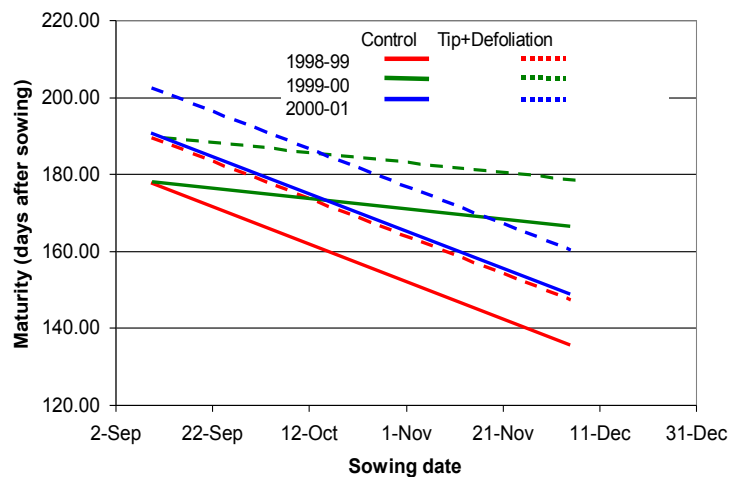
Maturity dates were later for delayed sowings compared with earlier sowings (Figure 1 – only the heavy damage treatment shown for clarity) but the actual crop period was slightly shorter

(Figure 1) – though at the expense of yield (Figure 3). The regression showed significant differences in responses to sowing date and damage between experiments, as indicated by different relationships for each of the experiments in figure 1-3). The response of crop maturity to defoliation or tip damage was not influenced by sowing date, i.e. there was no interaction between damage and sowing date, all sowing dates responded similarly. Overall, tip damage caused a delay of about 5 days, defoliation about 7 days and the combination of the two about 12 days.

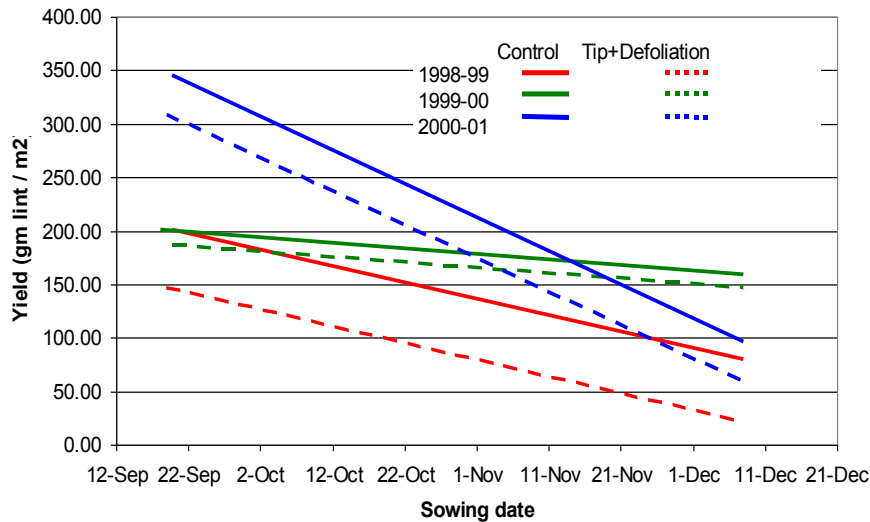
Yield declined with later sowing dates as expected, however the rate of decline was not consistent between experiments. Yield was not affected by tip damage regardless of sowing date. Defoliation caused a significant reduction in yield, which was consistent across sowing dates within an experiment, but differed between experiments in magnitude. The results suggest that there is no interaction between damage and sowing date in terms of yield, but that there are differences between experiments, probably due to differences in growing conditions.



**Figure 1.** Relationship between damage, sowing date and crop maturity for 3 experiments. For clarity only the extreme damage treatment is shown (defoliation plus tip damage at nodes 2, 4 and 6),  $r^2$  for the relationship is 81.4.



**Figure 2.** Relationship between damage, sowing date and days taken for the crop to mature maturity for 3 experiments. For clarity only the extreme damage treatment is shown (defoliation plus tip damage at nodes 2, 4 and 6).

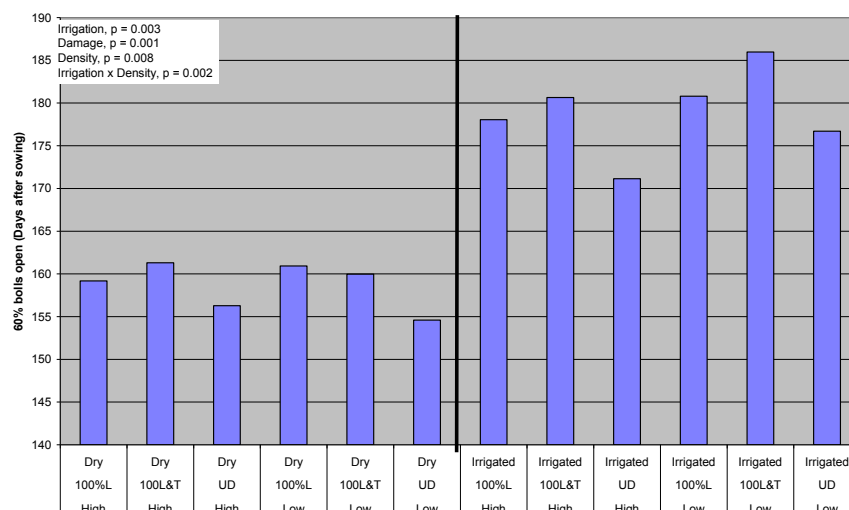


**Figure 3.** Relationship between damage, sowing date and yield for 3 experiments. For clarity only the extreme damage treatment is shown (defoliation plus tip damage at nodes 2, 4 and 6),  $r^2$  for the relationship is 85.8.

*(2) Interaction between plant density, water stress and damage*

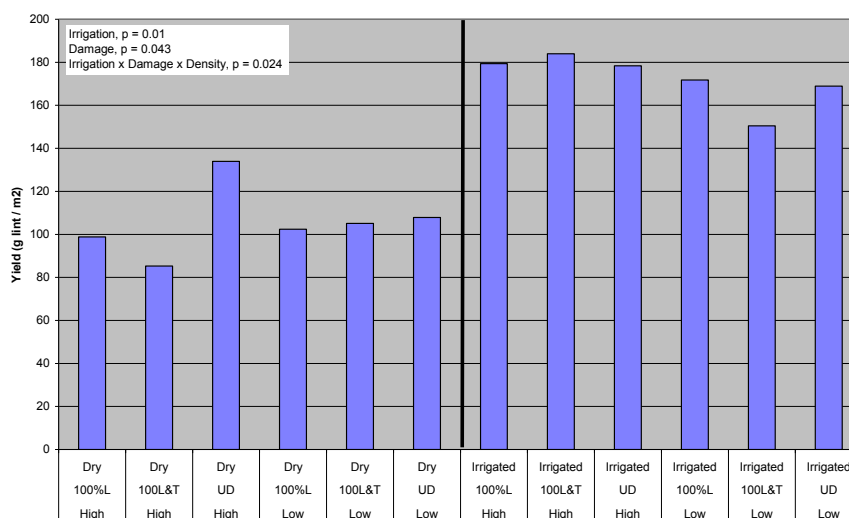
Dryland cotton growers have questioned whether tolerating early season damage is too risky, because dryland plant may not have the water available to compensate. Additionally earlier damage experiments have all used plant stands, which are typical of commercial cotton production (about 10-12 plants/m). Growers and consultants have often questioned the interaction between damage and plant stand, i.e., if plant stand is low then damage may have a greater effect on yield or delay. We tested these two questions and the interaction of the two (i.e. plant stand x water) in a simple experiment with two levels of irrigation (normal or none), two plant densities (5 or 10 plants/m) and three damage levels; (1) undamaged, (2) 100% defoliation at nodes 2, 4 and 6 and (3) 100% defoliation plus tip damage at nodes 2, 4 and 6. Soil water status was measured using a neutron probe and clear plastic was lain down between the rows in the dry treatments to reduce infiltration of rainfall. Following initial irrigation at planting to ensure establishment, the dry crops received no further irrigation water. Clear differences in soil water status were achieved. The results of the two experiments (1998-99 and 1999-00) were combined for analysis. There were not significant effects differences between years.

**Maturity** - Water stressed cotton matured significantly earlier than irrigated cotton as expected ( $p = 0.003$ , Figure 4). The low-density cotton was also slightly later maturing than the high-density cotton for the irrigated cotton but not the dry cotton ( $p = 0.008$ ). Damaged treatments were all generally slightly later than the undamaged control ( $p = 0.0012$ ). The effect of damage was slightly higher in the irrigated than the dry cotton ( $p = 0.06$ ). In the dry cotton the defoliation and the defoliation plus tip damage treatments caused similar delays of about 5 days. In the irrigated cotton defoliation alone caused a delay of about 6 days and addition of tip damage a further 4 days. There were no interactions between damage and plant stand.



**Figure 4.** Effects of water stress, plant stand and damage on maturity of cotton (days after sowing for 60% of bolls open). Irrigated cotton was fully irrigated while dry received no water other than at sowing. Low refers to plant stand of 5 plants  $m^2$  and high to 10 plants  $m^2$ . UD is undamaged, 100%L is 100% defoliation at 2, 4 and 6 nodes and 100L&T is 100% defoliation plus tip damage at 2, 4 and 6 nodes.

Yield – Water stressed cotton had a significantly reduced yield as expected ( $p = 0.01$ , Figure 5). Recovery from damage was complete in the high-density irrigated cotton (0.024). In the low density irrigated cotton recovery was complete for the defoliation treatment but the addition of tip damage caused loss of 20  $g\ lint\ m^{-1}$ . This pattern was reversed in the dry cotton where recovery was complete at the lower plant stand but not at the high plant stand, where losses of about 27  $g\ lint\ m^{-1}$  occurred in the defoliation treatments and the combination of tip damage and defoliation causing a loss of about 45  $g\ lint\ m^{-1}$ .



**Figure 5.** Effects of water stress, plant stand and damage on yield of cotton. See caption of Figure 4 for details.

Conclusions - Overall the results show that the maturity of dry cotton was less affected by damage than the irrigated cotton regardless of plant stand. In contrast, in terms of yield there

was a strong interaction between water stress, density and damage. It is possible that under full irrigation, plants at a lower stand take longer to achieve full light interception following the combination of defoliation plus tip damage than those at a higher stand. This would be expected to delay maturity, as was found, and thereby potentially reduce yield because the crop is maturing under less suitable conditions. Under limited water the opposite may apply, the higher plant density may exploit the available water too quickly in the recovery process, thereby limiting recovery compared to a lower plant density where plants are able to exploit water for longer. The results suggest that better recovery from damage is likely to be achieved by planting at close to the optimum of 10 plants m<sup>2</sup> in irrigated cotton, while if the cotton is solid planted it is better to plant at a lower density.

### (3) Effect of tip damage on yield and maturity

Two experiments (1998-90 and 1999-00) investigated the effects of different numbers of events of heavy damage (simulating the effects of tip worm or mirids) or light tip damage (simulating the effects of mirids or *Helicoverpa* spp.). Light tip damage was repeated weekly three, five or seven times beginning from node two; heavy damage was inflicted one, three or five times beginning at node two. 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 7 treatments in total, including the undamaged control. These two experiments were replicates of the same experimental design and hence were analysed together.

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 experiment 5 or at 2.7, 5.9, 9.5, 11.2, 11.3, 14.9 and 15.2 nodes in experiment 6. Boll number did not differ significantly between experiments ( $F = 0.33$ ;  $df = 1, 3$ ;  $P = 0.6$ ) or treatments ( $F = 0.53$ ;  $df = 6, 36$ ;  $P = 0.78$ ) averaging  $91.8 \pm 2.1$  bolls m<sup>-1</sup> (mean  $\pm$  SE) at maturity.

Boll weight differed significantly between experiments (experiment 5, 1.86 g; experiment 6, 2.05 g) ( $F = 13.3$ ;  $df = 1, 3$ ;  $P = 0.035$ ) and between treatments ( $F = 3.5$ ;  $df = 3, 36$ ;  $P = 0.008$ ). Light damage 7 times or heavy damage 3 or 5 times reduced boll weight (Table 1). Yield did not differ between experiments ( $F = 2.44$ ;  $df = 1, 3$ ;  $P = 0.21$ ) but differed between treatments ( $F = 3.2$ ;  $df = 3, 36$ ;  $P = 0.012$ ). Light damage 7 times or heavy damage 5 times significantly reduced yield (Table 1).

Maturity date (DAS) differed significantly between experiments (experiment 5, 176.7 g; experiment 6, 188.6 d;  $F = 739.8$ ;  $df = 1, 3$ ;  $P < 0.001$ ) and between treatments ( $F = 23.6$ ;  $df = 3, 36$ ;  $P < 0.001$ ). Lighter damage treatments, light damage 3 times or heavy damage once caused minor delays of 2 to 5 d. Intermediate damage, light damage 5 times or heavy damage 3 times caused longer delays of 8 to 9 d, while the heavier damage treatments, light damage 7 times or heavy damage 5 times caused substantial delays of 13 to 14 d (Table 1).

**Table 1.** Number of bolls, boll weight, yield and maturity of treatments in combined experiments 1998-90 and 1999-00.

Damage type	No. of tip damage events	Boll wgt (g)	Yield (g/m)	Crop maturity	
				60% open bolls (DAS)	Difference from control (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	

\* = significantly different from control at  $p = 0.05$

Our results show that cotton is able to compensate well for repeated tip damage events up to a point. Cotton tolerated up to 7 light tip damage events without affecting yield and up to 3 without affecting maturity. Lower amounts of heavy tip damage could be tolerated, e.g. 3 events did not reduce yield and 1 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 4 or 6 true leaves or at first-square did not reduce yield and caused delays of 1-4 days. 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 promote production of vegetative branches, which in turn produce fruiting branches. 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 in press). The delay in re-establishment 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 the plants growth is delayed sufficiently to push the fruit maturation period into less favourable growing conditions at the end of the season or because the plants capacity to develop a full canopy is curtailed, thereby reducing light interception and the plants assimilate supply and hence yield potential. Intraspecific variation in cotton responses to tip damage has been identified that also needs to be considered, as the recovery of some varieties is faster following tip damage than others (Sadras and Fitt, 1997).

*(4) Relationships between damage and crop maturity or yield – statistical models.*

Six experiments were done over five cotton-growing seasons (experiment 1, 1994-95;

experiment 2 and 3, 1996-97; experiment 4, 1997-98; experiment 5, 1999-2000 and experiment 6, 2000-2001) to allow for different damage combinations and for differences between seasons. The outcomes of these experiments were reported in the final report for CSP74C. 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 experiment was 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 inflicted ( $D_D$ , 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 exertion of leaves) removed, assuming that in the terminal there are 4 phyllochrons, two visible and two embryonic, ( $T_S$ , none = 0; light = 4 phyllochrons; heavy = 6 phyllochrons).

Our expectation was that effects on yield or maturity would be due to the interaction between the severity of the damage and its duration or repetition. Hence we calculated interaction terms for defoliation ( $D_R D_D$ ) and tip damage ( $T_E T_S$ ). These were regressed against the delay in maturity (d) of each treatment compared with the control for each experiment and the crop yield, expressed as the % reduction in yield compared with the control i.e. (treatment yield x 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, i. e.  $D_R D_D + T_E T_S$ , and  $D_R D_D \times T_E T_S$ . 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;

$$\text{Days Delay} = 0.45T_E T_S + 1.198e^{-6}D_R^{3.14}D_D + \text{Experiment} \quad r^2 = 0.85, \text{ Equation 1}$$

Where; Experiment 1 = -2.56, Experiment 2 = 1.82, Experiment 3 = 5.36, Experiment 4 = -2.48, Experiment 5 = -0.94 and Experiment 6 = 1.46. The interaction term  $D_R D_D \times T_E T_S$  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;

$$\text{Days Delay} = 0.48T_E T_S + 1.3e^{-6}D_R^{3.14}D_D \quad r^2 = 0.66, \text{ Equation 2}$$

Crop yield was less well explained ;

$$\% \text{ yield reduction} = -0.63T_E T_S + -1.67e^{-7}D_R^{3.47}D_D + \text{Experiment} \quad r^2 = 0.46, \text{ Equation 3}$$

Where; Experiment 1 = 7.26, Experiment 2 = 0.78, Experiment 3 = -4.22, Experiment 4 = 2.76, Experiment 5 = 4.78 and Experiment 6 = 3.47. The interaction term  $D_R D_D \times T_E T_S$  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;

$$\% \text{ yield reduction} = -0.41T_E T_S + -1.41e^{-7}D_R^{3.47}D_D \quad r^2 = 0.31, \text{ Equation 4}$$

Simple sensitivity analyses were done using Equations 2 and 4 to help derive potential thresholds for management of defoliation or tip damage (Tables 2 & 3). As an indication of a link between damage and commercial practice we assumed that delay was significant if it was longer than 5 days, which is the level that normally begins to cause concern for cotton

growers. We assumed yield loss was significant if it was greater than 4%. This was based on a grower wanting to do more than cover the cost of control, ie double his money, assuming that the crop is valued at \$2,800 per ha (7 bales, 227 kg per bale, \$400 per bale) and control costs of \$50/ha (\$40 insecticide + \$10 application), hence a yield loss of about 2% is required just to re-coup control costs. Both crop yield and maturity are relatively insensitive to defoliation, due largely to the 'power' nature of their response to the proportion of leaf area removed. Defoliation up to 70% continuing as late as 6 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 were caused a delay of more than 5 days 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 2 and 3).

The values shown in Tables 2 and 3 can serve as tentative thresholds for plant damage that can be used in conjunction with pest abundance thresholds to allow better decisions. As an example, modified threshold for thrips and *Helicoverpa* in Australia now incorporate assessment of both pest abundance and plant damage and emphasise that both must be over threshold before pest control is justified (Deutscher and Wilson, 1999; Mensah and Wilson, 1999). In the future the information obtained in experiment 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.