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Carbamate and organophosphate resistance in cotton pests in India, 1995 to 1999

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Abstract

Monitoring for organophosphate and carbamate resistance was carried out on five major insect pests of cotton collected from 22 cotton-growing districts across India. Resistance was monitored in *Helicoverpa armigera* (Hübner) and *Pectinophora gossypiella* (Saunders) for the period 1995–1999 and for *Spodoptera litura* (Fabricius), *Earias vittella* (Fabricius) and *Bemisia tabaci* (Gennadius) in a survey conducted during the 1997–98 cropping season. Of the 53 field strains of *H. armigera*, only four were found to exhibit resistance to quinalphos, the highest 15-fold, whereas all 16 field strains tested were found to be resistant to monocrotophos. Similarly, out of 40 field strains tested, only eight were found to express appreciable resistance to methomyl. Resistance in *P. gossypiella* to quinalphos was high in the majority of the strains tested. Of the seven strains of *E. vittella* tested, two strains from northern India exhibited > 70-fold resistance to monocrotophos. Of the 11 *S. litura* strains tested, only four were found to exhibit resistance factors of 10 to 30-fold to quinalphos and monocrotophos. All of the *B. tabaci* field strains exhibited resistance to methomyl and monocrotophos and susceptibility to triazophos. Practical implications for pest control resulting from the observed patterns of cross-resistance between quinalphos, monocrotophos and methomyl are discussed.

Introduction

Cotton occupies only 5% of the total cultivable area in India but consumes more than 55% of the total insecticides used in the country (Puri, 1995). Until the introduction of synthetic pyrethroids in 1982, compounds belonging to the organophosphate and carbamate groups were amongst the most widely used insecticides on cotton in India. With reports of widespread resistance to the pyrethroids accumulating consistently over the past decade, there has been a renewed interest in the use of insecticides other than pyrethroids for cotton pest management. Resistance to insecticides belonging to organophosphate and carbamate groups has been reported in the cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) and the leaf worm, *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) in India (Armes *et al.*, 1996, 1997). Less information is available on insecticide resistance in other major cotton pests such as the pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), the spotted bollworm, *Earias vittella* (Fabricius) (Lepidoptera: Noctuidae) and the whitefly, *Bemisia tabaci* (Gennadius)

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(Hemiptera: Aleyrodidae). Organophosphate and carbamate insecticides have been in use on cotton in India for the past 40 years. Much of the efficacy and sustainability of these groups of insecticides in cotton pest management will depend on the susceptibility of the major target pests.

Organophosphate insecticides represent 70% of the Indian arable insecticide market (Anon., 1997). Monocrotophos and quinalphos are two of the most widely used organophosphate insecticides in India, that together constitute 75% of the total organophosphate insecticide usage in the country. Interestingly, of the total, nearly 85% of quinalphos and 68% of monocrotophos are used solely on cotton in India (Anon., 1997). Of the carbamates, methomyl is the most widely used insecticide. Hence methomyl, monocrotophos and quinalphos were chosen as representative molecules to monitor resistance to carbamate and organophosphate insecticides in cotton pests in India. This study reports the results of a survey conducted during 1995–1999 to monitor insecticide resistance of major pests of cotton in India with a view to examining the occurrence and implications of cross resistance and future potential for carbamate and organophosphate use on cotton in the country.

Materials and methods

Insects

Larvae of *H. armigera, S. litura, P. gossypiella, E. vittella* and pupae of *B. tabaci* were collected in cotton fields from different cotton growing regions in India during the cropping seasons of 1995–1999. The lepidopterous larvae were reared on wheatgerm-based semi-synthetic diets, individually, in 7.5 ml cells of 12-well LINBRO® tissue culture plates. Larvae of *H. armigera* and *S. litura* were reared on diet described by Armes *et al.* (1992a) and larvae of *P. gossypiella* and *E. vittella* on diets according to Barlett & Wolf (1985) and Paul *et al.* (1987) respectively. Laboratory cultures of the lepidopterous species were established for each population from 150–200 moths. An insecticide susceptible strain of *H. armigera* was kindly provided by Dr Alan McCaffery, the University of Reading, UK. The susceptible strain, originally collected in southern Africa had been maintained at Reading for at least 15 years. Field populations of *B. tabaci* were maintained separately in cages on 3–4-week-old cotton plants. Some field populations of *H. armigera, S. litura, P. gossypiella* and *E. vittella* collected from traditionally unsprayed regions of Nagpur and Wardha exhibited low levels of resistance to almost all the groups of insecticides tested. These were established in the laboratory on semi-synthetic diet and insecticide bioassays were conducted repeatedly for the first few generations to assess consistency in susceptibility response. Data from three to four assays were pooled together and subjected to probit analysis using POLO-PC (Anon., 1987). The LD_{50}s thus obtained were used as checks for susceptibility of the field collected strains. The strains were maintained for at least seven to eight generations at the Central Institute for Cotton Research, Nagpur.

Survey areas

Cotton insect pests were collected from 22 districts of seven cotton growing states (Punjab, Haryana, Rajasthan, Maharashtra, Andhra Pradesh, Tamilnadu and Karnataka) in India (fig. 1). Together, the seven states account for about 80% of the total cotton growing area and 70% of the insecticides used in the country (Puri, 1995).

North zone

Insects were collected from cotton fields in the Dabwali and Sirsa districts of Haryana, Bhatinda district of Punjab and Sriganagnagar district of Rajasthan to start cultures. Most of the cotton crop in these districts is grown under intensive inputs and irrigated conditions. In the regions surveyed, an average of 8 to 17 applications of insecticides on cotton are common, with monocrotophos and fenvalerate the most popular (Kranthi *et al.*, in press). While the three bollworms occur simultaneously as early to mid season pests, peak whitefly infestations occur during mid season of the crop.

Central zone

Insects were collected in the Nagpur, Wardha, Amaravati, Akola, Parbhani, Yavatmal, Buldana and Nanded districts of Maharashtra. In the regions surveyed, 2 to 20 applications of insecticides are common on cotton, with a preference for endosulfan, monocrotophos, chlorpyriphos and cypermethrin (Kranthi *et al.*, in press). *Helicoverpa armigera* is the key pest in the region and in outbreak years causes extensive damage to cotton, pigeonpea, chickpea, sunflower and tomato. *Pectinophora gossypiella* occurs as a late season pest and farmers rarely spray insecticides as the infestation goes unnoticed. *Bemisia tabaci* and *E. vittella* occur as early to mid season pests.

South zone

In Andhra Pradesh, the collections were made from the Warangal, Medak, Karimnagar, Khammam, Guntur, Prakasam, Rangareddy and Mahbubnagar districts. The survey areas also included the Dharwad district of Karnataka and Coimbatore of Tamilnadu. In the regions surveyed, 8 to 30 applications were common on cotton, with preference for monocrotophos, cypermethrin, quinalphos, chlorpyiphos and methomyl (Kranthi *et al.*, in press). *Helicoverpa armigera* and *B. tabaci* are major pests of the region and occur during the reproductive phase of the crop. *Spodoptera litura* occurs late in the season and causes economic damage sporadically.

Insecticides used

The following technical grade insecticides were used for bioassays on lepidopterous insects: methomyl (98%; DuPont, France); monocrotophos (73% w/w; Khatau Junker Ltd, India) and quinalphos (72% w/w: Sandoz, India). The following formulated insecticides were used for bioassays on *B. tabaci*: triazophos (Hostathion 400 g/l EC, Agrevo, India), methomyl (Lannate 125 g/l L, DuPont, India) and monocrotophos (Monocil 360 g/l SL, DeNOCIL, India).

Log dose probit assays

Larvae from F_1 generation of the field strains were used for bioassays using a topical application procedure described previously (Kranthi *et al.*, 1997) as recommended

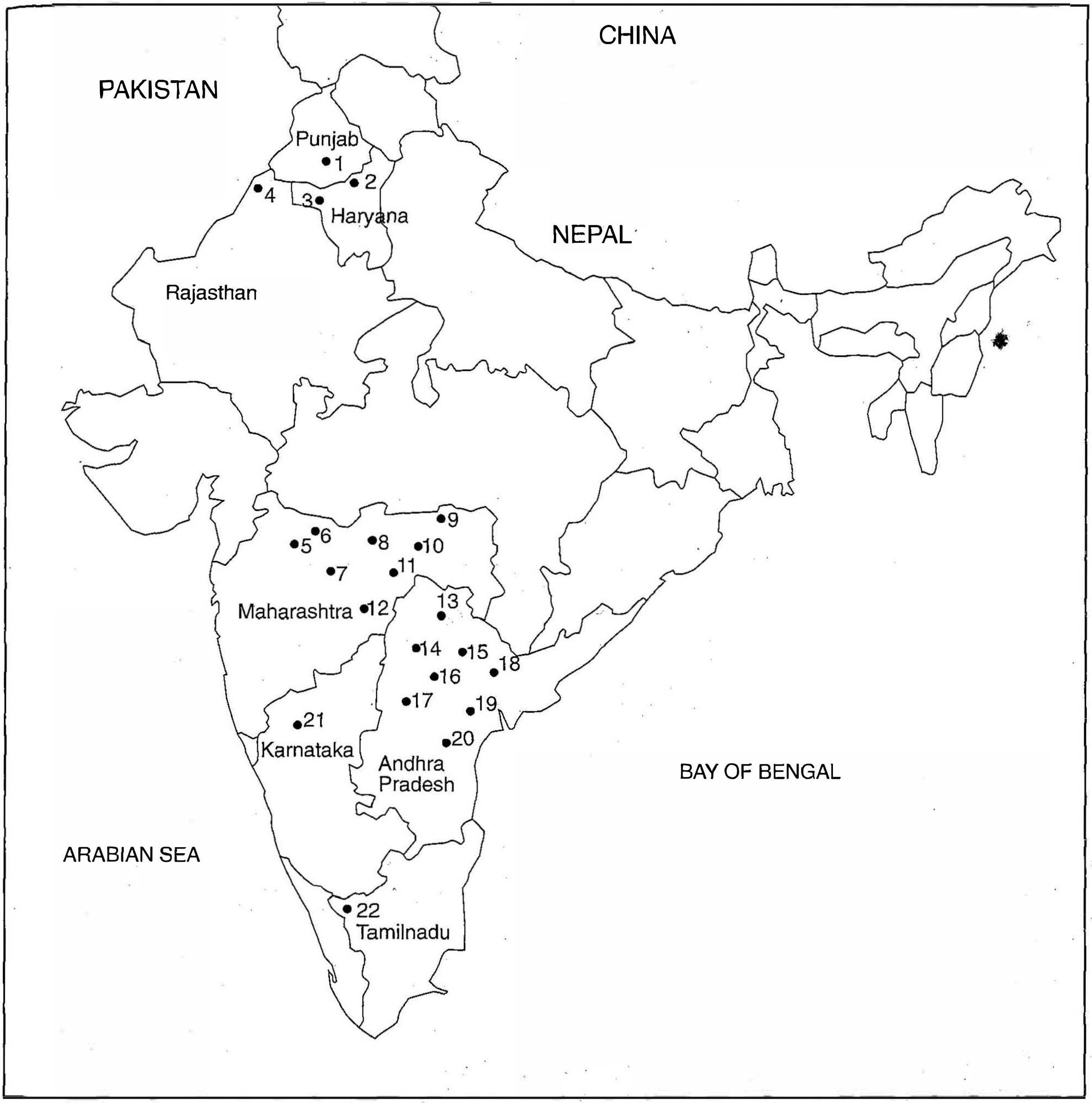

Fig. 1. Sampling sites in India. 1, Bhatinda; 2, Dabwali; 3, Sirsa; 4, Sriganganagar; 5, Buldana; 6, Akola; 7, Parbhani; 8, Amaravati; 9, Nagpur; 10, Wardha; 11, Yavatmal; 12, Nanded; 13, Karimnagar; 14, Rangareddy; 15, Warangal; 16, Medak; 17, Mahbubnagar; 18, Khammam; 19, Guntur; 20, Prakasam; 21, Dharwad; 22, Coimbatore.

by the Entomological Society of America (Anon., 1970). Third instar larvae of *H. armigera, S. litura,* and fourth instar larvae of *P. gossypiella* and *E. vittella* were used for bioassays. Technical grade insecticides were dissolved in acetone and 1.0 μl was applied using a Hamilton syringe dispenser, to the thoracic dorsum of at least 12 larvae at each of five or more concentrations in three replicates plus controls. Larvae were held individually in 12-well tissue culture plates containing semi-synthetic diet, at 25 ± 2°C and mortality assessments were made over six days according to Armes *et al.* (1996) based on the numbers of moribund and dead larvae.

Bioassays with whiteflies were based on the adult leaf-dip assays used by Cahill *et al.* (1995). Cotton (hybrid Ankur 651) was grown in the glasshouse. Leaf discs of 38 mm diameter were punched out from 2-week-old plants and immersed in serial dilutions (0.1, 1, 2, 4, 8, 16, 32, 64, 100 and 1000 ppm) over a range of five to six concentrations in three replicates. The leaf discs were air dried and then placed adaxial side down on a bed of agar gel (1.3%) in a plastic

Petri dish (39 mm diameter × 5 mm high). Control leaves were dipped in diluent only. *Bemisia tabaci* adult females were sorted out under a binocular microscope from a group of whiteflies (2–4 days old) briefly anaesthetized with carbon dioxide. Thirty whiteflies were released onto each leaf disc and each close fitting ventilated lid. As the whiteflies recovered from anaesthesia, the leaf punches were inverted so that the whiteflies orientated normally. Mortality was scored up to 72 h after treatment according to Cahill *et al.* (1996a).

All rearing and bioassay operations were carried out at 25 ± 2°C under a 12:12h light:dark regime. Data from the replicates were pooled and dose-mortality regressions were computed by probit analysis using POLO-PC (Anon., 1987). Corrections for control mortality, which never exceeded 2%, were made using Abbott's formula (Abbott, 1925). Resistance factors (RF) were calculated as LD_{50} of the field strain / LD_{50} of the susceptible strain. Correlation coefficients for pairwise comparison of log LD_{50}s were calculated according to Snedecor & Cochran (1989).

Results

Resistance in H. armigera

The lowest LD_{50} values for methomyl, quinalphos and monocrotophos were obtained on the Reading susceptible strain (table 1). The LD_{50} of methomyl against the susceptible 'Reading strain' was 0.13 µg per larva with a slope of 1.8. Of 40 field strains tested, only eight were found to express resistance to methomyl, the highest being 22-fold against a strain from Prakasam district (table 1). The results indicated that resistance appeared to be increasing over the past two to three years in most of the strains tested, as, prior to February 1998, resistance to methomyl was detected only in a single strain from the Guntur district.

All of the *H. armigera* reference susceptible strains exhibited low LD_{50} values to quinalphos ranging from 0.08 to 0.17 µg per larva, with steep slopes of 3.26 to 3.67. The field strains exhibited LD_{50} values within a range of 0.09 to 1.5 µg per larva with slopes of 1.1 to 3.7. In general, resistance across the country was low, with the highest levels of 10 to 15-fold observed in strains collected from the districts of Yavatmal, Prakasam and Guntur in south India. By contrast, the strains from Guntur exhibited appreciable resistance to quinalphos (i.e. > 8-fold) over a period of four years.

Resistance to monocrotophos ranged from 8 to 65-fold in the field strains tested. Highest resistance factors of 39 to 65-fold were recorded in the strains from Sirsa, Dabwali and Bhatinda in northern India. The slopes of the regression lines indicated heterogeneity in most strains with an uncharacteristically low slope of 1.4 even in the Reading susceptible strain.

Resistance in P. gossypiella

The Wardha strain from central India was found to be the most susceptible to quinalphos with an LD_{50} value of 0.38 µg per larva (table 2) and was used as the reference susceptible strain. The slopes of the regression lines obtained with quinalphos and monocrotophos against the Wardha strain were steep compared to all the other field strains. Though resistance factors to methomyl ranged between 4 to 24-fold, only two strains collected from Warangal and Medak in Andhra Pradesh could be categorized as resistant, due to non-overlapping of fiducial limits with the Wardha susceptible strain. Resistance to quinalphos was detected in almost all strains except those from Nagpur district in central India. Resistance factors were high at 118 to 380-fold in populations collected from Amaravati, Akola, Yavatmal, Warangal, Medak and Bhatinda districts. Resistance to monocrotophos was negligible with no evidence of resistance in strains from central India.

Resistance in E. vittella

The strain of *E. vittella* from Nagpur in central India was the most susceptible to quinalphos (table 3) and therefore used as the reference susceptible strain. Resistance to methomyl, quinalphos and monocrotophos was detected only in two strains collected from Sriganganagar and Sirsa in northern India. None of the strains collected from central India exhibited any noteworthy resistance to the three compounds. Resistance to monocrotophos was high at 72 and 111-fold in the strains from Sriganganagar and Sirsa, respectively.

Resistance in S. litura

The Bangalore susceptible strain exhibited steep dose-responses to all three insecticides, with slopes of 1.9 to 3.0 in probit assays (table 4). Resistance levels to methomyl, quinalphos and monocrotophos were low in the majority of the strains tested. The strain collected from Mahbubnagar in Andhra Pradesh exhibited the highest levels of resistance with factors ranging from 20 to 29-fold against the three insecticides.

Resistance in B. tabaci

In the absence of any baseline susceptibility data for methomyl and triazophos against *B. tabaci*, the field strains with the lowest LC_{50} were used as reference strain for assessing resistance to these compounds. Resistance levels exhibited by *B. tabaci* ranged from 15 to 80-fold to methomyl and 6 to 13-fold to monocrotophos (table 5). Interestingly, resistance to triazophos was un-detectable.

Pairwise correlations between log LD_{50}s of the insecticides

Correlation between the toxicity of quinalphos and methomyl was highly significant ($P < 0.01$) for *P. gossypiella* and *E. vittella* and significantly ($P < 0.05$) positive for all the lepidopterous species examined (table 6). The toxicity of monocrotophos and quinalphos was significantly ($P < 0.01$) correlated for *E. vittella* and *S. litura*, but was non-significant for *H. armigera* and *P. gossypiella*. Paired comparisons of the LD_{50}s for *E. vittella* showed a highly significant ($P < 0.01$) positive correlation between all three insecticides.

Discussion

Resistance to either methomyl, quinalphos and monocrotophos was detected in at least one region of India in all the species of cotton insect pests tested. Though it is

Table 1. Log dose probit response of field strains of *Helicoverpa armigera* to insecticides.

District	Collection date	Methomyl				Quinalphos				Monocrotophos			
		LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
Reading susceptible		0.13	0.04–0.47	1.8	–	0.08	0.04–0.12	3.3		0.65	0.50–0.85	1.4	
Nepal susceptible		–	–	–	–	0.12	0.07–0.2	3.7		–	–	–	–
Nagpur susceptible		–	–	–	–	0.17	0.15–0.2	3.4		–	–	–	–
Nagpur	Sep '95	–	–	–	–	0.22*	0.16–0.28	2.2	2	5.37*	3.7–8.17	1.0	8
	Jan '96	0.14	0.09–0.22	1.9	1	–	–	–	–	–	–	–	–
	Nov '96	–	–	–	–	0.40*	0.31–0.49	1.7	4	–	–	–	–
	Jan '97	–	–	–	–	0.26	0.11–0.50	2.5	2	–	–	–	–
	Oct '97	0.28	0.18–0.42	1.2	2	0.88*	0.66–1.24	1.6	9	–	–	–	–
	Feb '98	0.25	0.15–0.40	1.8	2	0.58*	0.43–0.76	1.4	6	7.26*	4.7–11.9	0.9	11
	Nov '98	0.23	0.13–0.38	0.8	1	–	–	–	–	–	–	–	–
	Dec '98	–	–	–	–	0.15	0.06–0.26	1.9	1	–	–	–	–
	Feb '99	0.20	0.15–0.27	1.7	1	0.26	0.08–0.58	2.5	2	–	–	–	–
Wardha	Oct '95	–	–	–	–	0.27*	0.19–0.34	1.9	3	–	–	–	–
	Oct '96	–	–	–	–	0.20*	0.14–0.27	1.9	2	–	–	–	–
	Jan '97	0.18	0.11–0.28	1.4	1	–	–	–	–	–	–	–	–
	Oct '97	0.21	0.09–0.45	1.8	1	0.24*	0.18–0.28	2.7	2	–	–	–	–
	Feb '98	0.14	0.09–0.25	1.7	1	0.09	0.05–0.15	2.1	1	–	–	–	–
	Nov '98	0.22	0.16–0.30	1.3	1	0.33*	0.18–0.66	2.2	3	–	–	–	–
Amaravati	Oct '97	0.29	0.19–0.43	1.5	2	0.48*	0.22–1.18	1.9	5	–	–	–	–
	Feb '98	0.19	0.11–0.34	1.1	1	0.42*	0.27–0.59	1.9	4	7.71*	4.9–12.9	0.8	12
	Jan '99	0.33	0.17–0.58	1.1	2	0.67*	0.47–1.12	1.7	7	–	–	–	–
Akola	Feb '98	1.87*	0.96–6.29	1.0	12	0.82*	0.50–1.21	2.9	8	12.6*	7.8–23.1	0.8	19
	Jan '99	0.51	0.37–0.74	2.3	4	0.42*	0.25–0.64	1.5	4	–	–	–	–
Parbhani	Feb '98	0.32	0.18–0.55	1.4	2	0.48*	0.42–0.58	2.7	5	–	–	–	–
	Oct '98	–	–	–	–	0.32*	0.14–0.56	2.9	3	–	–	–	–
	Jan '99	–	–	–	–	0.63*	0.48–0.84	1.7	6	–	–	–	–
Yavatmal	Oct '96	0.14	0.11–0.19	1.8	1	0.36*	0.26–0.44	1.8	3	–	–	–	–
	Nov '97	0.60	0.36–1.16	1.0	4	1.28*	0.91–2.14	1.4	13	–	–	–	–
	Feb '98	1.03*	0.64–1.74	1.6	7	0.59*	0.45–0.75	1.6	6	–	–	–	–
Buldana	Feb '98	0.46	0.29–0.71	1.1	3	0.41*	0.32–0.49	1.8	4	–	–	–	–
	Jan '99	–	–	–	–	0.42*	0.31–0.56	1.6	4	–	–	–	–
Nanded	Feb '98	0.50	0.24–1.19	1.8	4	0.22*	0.14–0.29	1.5	2	–	–	–	–
	Oct '98	–	–	–	–	0.32*	0.25–0.42	1.7	3	–	–	–	–
Warangal	Oct '97	0.60	0.32–1.18	1.1	4	0.25*	0.19–0.31	2.1	2	–	–	–	–
	Feb '98	0.33	0.18–0.76	1.2	2	0.50*	0.35–0.69	2.0	5	9.4*	5.3–14	1.4	14
	Nov '98	1.85*	1.33–2.70	1.2	14	0.27*	0.15–0.42	1.5	3	–	–	–	–
Medak	Feb '98	0.53	0.32–0.76	1.9	4	0.19*	0.12–0.31	1.2	2	15.7*	9.4–30.9	0.8	24
Karimnagar	Feb '98	0.40	0.02–1.2	1.1	3	0.50*	0.20–0.94	1.7	5	12.0*	7.8–17.9	1.3	18
Khammam	Feb '98	1.50*	0.7–2.6	1.1	11	0.40	0.02–0.73	2.0	4	12.0*	8.5–29.6	2.2	18
Guntur	Nov '95	0.17	0.09–0.27	1.2	1	0.77*	0.55–1.44	1.1	8	–	–	–	–
	Oct '97	1.27*	0.82–2.04	1.4	9	0.97*	0.81–1.19	3.7	10	8.3*	3.3–21.4	1.6	12
	Feb '98	1.20*	0.7–2.0	1.0	9	1.50*	1.20–2.05	2.7	15	–	–	–	–
	Oct '98	1.82*	1.12–4.40	1.4	14	0.87*	0.61–1.56	1.8	8	–	–	–	–
Prakasam	Feb '98	2.90*	0.60–6.8	1.5	22	1.30*	0.60–3.47	2.2	13	9.3*	6.8–12.5	2.6	14
Rangareddy	Nov '95	0.15	0.10–0.22	1.6	1	0.26*	0.18–0.32	1.9	2	7.81*	5.2–12.5	1.0	12
	Aug '96	–	–	–	–	0.19*	0.14–0.24	2.0	2	–	–	–	–
	Oct '97	–	–	–	–	0.50*	0.39–0.63	1.7	5	–	–	–	–
	Feb '98	0.55	0.21–1.31	1.2	4	0.41*	0.28–0.59	1.1	4	–	–	–	–
	Oct '98	–	–	–	–	0.57*	0.44–0.72	1.6	6	7.05*	4.8–10.9	1.0	11
	Jan '99	–	–	–	–	0.16	0.09–0.23	1.5	1	–	–	–	–
Mahbubnagar	Feb '98	2.09*	1.42–3.29	1.0	15	0.45*	0.35–0.55	1.9	4	–	–	–	–
Coimbatore	Oct '95	–	–	–	–	0.46*	0.36–0.55	1.8	4	–	–	–	–
	Nov '96	–	–	–	–	0.62*	0.50–0.76	1.7	6	–	–	–	–
	Nov '97	0.23	0.16–0.32	1.2	1	0.67*	0.56–0.78	2.5	6	–	–	–	–
	Mar '98	1.08*	0.78–1.53	1.2	7	0.52*	0.36–0.82	1.1	5	–	–	–	–
Dharwad	Jan '96	0.12	0.09–0.16	1.6	1	0.69*	0.51–1.06	1.3	7	16.6*	9.3–35.9	0.7	25
Bhatinda	Nov '98	1.87*	1.28–2.88	1.0	12	0.32*	0.22–0.42	2.7	3	42.5*	18.7–154	0.6	65
Dabwali	Nov '98	1.39*	0.99–1.99	1.2	10	0.38*	0.27–0.49	2.6	4	25.7*	13.1–68.7	0.6	39
Sirsa	Nov '98	0.25	0.18–0.33	1.6	2	0.42*	0.29–0.61	1.5	4	25.2*	13.6–62.5	0.7	39

* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed as μg per larva; FL, fiducial limits; RF, resistance factor.

Table 2. Log dose probit response of field strains of *Pectinophora gossypiella* to insecticides.

		Methomyl				Quinalphos				Monocrotophos			
District	Collection date	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
Wardha susceptible	Jan '97	15.2	7.6–47.6	0.8	–	0.38	0.27–0.50	2.7	–	2.54	2.1–3.01	1.5	–
Nagpur	Dec'96	16.5	8.6–50.0	0.9	1	0.63	0.42–0.89	1.5	1	–	–	–	–
	Dec '97	–	–		–	0.36	0.05–0.89	0.6	1	2.48	1.38–4.34	0.8	1
	Dec '98	68	21.7–902	0.7	4	0.52	0.33–0.76	1.4	1	2.94	1.65–6.89	1.0	1
Wardha	Dec '95	122	32–3130	0.7	8	–	–	–	–	1.80	0.84–3.46	1.3	1
	Oct '97	105	30–6650	0.7	7	–	–	–	–	3.05	1.75–5.41	0.9	1
	Feb '98	–	–		–	8.62*	4.0–47.3	0.8	21	–	–	–	–
Amaravati	Dec '97	–	–		–	153*	34–8090	0.6	382	4.08	2.64–7.11	0.9	1
	Feb '98	113	32–7510	0.7	8	100*	24–39000	0.9	250	3.02	1.68–6.46	1.3	1
Akola	Oct '97	101	29–2090	0.6	7	53.4*	25.7–399	1.3	140	4.00	2.16–8.15	0.7	1
	Feb '98	181	37–13800	0.6	12	61*	16–33100	0.9	152	3.97	2.74–6.25	1.1	1
Parbhani	Feb '98	–	–		–	0.96*	0.63–1.45	1.3	2	–	–	–	–
Yavatmal	Dec '96	169	42–33000	0.8	11	44.9*	20.5–312	1.0	118	2.67	1.55–4.58	0.9	1
	Feb '98	106	26–4070	0.5	7	–	–	–	–	–	–	–	–
Buldana	Feb '98	156	34–8470	0.6	10	16.2*	6.81–143	0.8	40	–	–	–	–
Nanded	Feb '98	44	20.8–279	0.9	3	1.89*	1.22–3.51	1.2	5	2.58	1.89–3.64	1.4	1
Warangal	Feb '98	358*	60–3640	0.8	24	77.1*	24–1650	0.9	192	5.45*	3.4–10.3	0.9	2
Medak	Feb '98	222*	82–2050	0.9	15	52.5*	19.8–535	0.9	131	5.51*	3.55–9.88	1.0	2
Bhatinda	Nov '98	225	25–61200	0.5	15	87.1*	25–1650	0.7	218	21.2*	9.35–89.2	0.7	8
Sirsa	Nov '98	–	–		–	–	–	–	–	10.4*	5.66–26.5	0.8	4

* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed as μg per larva; FL, fiducial limits; RF, resistance factor.

Table 3. Log dose probit response of field strains of *Earias vittella* to insecticides.

		Methomyl				Quinalphos				Monocrotophos			
District	Collection date	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
Nagpur susceptible	Feb '96	0.18	0.13–0.23	3.6	–	0.11	0.07–0.02	1.7	–	0.16	0.04–0.30	2.7	–
	Feb '98	–	–	–	–	0.14	0.10–0.20	1.1	1	–	–	–	–
Wardha	Dec '98	0.20	0.11–0.42	1.0	1	0.09	0.06–0.12	1.4	1	0.20	0.15–0.27	1.7	2
Parbhani	Feb '98	0.12	0.04–0.31	1.2	1	0.11	0.08–0.15	1.3	1	0.21*	0.44–0.64	0.9	2
Akola	Feb '98	0.35	0.13–1.34	1.2	2	0.14	0.11–0.19	1.3	1	0.31	0.11–1.11	1.1	2
Sriganganagar	Feb '98	1.41*	0.67–3.21	1.6	8	0.28*	0.20–0.40	1.1	2	11.6*	8.31–17.0	1.3	72
Sirsa	Feb '98	4.18*	1.61–242	1.3	23	0.45*	0.32–0.67	1.1	4	17.8*	9.52–47.3	1.5	111

* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed as μg per larva; FL, fiducial limits; RF, resistance factor.

Table 4. Log dose probit response of field strains of *Spodoptera litura* to insecticides.

		Methomyl				Quinalphos				Monocrotophos			
District	Collection date	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
Bangalore susceptible[a]		0.46	0.37–0.55	3.0	–	0.12	0.10–0.15	2.0	–	5.9	4.4–7.8	1.9	–
Nagpur	Dec'95	0.11	0.08–0.15	1.7	1	0.19	0.14–0.26	1.3	1	25.5*	14.3–57.6	0.8	4
	Feb '98	0.10	0.06–0.19	1.7	1	0.18	0.13–0.27	2.2	1	21.3*	10.4–32.0	1.3	8
Amaravati	Feb '98	0.24	0.17–0.32	1.5	1	0.33*	0.24–0.46	1.3	2	42.9*	21–125	0.7	7
Parbhani	–	–	–	–	–	–	–	–	–	26.8*	14.9–61.7	0.8	4
Yavatmal	Feb '98	0.33	0.23–0.47	1.1	1	0.54*	0.36–0.86	0.9	4	49.7*	23.8–154	0.7	8
Warangal	Feb '98	2.56*	1.64–4.78	1.1	6	1.80*	0.85–6.44	1.1	15	104*	39–539	0.6	17
Karimnagar	Feb '98	0.18	0.12–0.27	1.8	1	1.48*	1.12–2.26	2.1	12	75.3*	56.8–116	2.2	12
Mahbubnagar	Feb '98	9.0*	4.7–15.5	2.2	20	2.46*	1.78–4.85	2.4	20	176*	111–1180	1.8	29
Rangareddy	Feb '98	1.87*	0.96–3.60	1.1	4	0.69*	0.49–0.89	1.8	5	28.8*	21.3–38.7	1.9	4
Khammam	Nov '98	0.27	0.18–0.41	1.8	1	0.37*	0.27–0.47	2.5	3	41.4*	31.4–50.4	3.9	7
Bhatinda	Nov '98	0.53	0.32–0.89	1.4	1	1.11*	0.80–1.61	1.4	9	148*	50–1020	0.5	24

[a] Data of Bangalore susceptible strain from Armes *et al.* (1997).
* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed as μg per larva; FL, fiducial limits; RF, resistance factor.

Table 5. Log dose probit response of field strains of *Bemisia tabaci* to insecticides.

		Methomyl				Quinalphos				Monocrotophos			
District	Collection date	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
SUD susceptible[a]		–	–	–	–	–	–	–	–	14	9.8–18	2.6	–
Rangareddy	Feb '98	–	–	–	–	9.9	5.4–13	2.2	–	–	–	–	–
	Feb '98	–	–	–	–	28.3	7.6–569	0.5	3	–	–	–	–
	Feb '98	–	–	–	–	10.4	6.6–13	2.3	1	–	–	–	–
	Feb '98	–	–	–	–	24.6	6–17200	0.5	2	–	–	–	–
	Feb '98	–	–	–	–	17.0	5–1390	0.5	2	–	–	–	–
	Mar '98	–	–	–	–	8.2	4.8–10	3.8	1	189*	68–12900	0.7	13
	April '98	–	–	–	–	–	–	–	–	99*	81–117	3.8	7
	May '98	0.18	0.1–0.43	0.6	–	–	–	–	–	–	–	–	–
	June '98	10.3*	5.0–13.6	3.5	57	–	–	–	–	77*	52–102	1.8	6
	June '98	2.7*	1.3–5.0	0.8	15	–	–	–	–	–	–	–	–
	June '98	4.3*	2.6–6.25	1.1	24	–	–	–	–	–	–	–	–
	Oct '98	–	–	–	–	12.4	9.8–15	2.8	1	–	–	–	–
	Oct '98	–	–	–	–	11.5	5–82.5	0.6	1	–	–	–	–
Guntur	Oct '98	–	–	–	–	12.9	9.5–16	2.4	1	–	–	–	–
	Nov '98	14.4*	8.2–19.5	2.2	80	–	–	–	–	–	–	–	–
	Nov '98	12.5*	8.0–15.3	4.2	69	–	–	–	–	–	–	–	–
	Nov '98	10.7*	4.6–13.8	4.5	59	–	–	–	–	–	–	–	–
	Dec '98	–	–	–	–	11.2	8.1–14	2.3	1	–	–	–	–
	Dec '98	–	–	–	–	13.7	10.3–17	2.4	1	–	–	–	–
Mahbubnagar	Oct '98	–	–	–	–	12.9	8.7–17	3.1	1	–	–	–	–
	Dec '98	10.6*	4.3–13.6	4.4	24	–	–	–	–	–	–	–	–

[a] Data of SUD susceptible from Cahill *et al.* (1995).
* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed in ppm; FL, fiducial limits; RF, resistance factor.

not clear as to what level of laboratory measured resistance can cause field control failures, it is likely that the extent of difficulties in pest control will certainly be dictated by the severity of resistance. For example, even low levels of 10 to 20-fold resistance to methomyl or endosulfan have been considered to be sufficient to cause field control failures, as both compounds are inherently not very effective against *H. armigera* larvae (McCaffery *et al.*, 1989; Gunning *et al.*, 1992), whereas resistance factors of even up to 50-fold to cypermethrin have not caused perceptible field control difficulties (K.R. Kranthi, unpublished data). In India, monocrotophos, quinalphos and methomyl are the most widely used insecticides in cotton pest management apart from pyrethroids and endosulfan. Hence a measure of resistance in cotton insect pests to these molecules was not unexpected. Until the late 1980s, resistance to organophosphates was almost negligible, with highest resistance factors of 9-fold to quinalphos, and 3-fold to monocrotophos in *H. armigera* (McCaffery *et al.*, 1989; Armes *et al.*, 1992b). Later, Armes *et al.* (1996) reported the absence of resistance to monocrotophos, but observed resistance levels of up to 59-fold to quinalphos and > 30-fold to methomyl in *H. armigera* field strains in India. High levels of > 300-fold resistance to methomyl were also reported from China (Cheng & Liu, 1996). The results indicate that resistance to monocrotophos, which was earlier at undetectable levels, is now ubiquitous in India. Resistance to monocrotophos was particularly high in the northern states of India in Punjab (Bhatinda) and Haryana (Dabwali and Sirsa). This was not surprising, as the use of monocrotophos in cotton is extensive in northern India. Moreover, of the total monocrotophos used in the north, nearly 90% is allocated for cotton pest management (Anon., 1997). High levels of 200 and 720-fold resistance to monocrotophos in *H. armigera* were reported from China

Table 6. Pairwise correlation coefficient comparisons between log LD_{50}s of the insecticides.

Insect species	Insecticide	Methomyl	Monocrotophos
Helicoverpa armigera	Monocrotophos	0.427 [ns]	
	Quinalphos	0.369 [0.05]	0.442 [ns]
Pectinophora gossypiella	Monocrotophos	0.510 [ns]	
	Quinalphos	0.874 [0.01]	0.521 [ns]
Earias vittella	Monocrotophos	0.962 [0.01]	
	Quinalphos	0.976 [0.01]	0.969 [0.01]
Spodoptera litura	Monocrotophos	0.577 [ns]	
	Quinalphos	0.683 [0.05]	0.898 [0.01]

Superscripts indicate significance of the regression; ns, non-significant.

Table 2. Log dose probit response of field strains of *Pectinophora gossypiella* to insecticides.

		Methomyl				Quinalphos				Monocrotophos			
District	Collection date	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
Wardha susceptible	Jan '97	15.2	7.6–47.6	0.8	–	0.38	0.27–0.50	2.7	–	2.54	2.1–3.01	1.5	–
Nagpur	Dec'96	16.5	8.6–50.0	0.9	1	0.63	0.42–0.89	1.5	1	–	–	–	–
	Dec '97	–	–		–	0.36	0.05–0.89	0.6	1	2.48	1.38–4.34	0.8	1
	Dec '98	68	21.7–902	0.7	4	0.52	0.33–0.76	1.4	1	2.94	1.65–6.89	1.0	1
Wardha	Dec '95	122	32–3130	0.7	8	–	–	–	–	1.80	0.84–3.46	1.3	1
	Oct '97	105	30–6650	0.7	7	–	–	–	–	3.05	1.75–5.41	0.9	1
	Feb '98	–	–		–	8.62*	4.0–47.3	0.8	21	–	–	–	–
Amaravati	Dec '97	–	–		–	153*	34–8090	0.6	382	4.08	2.64–7.11	0.9	1
	Feb '98	113	32–7510	0.7	8	100*	24–39000	0.9	250	3.02	1.68–6.46	1.3	1
Akola	Oct '97	101	29–2090	0.6	7	53.4*	25.7–399	1.3	140	4.00	2.16–8.15	0.7	1
	Feb '98	181	37–13800	0.6	12	61*	16–33100	0.9	152	3.97	2.74–6.25	1.1	1
Parbhani	Feb '98	–	–		–	0.96*	0.63–1.45	1.3	2	–	–	–	–
Yavatmal	Dec '96	169	42–33000	0.8	11	44.9*	20.5–312	1.0	118	2.67	1.55–4.58	0.9	1
	Feb '98	106	26–4070	0.5	7	–	–	–	–	–	–	–	–
Buldana	Feb '98	156	34–8470	0.6	10	16.2*	6.81–143	0.8	40	–	–	–	–
Nanded	Feb '98	44	20.8–279	0.9	3	1.89*	1.22–3.51	1.2	5	2.58	1.89–3.64	1.4	1
Warangal	Feb '98	358*	60–3640	0.8	24	77.1*	24–1650	0.9	192	5.45*	3.4–10.3	0.9	2
Medak	Feb '98	222*	82–2050	0.9	15	52.5*	19.8–535	0.9	131	5.51*	3.55–9.88	1.0	2
Bhatinda	Nov '98	225	25–61200	0.5	15	87.1*	25–1650	0.7	218	21.2*	9.35–89.2	0.7	8
Sirsa	Nov '98	–	–		–	–	–	–	–	10.4*	5.66–26.5	0.8	4

* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed as μg per larva; FL, fiducial limits; RF, resistance factor.

Table 3. Log dose probit response of field strains of *Earias vittella* to insecticides.

		Methomyl				Quinalphos				Monocrotophos			
District	Collection date	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
Nagpur susceptible	Feb '96	0.18	0.13–0.23	3.6	–	0.11	0.07–0.02	1.7	–	0.16	0.04–0.30	2.7	–
	Feb '98	–	–	–	–	0.14	0.10–0.20	1.1	1	–	–	–	–
Wardha	Dec '98	0.20	0.11–0.42	1.0	1	0.09	0.06–0.12	1.4	1	0.20	0.15–0.27	1.7	2
Parbhani	Feb '98	0.12	0.04–0.31	1.2	1	0.11	0.08–0.15	1.3	1	0.21*	0.44–0.64	0.9	2
Akola	Feb '98	0.35	0.13–1.34	1.2	2	0.14	0.11–0.19	1.3	1	0.31	0.11–1.11	1.1	2
Sriganganagar	Feb '98	1.41*	0.67–3.21	1.6	8	0.28*	0.20–0.40	1.1	2	11.6*	8.31–17.0	1.3	72
Sirsa	Feb '98	4.18*	1.61–242	1.3	23	0.45*	0.32–0.67	1.1	4	17.8*	9.52–47.3	1.5	111

* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed as μg per larva; FL, fiducial limits; RF, resistance factor.

Table 4. Log dose probit response of field strains of *Spodoptera litura* to insecticides.

		Methomyl				Quinalphos				Monocrotophos			
District	Collection date	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
Bangalore susceptible[a]		0.46	0.37–0.55	3.0	–	0.12	0.10–0.15	2.0	–	5.9	4.4–7.8	1.9	–
Nagpur	Dec'95	0.11	0.08–0.15	1.7	1	0.19	0.14–0.26	1.3	1	25.5*	14.3–57.6	0.8	4
	Feb '98	0.10	0.06–0.19	1.7	1	0.18	0.13–0.27	2.2	1	21.3*	10.4–32.0	1.3	8
Amaravati	Feb '98	0.24	0.17–0.32	1.5	1	0.33*	0.24–0.46	1.3	2	42.9*	21–125	0.7	7
Parbhani	–	–	–	–	–	–	–	–	–	26.8*	14.9–61.7	0.8	4
Yavatmal	Feb '98	0.33	0.23–0.47	1.1	1	0.54*	0.36–0.86	0.9	4	49.7*	23.8–154	0.7	8
Warangal	Feb '98	2.56*	1.64–4.78	1.1	6	1.80*	0.85–6.44	1.1	15	104*	39–539	0.6	17
Karimnagar	Feb '98	0.18	0.12–0.27	1.8	1	1.48*	1.12–2.26	2.1	12	75.3*	56.8–116	2.2	12
Mahbubnagar	Feb '98	9.0*	4.7–15.5	2.2	20	2.46*	1.78–4.85	2.4	20	176*	111–1180	1.8	29
Rangareddy	Feb '98	1.87*	0.96–3.60	1.1	4	0.69*	0.49–0.89	1.8	5	28.8*	21.3–38.7	1.9	4
Khammam	Nov '98	0.27	0.18–0.41	1.8	1	0.37*	0.27–0.47	2.5	3	41.4*	31.4–50.4	3.9	7
Bhatinda	Nov '98	0.53	0.32–0.89	1.4	1	1.11*	0.80–1.61	1.4	9	148*	50–1020	0.5	24

[a] Data of Bangalore susceptible strain from Armes *et al.* (1997).
* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed as μg per larva; FL, fiducial limits; RF, resistance factor.

Table 5. Log dose probit response of field strains of *Bemisia tabaci* to insecticides.

District	Collection date	Methomyl				Quinalphos				Monocrotophos			
		LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF	LD_{50}	95% FL	Slope	RF
SUD susceptible[a]		–	–	–	–	–	–	–	–	14	9.8–18	2.6	–
Rangareddy	Feb '98	–	–	–	–	9.9	5.4–13	2.2	–	–	–	–	–
	Feb '98	–	–	–	–	28.3	7.6–569	0.5	3	–	–	–	–
	Feb '98	–	–	–	–	10.4	6.6–13	2.3	1	–	–	–	–
	Feb '98	–	–	–	–	24.6	6–17200	0.5	2	–	–	–	–
	Feb '98	–	–	–	–	17.0	5–1390	0.5	2	–	–	–	–
	Mar '98	–	–	–	–	8.2	4.8–10	3.8	1	189*	68–12900	0.7	13
	April '98	–	–	–	–	–	–	–	–	99*	81–117	3.8	7
	May '98	0.18	0.1–0.43	0.6	–	–	–	–	–	–	–	–	–
	June '98	10.3*	5.0–13.6	3.5	57	–	–	–	–	77*	52–102	1.8	6
	June '98	2.7*	1.3–5.0	0.8	15	–	–	–	–	–	–	–	–
	June '98	4.3*	2.6–6.25	1.1	24	–	–	–	–	–	–	–	–
	Oct '98	–	–	–	–	12.4	9.8–15	2.8	1	–	–	–	–
	Oct '98	–	–	–	–	11.5	5–82.5	0.6	1	–	–	–	–
Guntur	Oct '98	–	–	–	–	12.9	9.5–16	2.4	1	–	–	–	–
	Nov '98	14.4*	8.2–19.5	2.2	80	–	–	–	–	–	–	–	–
	Nov '98	12.5*	8.0–15.3	4.2	69	–	–	–	–	–	–	–	–
	Nov '98	10.7*	4.6–13.8	4.5	59	–	–	–	–	–	–	–	–
	Dec '98	–	–	–	–	11.2	8.1–14	2.3	1	–	–	–	–
	Dec '98	–	–	–	–	13.7	10.3–17	2.4	1	–	–	–	–
Mahbubnagar	Oct '98	–	–	–	–	12.9	8.7–17	3.1	1	–	–	–	–
	Dec '98	10.6*	4.3–13.6	4.4	24	–	–	–	–	–	–	–	–

[a] Data of SUD susceptible from Cahill *et al.* (1995).
* Designated LD_{50} values are significantly different from the susceptible strain through non-overlap of fiducial limits.
LD_{50}, median lethal dose expressed in ppm; FL, fiducial limits; RF, resistance factor.

not clear as to what level of laboratory measured resistance can cause field control failures, it is likely that the extent of difficulties in pest control will certainly be dictated by the severity of resistance. For example, even low levels of 10 to 20-fold resistance to methomyl or endosulfan have been considered to be sufficient to cause field control failures, as both compounds are inherently not very effective against *H. armigera* larvae (McCaffery *et al.*, 1989; Gunning *et al.*, 1992), whereas resistance factors of even up to 50-fold to cypermethrin have not caused perceptible field control difficulties (K.R. Kranthi, unpublished data). In India, monocrotophos, quinalphos and methomyl are the most widely used insecticides in cotton pest management apart from pyrethroids and endosulfan. Hence a measure of resistance in cotton insect pests to these molecules was not unexpected. Until the late 1980s, resistance to organophosphates was almost negligible, with highest resistance factors of 9-fold to quinalphos, and 3-fold to monocrotophos in *H. armigera* (McCaffery *et al.*, 1989; Armes *et al.*, 1992b). Later, Armes *et al.* (1996) reported the absence of resistance to monocrotophos, but observed resistance levels of up to 59-fold to quinalphos and > 30-fold to methomyl in *H. armigera* field strains in India. High levels of > 300-fold resistance to methomyl were also reported from China (Cheng & Liu, 1996). The results indicate that resistance to monocrotophos, which was earlier at undetectable levels, is now ubiquitous in India. Resistance to monocrotophos was particularly high in the northern states of India in Punjab (Bhatinda) and Haryana (Dabwali and Sirsa). This was not surprising, as the use of monocrotophos in cotton is extensive in northern India. Moreover, of the total monocrotophos used in the north, nearly 90% is allocated for cotton pest management (Anon., 1997). High levels of 200 and 720-fold resistance to monocrotophos in *H. armigera* were reported from China

Table 6. Pairwise correlation coefficient comparisons between log LD_{50}s of the insecticides.

Insect species	Insecticide	Methomyl	Monocrotophos
Helicoverpa armigera	Monocrotophos	0.427^{ns}	
	Quinalphos	$0.369^{0.05}$	0.442^{ns}
Pectinophora gossypiella	Monocrotophos	0.510^{ns}	
	Quinalphos	$0.874^{0.01}$	0.521^{ns}
Earias vittella	Monocrotophos	$0.962^{0.01}$	
	Quinalphos	$0.976^{0.01}$	$0.969^{0.01}$
Spodoptera litura	Monocrotophos	0.577^{ns}	
	Quinalphos	$0.683^{0.05}$	$0.898^{0.01}$

Superscripts indicate significance of the regression; ns, non-significant.

(Cheng & Liu, 1996) and Pakistan (Ahmad *et al.*, 1995) respectively. In China, *H. armigera* strains which were susceptible to monocrotophos till 1993 (Wu *et al.*, 1995) exhibited appreciable levels of resistance by 1995 (Wu *et al.*, 1996).

Resistance in pink bollworm was high only to quinalphos in most of the strains tested. In general, reports of *P. gossypiella* resistance to insecticides have been rare. For example, Tang *et al.* (1988) could not find any evidence of insecticide resistance in *P. gossypiella* in China. However, resistance to azinphosmethyl and permethrin was reported from strains collected in Arizona and California (Osman *et al.*, 1991). More than 70-fold resistance to monocrotophos was recorded in strains of *E. vittella* from Sriganganagar and Sirsa in northern India. Monocrotophos, which was earlier found to be effective for the control of *E. vittella*, has been showing poor field efficacy in recent times in northern India (J. Singh, Punjab Agricultural University, Punjab, personal communication). With limited chemistry available for early season sprays to combat the problem of *P. gossypiella* and *E. vittella*, bollworm management may pose a major problem in times to come.

The *S. litura* strain, collected from Mahbubnagar in southern India, exhibited the highest levels of resistance to the three insecticides tested. This was not surprising, as methomyl, quinalphos and monocrotophos were used very frequently for the management of *S. litura* on groundnut crops in Mahbubnagar during the period of survey. Resistance in *S. litura* to endosulfan, carbaryl and malathion was reported in field strains from Haryana (Verma *et al.*, 1971), West Bengal (Mukherjee & Srivastava, 1970) and Andhra Pradesh (Ramakrishnan *et al.*, 1984). Recently, Armes *et al.* (1996) reported resistance levels of up to 13-fold to quinalphos, 362-fold to monocrotophos and 19-fold to methomyl, in *S. litura* strains collected from Andhra Pradesh. Due to the low resistance levels in the majority of the strains tested, methomyl is expected to remain effective against *S. litura* in most parts of the country for the time being.

All of the field strains of *B. tabaci* exhibited a measure of resistance to methomyl and monocrotophos and susceptibility to triazophos. Insecticides such as monocrotophos and triazophos are still widely used on cotton and other crops in Andhra Pradesh to keep the whitefly populations under check. Interestingly, the populations appeared to be fully susceptible to triazophos despite its extensive usage. Cahill *et al.* (1996b) reported resistance to monocrotophos and other organophosphate insecticides in *B. tabaci* from USA, central America, Europe, Pakistan, Sudan and Israel. Dittrich *et al.* (1985) reported high levels of resistance to organophosphate insecticides in strains of *B. tabaci* from Sudan. In India, monocrotophos, which has been one of the most popular insecticides used for whitefly control, appears to have become less effective in recent times (K.R. Kranthi, unpublished data), probably due to the widespread development of resistance.

The data indicated positively correlated cross-resistance only between quinalphos and methomyl against all the insect species (table 6). However, resistance to monocrotophos was not correlated with quinalphos and methomyl in *H. armigera* and *P. gossypiella* suggesting that resistance to these compounds may be mediated through different mechanisms. Toxicity of the phosphate group of organophosphate insecticides such as monocrotophos is unaffected by oxidase inhibitors (Forrester *et al.*, 1993) and resistance to such compounds has been mostly attributed to insensitive acetylcholine-esterase based mechanisms (Oppenoorth, 1985). However, the phosporothionate group of insecticides such as quinalphos, undergo an oxidative activation catalysed by mixed function oxidases before they act as AChE inhibitors. Hence, oxidative inhibitors antagonize their toxicity (Forrester *et al.*, 1993). Thus, due to the structural differences and also the differential metabolic fate of the compounds, it is probable that resistance may be mediated through different mechanisms. The absence of a common resistance mechanism that could confer cross-resistance between the three compounds suggests that the use of the compounds in rotations or sequences for resistance management should be explored.

One of the basic aspects of resistance management is to devise approaches to minimize reliance on insecticides so that the selection pressure can be alleviated. Development of effective proposals to counter resistance need to be based on information on occurrence and degree of resistance and the local resistance patterns in field populations of insect pests to different insecticides. Because the history of pesticide application varies, resistance patterns also differ. For such differences to be exploited they need to be properly documented. The variation in resistance factors to the insecticides tested in this study was relatively small in *H. armigera, S. litura, E. vittella* and *B. tabaci* collected from adjacent districts over large geographical areas, suggesting the possibility of intermixing of resistant and susceptible populations through dispersal and migration. Daly & Gregg (1985) demonstrated significant gene flow between populations of *H. armigera* in Australia due to its high vagility. A facultative migrant gene flow in *H. armigera* can result in resistant alleles reaching untreated populations (Daly, 1993) or vice versa. However, resistance factors varied markedly over short distances in *P. gossypiella* in some parts of the country. The districts of Akola and Yavatmal are separated from Parbhani by about 100 km, but harboured *P. gossypiella* strains that were at least 60 times more resistant to quinalphos compared with the Parbhani strain. The data suggest that populations of *P. gossypiella* may not be contiguous and region specific resistance strategies may have to be devised for such pests. Moreover, the low slopes obtained from the probit assay data suggested that the *P. gossypiella* populations were heterogeneous, thereby indicating the widespread occurrence of heterozygous strains. Because heterozygotes are the most common carriers of resistance, they are the most important genotype from a resistance management perspective (Roush & Mckenzie, 1987). The widespread occurrence of heterozygosity in field populations may contribute to rapid increases in resistance levels even as a result of just a few insecticide applications. This phenomenon is exemplified by the transient decline in pyrethroid resistance in *H. armigera* strains following a withdrawal of pyrethroid use for five years until 1987 in Turkey. Reverted populations were found to maintain a rather high frequency of resistance alleles, which led to the re-establishment of high resistance after only a few selections (Dittrich *et al.*, 1990). This study suggests that strategies for resistance management in cotton pests must be specifically devised to take into account local variation in patterns of resistance and the extent of heterogeneity in field populations in India so as to prevent any sudden increases in resistance that can result in loss of insecticide efficacy.

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References

Abbott, W.S. (1925) A method of computing the effectiveness of an insecticide. *Journal of Economic Entomology* **18**, 265–267.

Ahmad, M., Arif, M.I. & Ahmad, Z. (1995) Monitoring insecticide resistance *of Helicoverpa armigera* (Lepidoptera: Noctuidae) in Pakistan. *Journal of Economic Entomology* 88, 771–776.

Anon. (1970) Standard method for detection of insecticide resistance in *Heliothis zea* (Boddie) and *H. virescens* (Fab.). *Bulletin of the Entomological Society of America* **16**, 147–153.

Anon. (1987) *POLO-PC – a user's guide to Probit or Logit analysis.* 22 pp. California, LeOra Software, California.

Anon. (1997) Organophosphate insecticides – an Indian analysis. *The Pesticides World* **1**, 8–9.

Armes, N.J., Bond, G.S. & Cooter, R.J. (1992a) *The laboratory culture and development of Helicoverpa armigera.* Natural Resources Institute Bulletin 57, Natural Resources Institute, Chatham, UK, 1992.

Armes, N.J., Jadhav, D.R., Bond, G.S. & King, A.B.S. (1992b) Insecticide resistance in *Helicoverpa armigera* in south India. *Pesticide Science* 34, 355–364.

Armes, N.J., Jadhav, D.R. & De Souza, K.R. (1996) A survey of insecticide resistance in *Helicoverpa armigera* in the Indian sub-continent. *Bulletin of Entomological Research* **86**, 499–514.

Armes, N.J., Wightman, J.A., Jadhav, D.R. & Ranga Rao, G.V. (1997) Status of insecticide resistance in *Spodoptera litura* in Andhra Pradesh, India. *Pesticide Science* **50**, 240–248.

Barlett, A.C. & Wolf, W.W. (1985) *Pectinophora gossypiella,* pp. 415–430 *in* Moore, R.F. & Singh, P. (*Eds*) *Handbook of insect rearing,* Vol. 2. Amsterdam, Elsevier.

Cahill, M., Byrne, F.J., Gorman, K., Denholm, I. & Devonshire, A.L. (1995) Pyrethroid and organophosphate resistance in the tobacco whitefly, *Bemisia tabaci* (Homoptera: Aleyrodidae). *Bulletin of Entomological Research* **85**, 181–187.

Cahill, M., Gorman, K., Day, S. & Denholm, I. (1996a) Baseline determination and detection of resistance to imidacloprid in *Bemisia tabaci* (Homoptera: Aleyrodidae). *Bulletin of Entomological Research* **86**, 343–349.

Cahill, M., Denholm, I., Byrne, F.J. & Devonshire, A.L. (1996b) Insecticide resistance in *Bemisia tabaci* – current status and implications for management. pp. 75–80 in *Proceedings, Brighton Crop Protection Conference – Pests and Diseases.* British Crop Protection Council.

Cheng, G. & Liu, Y. (1996) Cotton bollworm resistance and its development in northern cotton region of China 1984–1985. *Resistant Pest Management* **8**, 32–33.

Daly, J.C. (1993) Ecology and genetics of insecticide resistance in *Helicoverpa armigera*: interactions between selection and gene flow. *Genetica* **90**, 217–226.

Daly, J.C. & Gregg, P. (1985) Genetic variation in *Heliothis* in Australia: species identification and gene flow in the two pest species *H. armigera* (Hübner) and *H. punctigera* (Wallengren) (Lepidoptera: Noctuidae). *Bulletin of Entomological Research* **75**, 169–184.

Dittrich, V., Hassan, S.C. & Ernst, G.H. (1985) Sudanese cotton and the whitefly: a case study of the emergence of a new primary pest. *Crop Protection* 4, 161–176.

Dittrich, V., Uk, S. & Ernst, G.H. (1990) Chemical control and insecticide resistance of whiteflies, pp. 263–285 *in* Gerling, D. (*Ed.*) *Whiteflies and their bionomics, pest status and management.* Intercept Ltd, UK.

Forrester, N.W., Cahill, M., Bird, L.J. & Layland, J.K. (1993) Management of pyrethroid and endosulfan resistance in *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Australia. *Bulletin of Entomological Research,* Supplement No. **1**, 1–132.

Gunning, R.V., Balfe, M.E. & Easton, C.S. (1992) Carbamate resistance in *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) in Australia. *Journal of the Australian Entomological Society* **31**, 97–102.

Kranthi, K.R., Armes, N.J., Nagarjun, G.V., Rao, R.S. & Sundaramurthy, V.T. (1997) Seasonal dynamics of metabolic mechanisms mediating pyrethroid resistance in *Helicoverpa armigera* in central India. *Pesticide Science* **50**, 91–98.

Kranthi, K.R., Banerjee, S.K. & Russell, D. (in press) Insecticide resistance management of cotton pests. *Pestology.*

McCaffery, A.R., King, A.B.S., Walker, A.J. & El-Nayir, H. (1989) Resistance to synthetic pyrethroids in the bollworm, *Heliothis armigera* from Andhra Pradesh, India. *Pesticide Science* **27**, 65–76.

Mukherjee, A.B. & Shrivastava, V.S. (1970) Bioassay of relative toxicity of some pesticides to the larvae of *Spodoptera litura* (Fab.) (Lepidoptera: Noctuidae). *Indian Journal of Entomology,* **32**, 251–255.

Oppenoorth, F.J. (1985) Biochemistry and genetics of insecticide resistance. pp. 731–773 *in* Kerkut, G.A. & Gilbert, L.I. (*Eds*) *Comprehensive insect physiology, biochemistry and pharmacology,* Vol. 12 *Insect control.* Oxford, Pergamon Press.

Osman, A.A., Watson, T.F. & Sivasupramaniam, S. (1991) Susceptibility of field populations of pink bollworm (Lepidoptera: Gelechiidae) to azinphosmethyl and permethrin and synergism of permethrin. *Journal of Economic Entomology* **84**, 358–362.

Paul, A.V.N., Prasad, B. & Gautam, R.D. (1987) Artificial diets for *Pectinophora gossypiella* and *Earias vittella* bollworms of cotton. *Indian Journal of Agricultural Sciences* **57**, 89–92.

Puri, S.N. (1995) Present status of IPM in India. *National Seminar on Integrated Pest Management in Agriculture.* December 29–30, 1995. Nagpur, Maharashtra.

Ramakrishnan, N., Saxena, V.S. & Dhingra, S. (1984) Insecticide resistance in the population of *Spodoptera litura* (Fab.) in Andhra Pradesh. *Pesticides* **18**, 23–27.

Roush, R.T. & McKenzie, J.A. (1987) Ecological genetics of insecticide and acaricide resistance. *Annual Review of Entomology* **32**, 361–380.

Snedecor, G.W. & Cochran, W.G. (1989) *Statistical methods*, 8th edn. Iowa State University Press, USA.

Tang, Z.H., Gong, K.Y. & You, Z.P. (1988) Present status and counter measures of insecticide resistance in agricultural pests in China. *Pesticide Science* 23, 189–198.

Verma, A.N., Verma, N.D. & Singh, R. (1971) Chemical control of *Prodenia litura* (Fab.) (Lepidoptera: Noctuidae) on cauliflower. *Indian Journal of Horticulture* 28, 240–243.

Wu, Y., Shen, J., Tan, F. & You, Z. (1995) Mechanism of fenvalerate resistance in *Helicoverpa armigera* (Hübner). *Journal of the Nanjing Agricultural University* 18, 63–68.

Wu, Y., Shen, J., Chen, J., Lin, X & Li, A. (1996) Evaluation of two resistance monitoring methods in *Helicoverpa armigera:* topical application and leaf dipping method. *Journal of Plant Protection* 5, 3–6.

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