

**COTTON RESEARCH AND DEVELOPMENT CORPORATION**

# **FINAL REPORT**

**"Insecticide resistance in field-collected cotton aphid."**

**DAN 117C**

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## PLAIN ENGLISH SUMMARY

Cotton aphid, is an important late season pest in Australian cotton. It can be specifically targeted for control, or is sometimes coincidentally controlled by organophosphate sprays directed at other pests. Cotton aphid is usually controlled with cheap organophosphate insecticides such as dimethoate, and recently Pirimor® and Pegasus® were additionally registered for its control. Overseas studies have found cotton aphid to be resistant to many insecticides which have lead to complete control failures.

During the 1998-99 Australian cotton season, transgenic Ingard® cotton accounted for about 20% of the cotton area giving an overall reduction in insecticide use. Typically there were reductions of about 50% in insecticide use on Ingard® cotton in the first half of the season. This gave an overall reduction in selection pressure for resistance but created an environment where aphid populations could build to high levels earlier in the season. If cotton aphid is then specifically targeted for control, insecticide resistance may develop and honey dew contamination of the cotton lint could result. Up until the 1998-99 cotton season, control failures against cotton aphid in Australia have not been shown to be due to resistance, even though pyrethroid and endosulfan resistance have now been detected. This study aims to document the level and abundance of pyrethroid and endosulfan resistance in field-collected cotton aphid. It additionally aims to screen a number of strains for carbamate and organophosphate resistance to ascertain why there continues to be reported failures to those chemicals.

This study found organophosphate and Pirimor® resistance to be generally absent from NSW strains of cotton aphid. Conversely, NSW cotton aphid were often endosulfan and pyrethroid resistant. In contrast to NSW, organophosphate and Pirimor® resistance was common in WA,

NT and Qld, and often at a high or extreme levels. Extreme levels of resistance in cotton aphid was also detected in crops other than cotton, such as melons and cucumbers. In all states surveyed there were instances of Pirimor® resistance in cotton aphid exceeding >1,500x. Some of these high level resistances have been directly linked to field-control failures of Pirimor®, a first for Australian cotton. Clearly, resistance in cotton aphid has the potential to seriously impact the Australian cotton industry. Resistance management of cotton aphid should now be an industry priority and should be implemented in time for the 1999-00 cotton season.

There should be systematic monitoring of field-collected strains of cotton aphid to aid effective resistance management. Indicative organophosphates, Pirimor® and the novel chemicals Pegasus® and Confidor® should be included into any monitoring program. Monitoring data would be used to verify, and where considered necessary modify, a resistance management strategy for cotton aphid. It is also desirable to investigate alternative chemistries and underlying resistance mechanisms for cotton aphid control. Finally, it would be useful to ascertain, what influence if any, resistant cotton aphids from horticulture, may have on cotton.

**Addendum to plain English summary: abstract-** In an earlier study we established base-line data to detect resistance in *Aphis. gossypii* Glover and used that data to detect endosulfan and pyrethroid resistance. This study expands upon that discovery and aims to survey for endosulfan and pyrethroid resistance in *A. gossypii* Australia-wide. It additionally aimed to monitor for pirimicarb and organophosphate resistance, which unusually was not detected in the earlier study. Organophosphate and pirimicarb resistance was detected and there was a general dichotomy of response between NSW and other than NSW (WA, Qld and NT). *A. gossypii* from NSW was almost organophosphate and pirimicarb resistance free, conversely, NSW strains were often endosulfan and pyrethroid resistant. Organophosphate and pirimicarb

resistant *A. gossypii* was abundant in WA, NT and Qld and at high to extreme levels. Pirimicarb resistance levels against *A. gossypii* were >1,500x in all states and were linked to field-control failures for the first time. Resistant *A. gossypii* have the potential to seriously impact the Australian cotton industry and is elaborated upon in the discussion. Resistance management of *A. gossypii* should now be an industry priority.

## BACKGROUND

Cotton aphid *Aphis gossypii* Glover is a worldwide pest of many plant species including cotton (Blackman & Eastop 1984). It is the main aphid pest of cotton throughout the world causing significant problems in Thailand, the Sudan, USSR and the USA, due to honeydew contamination of the open boll lint (Schepers 1989). *A. gossypii*, is an important late season pest in Australian cotton, and can be specifically targeted for control, or sometimes coincidentally controlled by organophosphate sprays directed at other pests, especially *Helicovera* spp.. *A. gossypii* is usually controlled with cheap organophosphate insecticides such as dimethoate, or in an IPM system with the more expensive carbamate pirimicarb (Harris & Shaw 1998). Recently, the thiourea diafenthiuron was registered for control of *A. gossypii* (Harris & Shaw 1998), which may be useful for alternation with the former compounds.

Overseas studies have found *A. gossypii* to be resistant to insecticides in all the major insecticide groups. In Hawaii, where *A. gossypii* is a major pest of cucurbits, resistance levels to the organophosphate insecticide oxydemeton-methyl were >2,000x (Hollingsworth *et al.* 1994). Kerns and Gaylor (1992) found organophosphate and pyrethroid resistance in *A. gossypii* from cotton fields in Texas and Alabama, while O'Brien *et al.* (1992) found carbamate and organochlorine resistance in cotton aphid from Mississippi. Tang (1992) found

1,000x resistance to deltamethrin in *A. gossypii* from China. Recently, Chinese researchers documented high levels of resistance to several compounds against *A. gossypii* (Guilin *et al.* 1997) which could lead to complete control failure.

Transgenic cotton accounted for about 20% of the cotton area in the 1998-99 season giving an overall reduction in insecticide use in the transgenic (Ingard®) variety. Reductions in insecticide use were achieved by the Ingard® cotton expressing the Cry IAc gene for *Bacillus thuringiensis* (*Bt*) subsp. *kurstaki* delta endotoxin for *Helicoverpa* spp. control (Fitt 1998).

Typically there are reductions of about 50% in insecticide use on transgenic cotton. Most reductions are in the first half of the season, when the transgenic cotton is most efficacious against *Helicoverpa* spp.. Reductions in insecticide use on transgenic cotton may allow aphid populations to build to high levels earlier in the transgenic cotton. This is especially expected where growers favour the sprayed refuge option (for every 100 ha of Ingard® cotton there must be in close proximity 100 ha of conventionally managed cotton, for *Helicoverpa* spp.) (Wilson 1996). Additionally, spray drift from the sprayed refuge option may kill beneficials but not resistant species (L. Wilson pers. com.). Secondary pests, such as *A. gossypii*, which were once suppressed by early season sprays of endosulfan for *Helicoverpa* spp., may increase in number. If *A. gossypii* is targeted specifically for control insecticide resistance may develop and honey dew contamination of the cotton lint could result.

In Australia, *A. gossypii* control failures have not been shown to be due to resistance, even though pyrethroid and endosulfan resistance have now been detected in Australian cotton aphid (Herron *et al.* 1999). However, the detection of resistance in cotton aphid was based on a small number of strains and so the abundance of resistance and the resistance range within field collected populations is not known. Carbamate and organophosphate resistance still have not been detected (Herron *et al.* 1999). This study will document the level and abundance of

pyrethroid and endosulfan resistance in field-collected cotton aphid. It will additionally screen a large number of strains for carbamate and organophosphate resistance to ascertain why there continues to be reported failures to those chemicals.

## OBJECTIVES

The project aims are:

- Construction of additional cages to isolate field-collected strains of *A. gossypii*.
- Establishment of additional base-line data.
- Generation of monitoring data against endosulfan bifenthrin, esfenvalerate, deltamethrin, pirimicarb, dimethoate and profenofos for field-collected strains of *A. gossypii* using a discriminating-dose technique
- To conduct full log-dose assays on strains that do not show 100% mortality at the discriminating-dose to give resistance levels.

## MATERIALS & METHODS

### Insecticides

Products tested, their supplier, common name, chemical group, formulation and active ingredient concentration are given in Table 1.

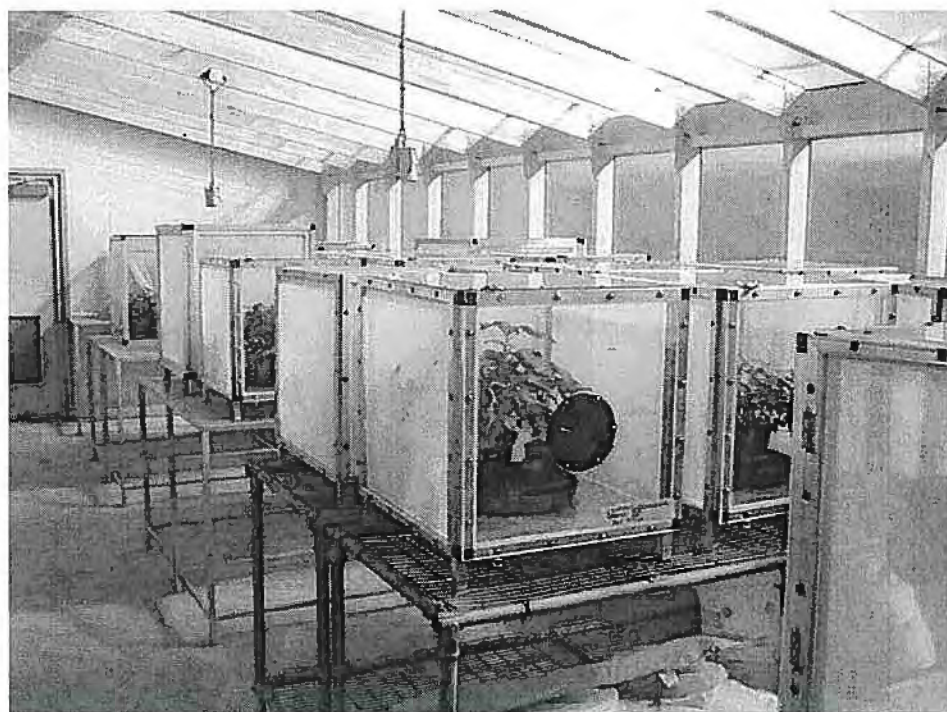
### Aphids

Strains of cotton aphid were collected Australia-wide and sent by overnight courier for processing. Aphids were tested at the Biological and Chemical Research Institute (pre May

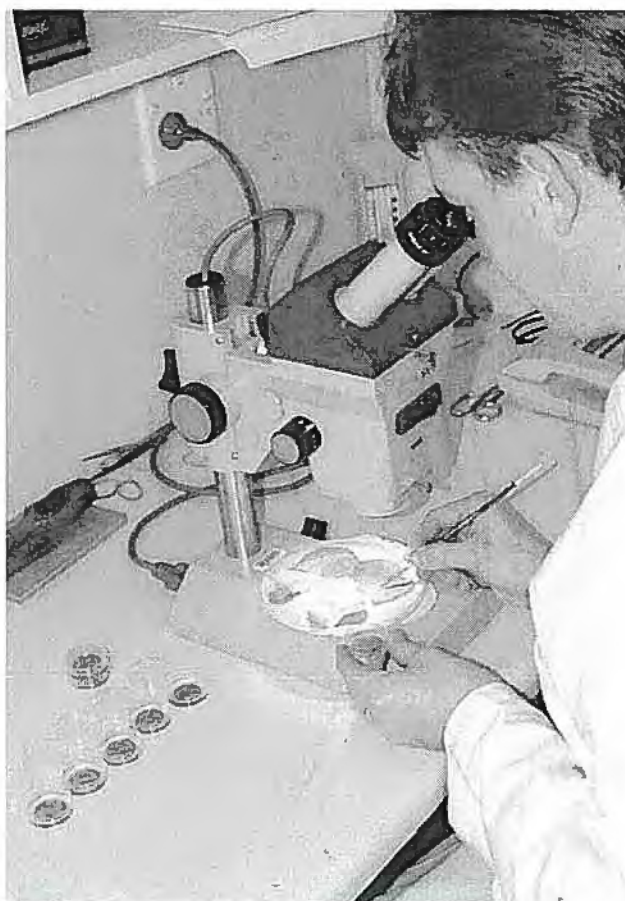
1998) or the Elizabeth Macarthur Agricultural Institute (post May 1998). Aphids were cultured on pesticide-free cotton, variety 'Deltapine 90', at  $25 \pm 4$  °C in a mass culture facility under natural light. Strain integrity was assured by maintaining populations in purpose built aphid proof cages constructed as part of the study (Plate 1). Strains Adelaide Garden, Jabiru Garden and Kununurra Town were collected from domestic backyards. The remaining cotton aphid populations were collected from cotton or intensive horticulture in close proximity to cotton.

### **Bioassay method**

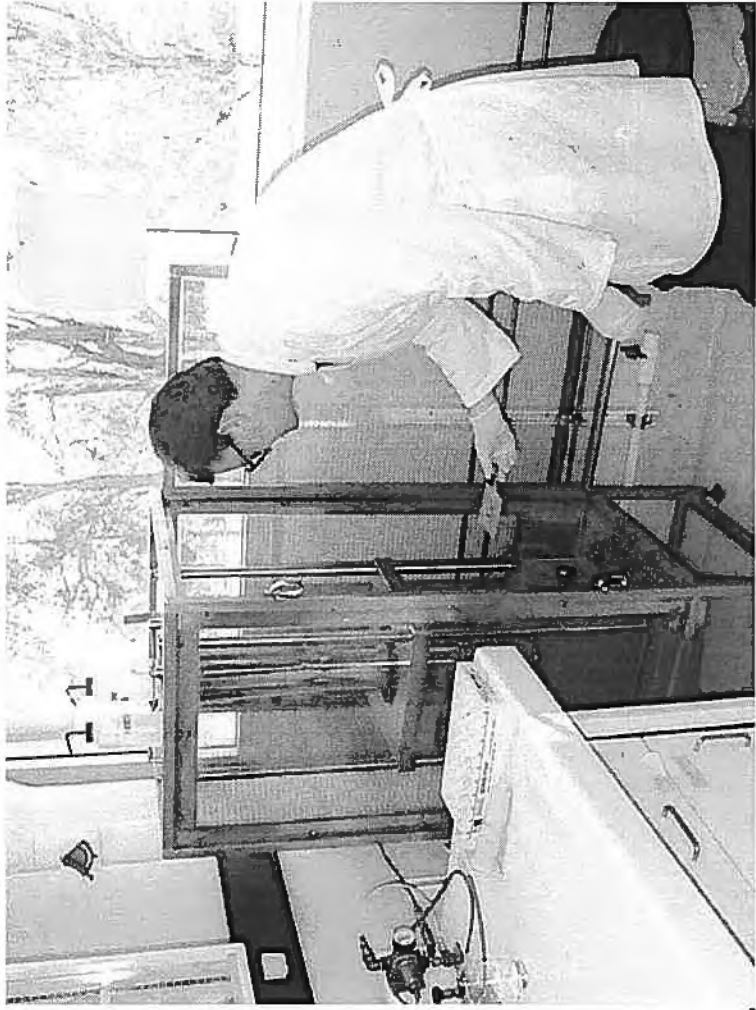
The method of testing *A. gossypii* is as described in Herron *et al.* (1999). Briefly, the method utilised 35 mm Petri dishes into which an excised cotton plant leaf disc was placed onto 3 mL of liquid cooling agar. When the agar had cooled and set, batches (batch = ca. 20 aphids) of adults were transferred onto the leaf discs (Plate 2) and sprayed with the aid of a Potter spray tower producing an aqueous deposit of  $1.6 \pm 0.07$  mg cm<sup>-2</sup> with a 2 mL aliquot (Plate 3). Five batches of aphids were exposed to a single discriminating concentration of 7 chemicals. The discriminating concentration was the LC99.9 value for susceptible strain A which had been designated as the 'type' susceptible (Herron 1999). Strains with survivors at the discriminating-dose were further tested against a range (3-5) of concentrations (log-dose probit assays). Each log-dose probit assay was replicated a minimum of four times and included a water only sprayed control. After spraying, Petri dishes were covered with clear plastic film (Plate 4) and perforated with a fine needle to prevent condensation. Tests were maintained at  $25 \pm 0.1$  °C in constant light for 24 h until mortality was assessed.



*Plate 1. Aphid proof cages constructed to maintain strain integrity within a mass-culture insectary.*



*Plate 2. Transferring *Aphis gossypii* with the aid of a microscope to agar embedded leaf discs.*



*Plate 3. Spraying aphids with the aid of a Potter spray tower.*



*Plate 4. Covering sprayed aphids with clear plastic wrap.*

## Analysis

Mortality at the discriminating concentration was corrected for control mortality (Abbott 1925) which did not exceed 10%. Probit regressions were computed on an IBM compatible PC using Probit 5 for Windows (Gillespie 1995). Probit regressions were calculated and LC50 and LC99.9 values estimated. Resistance factors were calculated by dividing the LC50 (99.9) of the field collected strain by LC50 (99.9) of laboratory susceptible strain A.

## RESULTS

There was little difference in the level of response between the three back yard collected strains, except for Kununurra Garden against omethoate, bifenthrin, endosulfan and profenofos (Table 3). Profenofos resistance was moderate to low ( $\leq 6.3x$  LC50 level) and restricted to aphid strains collected from Qld, WA and the NT only (Table 4). Similarly, omethoate resistance was not detected in NSW and restricted to aphid strains collected from Qld, WA and the NT only (Table 5). Omethoate resistance levels were up to a high 56x at the LC50 level. There was only one instance of low level pirimicarb resistance detected in NSW (1.8x at LC50)(Table 6). In contrast, extreme level pirimicarb resistance (up to 4,909x at LC50) was evident in Qld, WA and the NT. Endosulfan resistance was low to moderate ( $\leq 8.2x$  at LC50) and generally restricted to NSW only (Table 7). Deltamethrin resistance was again generally restricted to NSW only with resistance levels being moderate to high (up to 19x. at LC50) (Table 8). Unlike endosulfan and deltamethrin resistance, bifenthrin resistance was found in NSW, Qld and WA and resistance levels were high (up to 48x at LC50)(Table 9). Esfenvalerate resistance was detected in all states and resistance levels were moderate to high (up to 27x at LC50)(Table 10).

## DISCUSSION

For profenofos, omethoate, pirimicarb, endosulfan and deltamethrin there is a general dichotomy of response between strains collected from NSW and other than NSW. We think it likely these differences relate to overall insecticide use. We consider supporting evidence is apparent in the response of strains Kununurra 1 and Kununurra 2 to omethoate. Strain Kununurra 2 received at least two additional field applications of dimethoate compared to Kununurra 1. Resistance at the LC50 level consequently increased from 0.8x to 19x after the additional pesticide applications. We suggest that the ubiquitous distribution of bifenthrin resistance in *A. gossypii* indicates a general overuse of the product for *A. gossypii* control in Australia.

There is an anomaly evident between the discriminating-dose data and log-dose probability data in strain Myall Vale against pyrethroids (Tables 8, 9 and 10). This was likely due to the relatively long delay between finishing the discriminating-dose testing and commencing the log-dose probability assays. Records indicate discriminating-dose testing was completed during March 1999 but the log-dose probability assays were delayed until October 1999. The delay was due to the Insecticide Resistance Unit's relocation to EMAI from BCRI mid 1999. Such reversion is consistent with the findings of O'Brian *et al.* (1992), who found a significant loss of endosulfan and bifenthrin resistance following seven months laboratory culture without insecticide exposure. In contrast, O'Brian *et al.* (1992) found organophosphate resistance to be stable for up to eight months, a result also reflected in strain Myall Vale. The stability of organophosphate and pirimicarb resistance in *A. gossypii* is likely to limit the success of resistance management based on chemical alternation, because in the absence of immigration, alternation strategies rely upon fitness costs associated with resistance (Tabashnik 1990).

The high level organophosphate and pirimicarb resistance detected in this study (Tables 5 and 6) is consistent with overseas findings. Overseas studies have identified organophosphates generally, and pirimicarb specifically, as developing high level resistance in *A. gossypii* (Moore *et al.* 1996, Delorme *et al.* 1997). Those studies identified insensitive acetylcholinesterase (AChE) as the major mode of action for resistance with little detoxification evident. Interestingly, low level pyrethroid resistance in cotton aphid is caused by detoxification but high level resistance is also thought due to a target site insensitivity (Han *et al.* 1995).

This is the first time that resistance in *A. gossypii* from Australian cotton has been linked directly with field-control failures. Chemical failures were reported in all Emerald strains, and strain Rankine could only be controlled with the newly registered product diafenthiuron. Interestingly, pirimicarb failure associated with strain Walter happened despite there being no resistance evident at the LC50 level (Table 6). However, the strain was clearly heterogeneous as there was a 67x resistance detected at the LC99.9 level, indicating a small number of highly resistant aphids. This finding has important ramifications for pirimicarb use in cotton, as even a low proportion of resistant aphids could lead to a control failure. Consequently, pirimicarb should not be used if resistance is suspected.

If the major underlying mechanism is insensitive AChE then both organophosphate and carbamate insecticides are at risk, a point supported by our data (Tables 4, 5 and 6). Consecutive sprays of organophosphates or pirimicarb for *A. gossypii* control should be avoided and the number of sprays per season restricted. Results suggest that profenofos would be a good first organophosphate choice to use against cotton aphid because resistance is

currently low in all areas (Table 4), however field control failures with profenofos were reported in the Emerald region even though resistance was a low 4.8x. Pirimicarb can still be used in NSW but resistance has the potential to develop to an extreme level.

Pyrethroids are currently not recommended for control of Australian *A. gossypii* in cotton, however, high level pyrethroid resistance has been detected in this study. Cotton aphid probably endures high endosulfan and pyrethroid selection as there is high usage of these groups against the major cotton pest, *Helicoverpa* spp. Consequently, pyrethroids may not be a viable option for cotton aphid control if high-level organophosphate and carbamate resistance becomes more abundant. However, this study does show that pyrethroid resistance is unstable in Australian *A. gossypii*, and so may be responsive to resistance management. Yanchao *et al.* (1994) found that deltamethrin resistance in *A. gossypii* in China responded to resistance management with a 3-fold reduction in resistance levels in 3 years. Unfortunately, Yanchao *et al.* (1994) finally conclude deltamethrin use would need to be stopped for 3-5 years to regain useful efficacy, hardly a viable option for Australia.

A number of strains were collected from crops, other than cotton, such as melons and cucumbers (Table 2). These strains possessed a number of resistant aphids with strain Kununurra Melons resistant to all chemicals except for endosulfan. Interestingly, esfenvalerate and deltamethrin resistance was detected in Kununurra Melons and not in Kununurra Cotton (Tables 8 and 10). Consequently, if crops that support cotton aphid, such as cucumbers or melons, are grown in the vicinity of cotton, immigrant aphids may have a deleterious effect on the cotton. If resistance is selected in cotton aphid in the non-cotton crop, and the resistant aphids find their way into the cotton, the aphids could be further selected causing control failure

One aim of this study was to establish additional base-line data against *A. gossypii*. Three likely susceptible strains were collected from home gardens (Table 3) and evaluated against several chemicals. There was generally little difference in the level of response between the strains indicating susceptibility, except some responses for Kununurra Garden. Early testing results for Kununurra Garden against omethoate, bifenthrin, endosulfan and profenofos were compared against the theoretical discriminating dose derived from susceptible A. A small proportion of survivors at the discriminating-dose were evident against omethoate, bifenthrin, endosulfan and profenofos, indicating a low frequency of resistant *A. gossypii*. As the strain was not completely susceptible, testing was abandoned before all the log-dose probability assays were complete. In some instances, results for Kununurra Garden are not replicated so no errors have been given for the strain in Table 3.

## RECOMMENDATIONS

The study should be continued and:

- Monitor field-collected strains of *A. gossypii* for resistance against an indicative range of OPs, pirimicarb and the new chemicals diafenthiuron and imidacloprid.
- Implement a resistance management strategy for *A. gossypii* based on chemical alternation and restriction of chemical use.
- Investigate if OP and pirimicarb resistance in *A. gossypii* is persistent to ascertain if resistant individuals are likely to endure season to season

- Investigate alternative chemistries for *A. gossypii* control including cross-resistance testing.
- Investigate underlying resistance mechanisms involved in *A. gossypii* resistance in cooperation with Dr Robin Gunning and IACR Rothamsted.
- Continuously refine *A. gossypii* management in Australian cotton as new data becomes available.

### ACKNOWLEDGEMENTS

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- Herron, G. and Powis, K. (1998) Insecticide resistance in field-collected cotton aphid. pp. 453-459. *In*: Proceedings of the 9th Australian Cotton Conference, Hotel Conrad and Jupiters Casino, Broad Beach, Gold Coast, August 12-14, 1998

## OTHER COMMUNICATION OF RESULTS

- A series of grower talks in Central Queensland during December 1999, following the linking of resistance with field control failures in the Emerald region.
- Two presentations to the Transgenic and Insect Management Strategies (TIMS) committee updating them of resistance in cotton aphid. The first presentation giving an Australia-wide situation update and the second a resistance management strategy for cotton aphid.
- Giving expert advice at a sitting of the TIMS technical sub-committee to review resistant management in cotton. Revised strategies for inclusion into the 1999-2000 Cotton Pesticides Guide.

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**Table 1.** Supplier, trade name, common name, chemical group, formulation# and concentration for seven pesticides tested against cotton aphid.

Supplier	Trade Name	Common Name	Chemical Group	Form.	Conc.
Crop Care	Endosulfan	endosulfan	organochlorine	EC	350 g/L
Bayer	Folimat	omethoate	organophosphate	LC	800 g/L
Crop Care	Pirimor	pirimicarb	carbamate	WP	500 g/Kg
Novartis	Curacron	profenofos	organophosphate	EC	500 g/L
Crop Care	Talstar	bifenthrin	pyrethroid	EC	100 g/L
Cyanamid	Hallmark	esfenvalerate	pyrethroid	EC	50 g/L
AgrEvo	Decis Forte	deltamethrin	pyrethroid	EC	27.5 g/L

# EC=emulsifiable concentrate, LC=liquid concentrate and WP=wettable powder.

**Table 2.** Collection details of cotton aphid strains tested

Date	Collector	Strain	Source	Comments*
?	Neil Forrester	Narrabri Field	Cotton- NSW- Narrabri	not tested- killed by parasites
6/3/97	Neil Forrester	Adelaide Garden	Hibiscus-home garden-Adelaide	Possibly susceptible
17/3/97	Lewis Wilson	Bancary	Cotton-NSW Narrabri-	Possibly sprayed
17/3/97	Lewis Wilson	Ellengerah	Cotton- NSW- Macquarie Valley	1x bifenthrin, 1x profenofos
17/3/97	Lewis Wilson	Field 32 Auscott Ewenmar	Cotton- NSW- Myall Vale	not tested- killed by parasites
19/3/97	Neil Forrester	Narrabri Home Garden	Hibiscus- NSW- Narrabri	not tested- killed by parasites
2/4/97	Neil Forrester	Jabiru Garden	Hibiscus-N.T.	Possibly susceptible
2/4/97	Neil Forrester	Kununurra Town	Hibiscus-W.A.	Possibly susceptible
10/4/97	?	Maul's Creek	Cotton- NSW	not tested- killed by parasites
23/4/97	Neil Forrester	Waverly	Cotton-NSW- Burren Junction	Possibly sprayed
18/7/97	Ian Lacey	Kununurra 1	Cotton-W.A.-Res. Station	Possibly sprayed
12/8/97	Graham Young	Berrimah	Cucumbers-N.T.- Berrimah	
11/9/97	Ian Lacy	Kununurra 2	Cotton-W.A.-Res. Station	2x or 3x dimethoate
2/9/97	Robyn Gunning	Bowen	Cotton-Qld- Bowen	
16/9/97	Gary Fitt	Katherine	Cotton-N.T.-DPI Res. Station	
12/3/98	Neil Forrester	The Brae	Cotton-NSW- ACRI Narrabri	
12/3/98	Lewis Wilson	Auscott Warren Field 12	Cotton-NSW- Myall Vale	
17/3/98	Neil Forrester	Myall Vale	Cotton-NSW-Wee Waa	
23/3/98	Neil Forrester	Glenbar	Cotton-NSW- Gurley	
26/3/98	Neil Forrester	Nevada	Cotton-NSW- Mallaley	
29/7/98	Ian Lacey	Shamrock Gardens	Cotton-W.A.- Broome	
20/8/98	Brian Thistleton	Kununurra Cotton	Cotton-WA-Res. Institute	
20/8/98	Brian Thistleton	Kununurra Melon	Melon-W.A.- Kununurra	
4/9/98	Ian Lacy	Humpty Doo	Cucumber-N.T.- Humpty Doo	
29/9/98	Brian Thistleton	Cotton	Cotton-WA- Kununurra	Dead on arrival
29/9/98	Brian Thistleton	Melons Packsaddle	Melons-WA- Kununurra	Dead on arrival

Date	Collector	Strain	Source	Comments*
11/11/98	Brian Thistleton	Ord River Res. Station	Cotton-W.A.-Kununurra	
11/11/98	Brian Thistleton	Ord River Town	Cotton-W.A.-Kununurra	
1/12/98	Amanda Noone	Rankine	Cotton-Qld-Emerald	3x OP sprays, last omethoate
1/12/98	Amanda Noone	Walter	Cotton-Qld-Emerald	not sprayed
9/12/98	Richard Sequeira	Central Queensland	Cotton-Qld-Emerald	
10/3/99	Lewis Wilson	Wearmalong	Cotton-NSW-Gwyder Valley	
9/4/99	Neil Robertson	Darling Downs	Cotton-Qld-Dalby	ex Bonsai Bunchi Top
21/4/99	Dave Murray	Dalby	Cotton-Qld-Dalby	not tested- killed by parasites
22/4/99	Neil Forrester	Dalby Combined	Cotton-Qld-Dalby	not tested- killed by parasites
22/4/99	Geoff McIntyre	Bremners	Cotton-Qld-Dalby	not tested- killed by parasites
5/5/99	Matthew Watt	Warren	Cotton-NSW-Warren	Not cotton aphid-GPA

\*As supplied with aphid sample.

**Table 3.** Base-line data summary for the chemicals profenofos, omethoate, pirimicarb, endosulfan, deltamethrin, bifenthrin and esfenvalerate against strains Adelaide Garden, Jabiru Garden, Kununurra Garden and reference Susceptible A\*

chemical	Strain	$\chi^2$	d.f.	Slope ( $\pm$ s.e) <sup>+</sup>	LC50 % ai w/v (95% F.L) <sup>+</sup>	RF#
profenofos	Susc. A	3.9	2	3.9 (0.64)	0.00036 (0.00050-0.00027)	-
	Adelaide. Gar.	10.6	4	2.7 (0.38)	0.00036 (0.00045-0.00029)	1.0x
	Jabiru Gar.	24.7	3	3.0 (0.83)	0.00039 (0.00052-0.00030)	1.1x
	Kununurra. Gar.	13.8	2	2.7	0.00058	1.6x
omethoate	Susc. A	0.5	3	2.5 (0.13)	0.000070 (0.000094-0.000052)	-
	Adelaide. Gar.	21.9	4	2.5 (0.54)	0.00017 (0.00021-0.00013)	2.4x
	Jabiru Gar.	9.0	4	2.6 (0.36)	0.00011 (0.00014-0.000088)	1.6x
	Kununurra. Gar.	17.2	3	2.3	0.00022	3.1x
pirimicarb	Susc. A	5.6	2	3.4	0.00011 (0.00016-0.000083)	-
	Adelaide. Gar.	0.3	3	3.7 (0.11)	0.00014 (0.00017-0.00012)	1.3x
	Jabiru Gar.	1.2	3	3.4 (0.19)	0.00016 (0.00019-0.00013)	1.4x
	Kununurra. Gar.	3.3	3	2.0	0.00016	1.4x
endosulfan	Susc. A	0.8	2	4.0 (0.29)	0.0025 (0.0033-0.0019)	-
	Adelaide. Gar.	5.6	3	3.7 (0.50)	0.0058 (0.0072-0.0048)	2.3x
	Jabiru Gar.	2.1	3	4.4 (0.36)	0.0038 (0.0046-0.0031)	1.2x
	Kununurra. Gar.	0.4	1	1.9	0.0086	3.4x
deltamethrin	Susc. A	2.4	2	2.9 (0.40)	0.000024 (0.000034-0.000016)	-
	Adelaide. Gar.	12.1	4	2.3 (0.42)	0.000037 (0.000047-0.000029)	1.5x
	Jabiru Gar.	9.7	4	2.7 (0.32)	0.000021 (0.000025-0.000017)	0.9x
	Kununurra. Gar.	1.9	2	4.4	0.000034	1.4x
bifenthrin	Susc. A	0.5	1	4.0 (0.43)	0.0000089 (0.000026-0.0000031)	-
	Adelaide. Gar.	10.1	4	2.5 (0.40)	0.000017 (0.000022-0.000014)	1.9x
	Jabiru Gar.	6.1	3	3.1 (0.44)	0.000024 (0.000030-0.000019)	2.7x
	Kununurra. Gar.	0.7	1	1.8	0.000045	5.0x

chemical	Strain	$\chi^2$	d.f.	Slope ( $\pm$ s.e) <sup>+</sup>	LC50 % ai w/v (95% F.L) <sup>+</sup>	RF#
esfenvalerate	Susc. A	1.2	2	2.6 (0.26)	0.000012 (0.000018-0.000082)	-
	Adelaide. Gar.	7.5	3	2.8 (0.49)	0.000025 (0.000032-0.000020)	2.1x
	Jabiru Gar.	2.6	4	3.1 (0.21)	0.000018 (0.000022-0.000015)	1.6x
	Kununurra. Gar.	0.07	1	3.2	0.000026	1.0x

\*Laboratory reference susceptible strain of cotton aphid#LC50 of susceptible A  $\div$  LC50 field-collected strain

+no errors given for Kununurra Garden, refer to discussion

**Table 4.** Discriminating dose and resistance factors for field-collected strains of cotton aphid collected Australia-wide and tested against profenofos.

State	Strain	% M* at DD	Dose-Response Summary			
			LC50 % ai	RF#	LC99.9 % ai	RF#
N.S.W.	Bancary	100	-	-	-	-
	Ellengerah	100	-	-	-	-
	Ex-Moree	100	-	-	-	-
	Waverly	100	-	-	-	-
	The Brae	100	-	-	-	-
	A W Field 12	100	-	-	-	-
	Myall Vale	100	-	-	-	-
	Glenbar	100	-	-	-	-
	Nevada	100	-	-	-	-
	Wearmalong	100	-	-	-	-
QLD	Bowen	99	0.00034	0.9x	0.0021	1.0x
	Rankine	22	ab	ab	ab	ab
	Walter	90	0.00038	1.1x	0.003	1.4x
	Central Qld	48	0.0017	4.8x	0.04	18x
	Darling Downs	99	cr	cr	cr	cr
W.A.	Kununurra 1	92	0.00033	0.9x	0.0094	4.3x
	Kununurra 2	nt	0.00095	2.6x	0.011	5.0x
	Shamrock garden	100	-	-	-	-
	Kun. Cotton	14	0.0011	3.0x	0.38	17x
	Kun. Melon	3.7	ab	ab	ab	ab
	Ord River Res. Stat	29	0.0023	6.3x	0.021	10x
	Ord R. Town	100	-	-	-	-
N.T.	Berrimah	72	0.00027	0.8x	0.0034	1.6x
	Katherine	67	0.0017	4.7x	0.0062	2.8x
	Humpty Doo	22	0.0018	5.0x	0.0091	4.1x

% M at DD = Percent mortality at the discriminating dose

#RF = Resistance Factor,  $LC50(99.9) \text{ susceptible A} \div LC50(99.9) \text{ field-collected strain}$

nt = not tested, assumed resistant

- = not tested, discriminating-dose indicated no resistance

ab = testing abandoned, strain wiped out by parasites or disease

cr = log dose testing abandoned to allow time for cross-resistance testing

**Table 5.** Discriminating dose and resistance factors for field-collected strains of cotton aphid collected Australia-wide and tested against omethoate.

State	Strain	% M* at DD	Dose-Response Summary			
			LC50 % ai	RF#	LC99.9 % ai	RF#
N.S.W.	Bancary	100	-	-	-	-
	Ellengerah	100	-	-	-	-
	Ex-Moree	100	-	-	-	-
	Waverly	100	-	-	-	-
	The Brae	100	-	-	-	-
	A W Field 12	100	-	-	-	-
	Myall Vale	100	-	-	-	-
	Glenbar	100	-	-	-	-
	Nevada	100	-	-	-	-
	Wearmalong	100	-	-	-	-
QLD	Bowen	73	0.00012	1.7x	0.025	23x
	Rankine	0	ab	ab	ab	ab
	Walter	98	0.000086	1.2x	0.0027	2.5x
	Central Qld	0	0.0036	51x	0.1	92x
	Darling Downs	100	-	-	-	-
W.A.	Kununurra 1	89	0.000091	0.8x	0.046	42x
	Kununurra 2	nt	0.0014	19x	0.031	28x
	Shamrock garden	100	-	-	-	-
	Kun. Cotton	45	0.0011	16x	0.09	81x
	Kun. Melon	17	ab	ab	ab	ab
	Ord River Res. Stat	23	0.0032	46x	0.016	14x
	Ord R. Town	100	-	-	-	-
N.T.	Berrimah	71	0.000076	1.1x	0.041	37x
	Katherine	1	0.003	42x	0.045	42x
	Humpty Doo	1	0.0039	56x	0.074	67x

% M at DD = Percent mortality at the discriminating dose

#RF = Resistance Factor,  $LC50(99.9) \text{ susceptible A} \div LC50(99.9) \text{ field-collected strain}$

nt = not tested, assumed resistant

- = not tested, discriminating-dose indicated no resistance

ab = testing abandoned, strain wiped out by parasites or disease

**Table 6.** Discriminating dose and resistance factors for field-collected strains of cotton aphid collected Australia-wide and tested against pirimicarb.

State	Strain	% M* at DD	Dose-Response Summary			
			LC50 % ai	RF#	LC99.9 % ai	RF#
N.S.W.	Bancary	100	-	-	-	-
	Ellengerah	100	-	-	-	-
	Ex-Moree	100	-	-	-	-
	Waverly	100	-	-	-	-
	The Brae	100	-	-	-	-
	A W Field 12	100	-	-	-	-
	Myall Vale	100	-	-	-	-
	Glenbar	90	0.00020	1.8x	0.0038	4.2x
	Nevada	100	-	-	-	-
	Wearmalong	100	-	-	-	-
QLD	Bowen	82	0.00013	1.2x	3.7	4,066x
	Rankine	1	ab	ab	ab	ab
	Walter	96	0.00011	1.0x	0.061	67x
	Central Qld	3	0.19	1,727x	18.24	20,044x
	Darling Downs	99	cr	cr	cr	cr
W.A.	Kununurra 1	81	0.000026	0.2x	13.51	14,846x
	Kununurra 2	nt	0.071	646x	2.12	2,330x
	Shamrock garden	100	-	-	-	-
	Kun. Cotton	33	0.049	445x	76.5	84,066x
	Kun. Melon	0	ab	ab	ab	ab
	Ord River Res. Stat	6	0.54	4,909x	19.87	21,835x
	Ord R. Town	100	-	-	-	-
N.T.	Berrimah	56	0.000043	0.4x	1.75	1,868x
	Katherine	1	0.19	1,736x	4.07	4,471x
	Humpty Doo	0	0.44	4,016x	17.88	19,648x

% M at DD = Percent mortality at the discriminating dose

#RF = Resistance Factor,  $LC50(99.9) \text{ susceptible A} \div LC50(99.9) \text{ field-collected strain}$

nt = not tested, assumed resistant

- = not tested, discriminating-dose indicated no resistance

ab = testing abandoned, strain wiped out by parasites or disease

cr = log dose testing abandoned to allow time for cross-resistance testing

**Table 7.** Discriminating dose and resistance factors for field-collected strains of cotton aphid collected Australia-wide and tested against endosulfan

State	Strain	% M* at DD	Dose-Response Summary			
			LC50 % ai	RF#	LC99.9 % ai	RF#
N.S.W.	Bancary	98	0.0048	1.4x	0.11	3.1x
	Ellengerah	100	-	-	-	-
	Ex-Moree	100	-	-	-	-
	Waverly	100	-	-	-	-
	The Brae	66	0.0046	1.4x	0.19x	5.3x
	A W Field 12	66	0.0027	8.2x	0.25	6.9x
	Myall Vale	92	0.005	1.5x	0.025	0.7x
	Glenbar	96	0.013	4.1x	0.18	4.9x
	Nevada	84	0.0058	1.7x	0.17	4.7x
	Wearmalong	96	cr	cr	cr	cr
QLD	Bowen	100	-	-	-	-
	Rankine	100	-	-	-	-
	Walter	100	-	-	-	-
	Central Qld	99	0.004	1.2x	0.038	1.1x
	Darling Downs	100	-	-	-	-
W.A.	Kununurra 1	100	-	-	-	-
	Kununurra 2	100	-	-	-	-
	Shamrock garden	100	-	-	-	-
	Kun. Cotton	100	-	-	-	-
	Kun. Melon	100	-	-	-	-
	Ord River Res. Stat	100	-	-	-	-
	Ord R. Town	100	-	-	-	-
N.T.	Berrimah	100	-	-	-	-
	Katherine	100	-	-	-	-
	Humpty Doo	100	-	-	-	-

% M at DD = Percent mortality at the discriminating dose

#RF = Resistance Factor,  $LC50(99.9) \text{ susceptible A} \div LC50(99.9) \text{ field-collected strain}$

nt = not tested, assumed resistant

- = not tested, discriminating-dose indicated no resistance

ab = testing abandoned, strain wiped out by parasites or disease

cr = log dose testing abandoned to allow time for cross-resistance testing

**Table 8.** Discriminating dose and resistance factors for field-collected strains of cotton aphid collected Australia-wide and tested against deltamethrin.

State	Strain	% M* at DD	Dose-Response Summary			
			LC50 % ai	RF#	LC99.9 % ai	RF#
N.S.W.	Bancary	98	0.000034	1.4x	0.0022	8.5x
	Ellengerah	100	-	-	-	-
	Ex-Moree	100	-	-	-	-
	Waverly	100	-	-	-	-
	The Brae	16	0.00046	19x	0.0078	30x
	A W Field 12	21	0.00036	14x	0.0066	25x
	Myall Vale	15+	0.00003	1.3x	0.0002	0.8x
	Glenbar	27	0.00046	19x	0.0075	29x
	Nevada	22	0.00027	11x	0.0058	22x
	Wearmalong	10	cr	cr	cr	cr
QLD	Bowen	100	-	-	-	-
	Rankine	100	-	-	-	-
	Walter	100	-	-	-	-
	Central Qld	100	-	-	-	-
	Darling Downs	100	-	-	-	-
W.A.	Kununurra 1	100	-	-	-	-
	Kununurra 2	100	-	-	-	-
	Shamrock garden	100	-	-	-	-
	Kun. Cotton	100	-	-	-	-
	Kun. Melon	92	ab	ab	ab	ab
	Ord River Res. Stat	100	-	-	-	-
	Ord R. Town	100	-	-	-	-
N.T.	Berrimah	100	-	-	-	-
	Katherine	100	-	-	-	-
	Humpty Doo	100	-	-	-	-

+apparent reversion: anomaly between discriminating dose and log dose data

% M at DD = Percent mortality at the discriminating dose

#RF = Resistance Factor,  $LC50(99.9) \text{ susceptible A} \div LC50(99.9) \text{ field-collected strain}$

nt = not tested, assumed resistant

- = not tested, discriminating-dose indicated no resistance

ab = testing abandoned, strain wiped out by parasites or disease

cr = log dose testing abandoned to allow time for cross-resistance testing

**Table 9.** Discriminating dose and resistance factors for field-collected strains of cotton aphid collected Australia-wide and tested against bifenthrin.

State	Strain	% M* at DD	Dose-Response Summary			
			LC50 % ai	RF#	LC99.9 % ai	RF#
N.S.W.	Bancary	84	0.00002	2.2x	0.00022	4.2x
	Ellengerah	100	-	-	-	-
	Ex-Moree	100	-	-	-	-
	Waverly	100	-	-	-	-
	The Brae	7	0.00036	40x	0.0025	48x
	A W Field 12	6	0.00031	35x	0.0023	44x
	Myall Vale	31+	0.000011	1.2x	0.00012	2.3x
	Glenbar	0	0.00028	31x	0.0022	41x
	Nevada	12	0.00043	48x	0.0041	78x
	Wearmalong	2	cr	cr	cr	cr
QLD	Bowen	100	-	-	-	-
	Rankine	100	-	-	-	-
	Walter	100	-	-	-	-
	Central Qld	91	0.000012	1.3x	0.00018	3.4x
	Darling Downs	100	-	-	-	-
W.A.	Kununurra 1	100	-	-	-	-
	Kununurra 2	100	-	-	-	-
	Shamrock garden	76	0.000022	2.5x	0.00029	5.5x
	Kun. Cotton	56	0.000024	2.7x	0.00044	8.3x
	Kun. Melon	68	ab	ab	ab	ab
	Ord River Res. Stat	93	0.000014	1.6x	0.000098	1.8x
	Ord R. Town	100	-	-	-	-
N.T.	Berrimah	100	-	-	-	-
	Katherine	100	-	-	-	-
	Humpty Doo	100	-	-	-	-

+apparent reversion: anomaly between discriminating dose and log dose data

% M at DD = Percent mortality at the discriminating dose

#RF = Resistance Factor,  $LC50(99.9) \text{ susceptible A} \div LC50(99.9) \text{ field-collected strain}$

nt = not tested, assumed resistant

- = not tested, discriminating-dose indicated no resistance

ab = testing abandoned, strain wiped out by parasites or disease

cr = log dose testing abandoned to allow time for cross-resistance testing

**Table 10.** Discriminating dose and resistance factors for field-collected strains of cotton aphid collected Australia-wide and tested against esfenvalerate.

State	Strain	% M* at DD	Dose-Response Summary			
			LC50 % ai	RF#	LC99.9 % ai	RF#
N.S.W.	Bancary	95	0.000049	4.1x	0.0012	6.7x
	Ellengerah	100	-	-	-	-
	Ex-Moree	100	-	-	-	-
	Waverly	100	-	-	-	-
	The Brae	0	0.00032	27x	0.0035	19x
	A W Field 12	23	0.00024	20	0.0027	15x
	Myall Vale	8+	0.00004	3.3x	0.00035	1.9x
	Glenbar	16	0.00025	21x	0.0011	6x
	Nevada	17	0.00027	22x	0.007	39x
	Wearmalong	47	cr	cr	cr	cr
QLD	Bowen	100	-	-	-	-
	Rankine	98	ab	ab	ab	ab
	Walter	100	-	-	-	-
	Central Qld	95	0.000026	2.2x	0.0012	6.9x
	Darling Downs	98	cr	cr	cr	cr
W.A.	Kununurra 1	100	-	-	-	-
	Kununurra 2	100	-	-	-	-
	Shamrock garden	100	-	-	-	-
	Kun. Cotton	100	-	-	-	-
	Kun. Melon	90	ab	ab	ab	ab
	Ord River Res. Stat	100	-	-	-	-
	Ord R. Town	100	-	-	-	-
N.T.	Berrimah	100	-	-	-	-
	Katherine	100	-	-	-	-
	Humpty Doo	95	0.000056	4.6x	0.00073	4.1x

+apparent reversion: anomaly between discriminating dose and log dose data

% M at DD = Percent mortality at the discriminating dose

#RF = Resistance Factor,  $LC50(99.9) \text{ susceptible A} \div LC50(99.9) \text{ field-collected strain}$

nt = not tested, assumed resistant

- = not tested, discriminating-dose indicated no resistance

ab = testing abandoned, strain wiped out by parasites or disease

cr = log dose testing abandoned to allow time for cross-resistance testing