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Insecticide Resistance in *Helicoverpa armigera* in South India*

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Abstract Cypermethrin, quinalphos, endosulfan and methomyl were bioassayed against strains of *Helicoverpa armigera* collected from field crops in Andhra Pradesh and Tamil Nadu, South India, during the 1989–90 and 1990–91 cropping seasons. In 1989, high levels of resistance to cypermethrin were recorded in strains from cotton in the cotton-growing regions of Guntur, Andhra Pradesh, and Coimbatore, Tamil Nadu, and from pigeon pea near Hyderabad. There was no evidence for resistance to quinalphos or methomyl at that time. In 1990–91, sampling was more extensive, and although tolerance to cypermethrin was lower than in the previous season, the survey indicated that pyrethroid-resistant populations were present throughout much of Andhra Pradesh. Tolerance to quinalphos had increased slightly in 1990–91, while resistance to methomyl had increased substantially, particularly in the cotton-growing area of Guntur. Endosulfan tolerance had increased slightly compared to strains tested in 1986–88 in an earlier study. The geographic and temporal variations in severity of pyrethroid resistance in *H. armigera* in Andhra Pradesh are believed to arise because of dynamic interactions between local selection pressure and immigration of resistant and susceptible moths at certain times of the year.

1 INTRODUCTION

Large-scale failure to control *Helicoverpa armigera* (Hubner) (Lepidoptera: Noctuidae) in India was first recorded in the major cotton-growing region of Andhra Pradesh in 1987.[1] To combat the unprecedented *H. armigera* pest pressure, many farmers in the region were applying synthetic pyrethroid–endosulfan or organophosphate insecticides, sometimes as mixtures, at 2–3 day intervals during critical periods, resulting in over 30 sprays (against the 8–10 recommended) during the season (R M Sawicki, unpublished report). Synthetic pyrethroids constituted 50–70% of these applications, but growers were unable to achieve effective control with any of the available insecticides. As a result, average cotton yields for the major cotton-growing districts of Andhra Pradesh, Krishna, Guntur and Prakasam, declined from 436 kg ha^{-1} in 1986–87 to 168 kg ha^{-1} in 1987–88.[1] Later in the season, *H. armigera* populations moved to pulses where again insecticides failed to give effective control, and average yields of pigeon pea for the three districts declined from 392 kg ha^{-1} in 1986–87 to 214 kg ha^{-1} in 1987–88.[1] In the same season, poor control of *H. armigera* on pigeon pea was recorded at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, some 250 km NW of Guntur. Resistance to synthetic pyrethroids was subsequently confirmed to be a major cause of crop failures in Andhra Pradesh.[1,2]

In the following season, pyrethroid resistance levels declined markedly,[3] which was attributed to a decline in the use of synthetic pyrethroids due in part to their late release to farmers during the 1988–89 cotton season and to disillusionment with pyrethroid products. It was also believed that the source of resistant populations was restricted to the cotton belt, approximately 75 km wide and 200 km long, comprising Guntur, Prakasam and Krishna districts on the eastern seaboard of Andhra Pradesh.[3]

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This paper reports the results of insecticide bioassay tests conducted on 30 strains of *H armigera* collected from field crops in Andhra Pradesh and Tamil Nadu during the 1989 90 and 1990 91 cropping seasons

2 MATERIALS AND METHODS

2.1 Field strains

Samples of 2nd 6th instar *H armigera* larvae were collected from post rainy (October February) or summer (March June) season field crops between 1989 and 1991 at 18 locations in Andhra Pradesh and two in Tamil Nadu (Fig 1 Table 1) Fields with larval infestations of *H armigera* were identified and larvae collected by sampling throughout the field Samples from different fields within a region were kept separate in order to detect local resistance diversity Wherever possible, farmers were interviewed to determine whether insecticides had been sprayed on the crop and, if so, the frequency and types of insecticide used (Table 1) Samples comprised 130 600 larvae Except at the ICRISAT farm sites were sampled only once during

Fig. 1. Sampling sites where *H armigera* larvae were collected in Andhra Pradesh and Tamil Nadu during the 1989 90 and 1990–91 cropping seasons (refer to Table 1 for key to sites)

TABLE 1

Insecticide Usage at Sampling Sites where *H. armigera* Larvae were Collected in Andhra Pradesh and Tamil Nadu during the 1989–90 and 1990–91 Cropping Seasons

Collection site	*Map ref.*	*Collection date*	*Crop*	*Insecticides[1] (No. of sprays)*
Medak district				
ICRISAT	1	28 Sept.–5 Oct. 89	Pigeon pea	Mon (×2) Qui (×1) Met (×1)
ICRISAT	1	16–20 Nov. 89	Chick pea	Un
ICRISAT	1	17–23 Nov. 89	Pigeon pea	Fen (×1) Mon (×2) Met (×1)
ICRISAT	1	14–16 Mar. 90	Pigeon pea	Fen (×2) End (×1)
ICRISAT	1	20–21 Nov. 90	Pigeon pea	Un
ICRISAT	1	22–23 Nov. 90	Chick pea	Un
ICRISAT	1	10–15 Dec. 90	Cotton	End (×2) Dim (×1)
ICRISAT	1	11–15 Mar. 91	Pigeon pea	Un
Narsapur	3	19 Apr. 91	Tomato sunflower	Mon (×2)
Rangareddi district				
Shankarpalli	2	20 Mar. 91	Chick pea	Un
Warangal district				
Ghanpur	5	27 Dec. 90	Cotton	End (×4) [illegible] (×1)
Shivareddypalli	6	27 Dec. 90	Chick pea	Un
Raghunadapalli	4	28 Dec. 90	Chick pea	Un
Nalgonda district				
Suriapet	7	22 Feb. 91	Tomato	Qui (×2)
Krishna district				
Nandigama	8	25 Nov. 89	Pigeon pea	Un
Guntur district				
Guntur	10	24 Nov. 89	Cotton	Spr.[2] (×?)
Guntur	10	28 Nov. 90	Pigeon pea	End (×1) Qui (×1) Dic (×1)
Tadikonda	9	23 Jan. 91	Chick pea	End. Qui (Total ×3)
Tadikonda	9	23 Jan. 91	Cotton	End (×1) Mon (×1) Car (×1) Dim (×1)
Pasamure	12	24 Jan. 91	Chick pea	Spr.[2] (×2)
Kumaripalem	11	24 Jan. 91	Pigeon pea	Fen (×1) End (×1)
Mahbubnagar district				
Puthandurddy	13	16 Nov. 90	Pigeon pea	End (×1) Mon (×1) Dim (×1)
Prakasam district				
Ongole	14	24 Jan. 91	Chick pea	Spr.[2] (×?)
Kurnool district				
Nandyal	16	13 Nov. 90	Pigeon pea	End (×1)
Nandyal	16	14 Nov. 90	Cotton	Cyp (×3) Fen (×2) Del (×1) Mon (×2) Qui (×2) Neem (×2)
Govindapally	17	14 Nov. 90	Pigeon pea	End (×2) Mon (×1) Qui (×1)
Kalava	15	15 Nov. 90	Pigeon pea	Un[2]
Cuddapah district				
Duvvuru	18	15 Nov. 90	Pigeon pea	Un[2]
Tamil Nadu				
Coimbatore	20	29 Nov. 89	Cotton	Spr.[2] (×?)
Vriddhachalam	19	26 Feb. 91	Groundnut	Mon (×1) Qui (×1) End (×1) Fen (×1) Cyp (×1)

[1] Insecticides: Fen, fenvalerate; Cyp, cypermethrin; Del, deltamethrin; End, endosulfan; Car, carbaryl; Qui, quinalphos; Mon, monocrotophos; Dim, dimethoate; Dic, dichlorvos; Met, methomyl; Neem, neem product; Spr.[2] sprayed but insecticides not identified; Un, unsprayed; Un[2], probably unsprayed.

each season. In the 1989–90 season pupae were transported to the Natural Resources Institute (NRI) UK for subsequent testing of first generation larvae whereas in 1990–91 bioassays were conducted chiefly at ICRISAT. When sufficient 2nd–3rd instar larvae were collected in the field (> 240 larvae) bioassays were conducted on the field generation otherwise larvae were reared to adult in the laboratory and bioassays conducted on the resulting first generation. Field collected and first generation larvae were reared in the laboratory on an artificial diet based on chick pea flour (N J Armes unpublished) at 26 (± 1) C under natural photoperiod (c 13–11 h light–dark) at ICRISAT and constant 14–10 h light–dark at NRI.

2.2 Laboratory strains

Two baseline strains were maintained in the laboratory. One, the Sim Sim strain, was originally collected in the Sudan from rainfed sorghum and sunflower at Sim Sim near Gedaref, Kasalla Province, where few insecticides are used. The strain was replaced by field collected insects each year and was at the third and fifth laboratory generations at NRI when bioassays were conducted in 1990 and 1991 respectively. The second Delhi strain was obtained from the Indian Agricultural Research Institute (IARI), New Delhi. This strain was re-established annually from larvae collected on pigeon pea at the IARI farm in Delhi where pyrethroid resistance has not been implicated to date. It was at the fourth and third laboratory generations at the time of testing in 1990 and 1991 respectively. Neither strain had been subject to selection for susceptible genotypes.

2.3 Insecticides

The following technical grade insecticides were used for the topical bioassays: *cis trans* (c 50:50 ratio) cypermethrin (720 g kg^{-1}, ICI Agrochemicals, UK); quinalphos (700 g kg^{-1}, Sandoz AG, Switzerland); endosulfan (960 g kg^{-1}, Hoechst India); methomyl (980 g kg^{-1}, DuPont France). A cypermethrin EC formulation (Cymbush, 100 g litre^{-1}, EC, ICI Agrochemicals, UK) was used for the foliar residue assays.

2.4 Bioassay procedures

2.4.1 Topical bioassay

Serial dilutions of technical grade insecticides in analytical grade acetone were prepared and an Arnold pattern microapplicator (Burkard Scientific Ltd) used to deliver a 1.0-μl drop to the thoracic dorsum of each 3rd–4th instar larva in the weight range 30–50 mg. Moulting larvae were not dosed. Control larvae were treated with acetone alone. With few exceptions, at least 40 larvae (divided amongst 4–5 replicates) were treated at each of five or more concentrations plus control. The number of individuals treated from different strains reflected the relative availability of *H armigera* in the field and subsequent success at breeding in the laboratory. Larvae were held individually in 30-ml clear plastic cups with fresh artificial diet. Mortality was assessed 72 h after treatment; a larva was considered dead if it was unable to move in a co-ordinated manner when prodded. Larvae considered to be alive had grown significantly since the time of dosing and eaten at least some of the artificial diet.

2.4.2 Foliar residue bioassay

The procedure described by McCaffery *et al*[4] was followed. Cotton plant leaves were immersed in aqueous dilutions of the cypermethrin EC to which was added Triton X-100 surfactant (0.25 g litre^{-1}) to improve leaf wetting. Control leaves were dipped in distilled water plus surfactant. Three- to six-hour-old neonate larvae were transferred with a brush to 30-ml plastic pots in groups of five. A dry treated leaf was placed over the top of each pot and the lid snapped on, thereby securely holding the leaf disk under the lid. Eight replicates (total of 40 larvae) were prepared for each treatment and for the control. Mortality was determined 48 h post-treatment.

Bioassays were carried out at 26 (± 1) C under natural photoperiod (c 13–11 h light–dark) at ICRISAT and constant 14–10 h light–dark at NRI.

2.5 Data Analysis

Dose–mortality regressions were computed by probit analysis[10] using MLP 3.08 software[11]. Resistance factors at LD_{50} (RF) were calculated as LD_{50} field strain/LD_{50} Delhi or Sim Sim strain. The Sim Sim strain was more susceptible to cypermethrin than the Delhi strain (comparative RF = 2.1-fold in 1990 and 1.3-fold in 1991), however the Delhi strain was considered to be more representative of a baseline pyrethroid strain for Indian *H armigera* and in order not to overestimate the degree of resistance was used as the standard reference. For cypermethrin both resistance factors are quoted, as the LD_{50} value for the Sim Sim strain is closer to that of the susceptible strain used at Reading University[1,6] and thereby provides a comparison with earlier data.

3 RESULTS

3.1 Cypermethrin

3.1.1 Topical bioassay

In both years the log dose–probit (ldp) line slopes recorded for the Sim Sim strain (2.0 and 2.5) were higher than those for the Delhi strain (1.7 and 1.9) (Table 2). The Delhi strain may therefore not have been truly homogeneous with respect to pyrethroid resistance and

TABLE 2

Toxicity of Topically Applied Cypermethrin to 30–80 mg Larvae of Indian Field Strains and Laboratory Strains of *H. armigera*

Collection site	*Collection date*	*Parental host*	*n*	*LD* (95% *FL*) (μg larva^{-1})	*LD* (95% *FL*) (μg larva^{-1})	*Slope* (±SE)	*RI*	*RI*
1989–90 season								
Sim Sim	Sept–Oct 89	Artificial	280	0.01 (0.008–0.012)	0.042 (0.030–0.068)	2.00 (±0.22)		
Delhi	Nov 89	Artificial	285	0.21 (0.17–0.27)	1.7 (0.80–2.3)	1.70 (±0.21)		
ICRISAT	28 Sept–5 Oct 89	Pigeon pea	280	0.79 (0.63–1.1)	44 (26–111)	1.73 (±0.37)	4	79
ICRISAT	17–23 Nov 89	Pigeon pea	464	9.3 (6.6–13)	247 (124–679)	0.90 (±0.09)	44	979
ICRISAT	16–20 Nov 89	Chick pea	240	2.1 (1.6–2.9)	13 (8.3–26)	1.64 (±0.21)	10	214
ICRISAT[1]	14–16 Mar 90	Pigeon pea	320	2.1 (0.83–3.8)	125 (60–419)	0.70 (±0.11)	10	214
Nandigama	28 Nov 89	Pigeon pea	289	0.20 (0.12–0.31)	6.7 (3.1–23)	0.84 (±0.11)	1	20
Guntur	24 Nov 89	Cotton	283	21 (11–33)	481 (240–1905)	0.95 (±0.17)	100	2100
Coimbatore	29 Nov 89	Cotton	312	4.5 (3.3–6.2)	39 (23–94)	1.36 (±0.17)	91	450
1990–91 season								
Sim Sim strain	Sept 90	Artificial	240	0.01 (0.009–0.013)	0.033 (0.024–0.054)	2.53 (±0.32)		
Delhi strain	Nov 90	Artificial	137	0.13 (0.09–0.18)	0.89 (0.36–1.3)	1.91 (±0.29)		
ICRISAT	20–21 Nov 90	Pigeon pea	380	0.41 (0.29–0.56)	4.9 (3.2–8.9)	1.19 (±0.11)	3	41
ICRISAT	22–23 Nov 90	Chick pea	234	0.54 (0.31–0.85)	8.0 (2.8–11)	1.32 (±0.18)	4	54
ICRISAT	10–15 Dec 90	Cotton	344	0.83 (0.59–1.14)	10 (6.3–19)	1.18 (±0.17)	6	83
ICRISAT	11–15 Mar 91	Pigeon pea	394	3.32 (2.48–4.30)	28 (18–80)	1.37 (±0.17)	26	332
Narsapur	19 Apr 91	Sunflower	181	0.20 (0.13–0.28)	1.8 (0.93–3.6)	1.43 (±0.27)	2	20
		Tomato						
Shankarpalli	20 Mar 91	Chick pea	275	0.88 (0.42–0.83)	4.2 (2.5–9.4)	1.49 (±0.19)	4	58
Ghanpur	27 Dec 90	Cotton	238	0.95 (0.48–1.6)	52 (19–379)	0.74 (±0.13)	7	95
Shivareddypalli	27 Dec 90	Chick pea	465	0.52 (0.33–0.82)	36 (12–285)	0.70 (±0.11)	4	52
Raghunadapalli	28 Dec 90	Chick pea	461	0.86 (0.60–1.3)	28 (11–125)	0.87 (±0.13)	7	86
Suriapet	22 Feb 91	Tomato	168	3.3 (2.2–5.3)	28 (12–145)	1.44 (±0.31)	28	330
Guntur	28 Nov 90	Pigeon pea	255	0.80 (0.54–1.4)	9.3 (4.1–41)	1.20 (±0.19)	6	80
Tadikonda	23 Jan 91	Chick pea	320	1.8 (1.1–2.7)	40 (22–101)	0.95 (±0.17)	14	180
Tadikonda	23 Jan 91	Cotton	220	2.5 (1.9–3.4)	17 (11–33)	1.60 (±0.30)	19	250
Pasamure	24 Jan 91	Chick pea	350	3.1 (2.1–4.5)	77 (38–233)	0.91 (±0.11)	24	310
Kumaripalem	24 Jan 91	Pigeon pea	214	8.3 (5.7–12)	63 (35–191)	1.46 (±0.26)	64	830
Puthandurddy	16 Nov 90	Pigeon pea	310	0.07 (0.05–0.10)	0.74 (0.40–2.2)	1.35 (±0.19)	0.5	7
Ongole	24 Jan 91	Chick pea	211	3.8 (2.4–6.1)	67 (28–426)	1.00 (±0.20)	29	380
Nandyal	13 Nov 90	Pigeon pea	249	0.31 (0.19–0.47)	3.5 (2.1–7.9)	1.23 (±0.18)	2	31
Nandyal	14 Nov 90	Cotton	132	2.0 (1.0–3.3)	25 (13–100)	1.15 (±0.22)	15	200
Govindapally	14 Nov 90	Pigeon pea	128	0.11 (0.06–0.20)	1.2 (0.56–7.8)	1.23 (±0.27)	0.8	11
Kalava	15 Nov 90	Pigeon pea	399	0.20 (0.13–0.30)	4.7 (2.1–19)	0.92 (±0.14)	2	20
Duvvuru	15 Nov 90	Pigeon pea	172	0.14 (0.06–0.26)	5.1 (1.8–45)	0.82 (±0.16)	1	14
Vriddhachalam	26 Feb 91	Groundnut	187	1.45 (0.83–2.83)	60 (19–527)	0.79 (±0.13)	11	145

Resistance factors relative to Delhi/Sim Sim strains

[1] Heterogeneity χ significant at $P < 0.001$

[2] Bioassay on field generation

could have comprised mixed resistant and susceptible genotypes at the time of testing. However examination of the ldp lines did not show any systematic curvilinearity and heterogeneity was not significant (Heterogeneity χ $P > 0.05$).

There were marked geographic variations in the levels of pyrethroid resistance in the 30 field strains. Apart from two, all those tested showed similar or higher tolerance at LD_{50} to cypermethrin than did the Delhi strain (Table 2). Slopes of the ldp lines for most of the field strains were shallow (range 0.7–1.7) compared to those of the laboratory strains suggesting variable levels of heterogeneity.

Overall pyrethroid resistance levels were higher in the 1989–90 season. For example strains collected at ICRISAT from pigeon pea in November recorded RFs of 44 and 3 in 1989 and 1990 respectively. The 1989 sample exhibited marked heterogeneity (Heterogeneity χ $P < 0.001$) and the ldp line showed obvious segregation of phenotypes. In Guntur district, the strain collected from cotton in November 1989 recorded 100-fold resistance to cypermethrin, but in January 1991

resistance had fallen to 19 fold in larvae collected from cotton in the same district Neither strain showed any indication of segregation of phenotypes

In the 1990 91 season pyrethroids had not been used to any great extent in the majority of fields from which larval collections were made and only 13% of samples were collected from fields definitely known to have been sprayed at least once with pyrethroids (Table 1) The reason for the paucity of use of pyrethroids at the time of sampling is that 80% of total pyrethroid consumption in India is on cotton[15] and the first samples were not collected until mid-November mainly from pigeon pea which compared with cotton is only lightly sprayed by this time most cotton was at the lint stage and beyond attack by *H armigera* However where pyrethroids had been used substantial levels of resistance were indicated by high LD_{50} and LD_{90} values and correspondingly high LD_{50} RFs The highest RF recorded was 64 from insects collected at Kumaripalem Guntur district from a pigeon pea field sprayed 2 3 days previously with fenvalerate Further 15-fold resistance was recorded in a strain collected during November from irrigated cotton at Nandyal in Kurnool District which had been sprayed six times with pyrethroids at a time when resistance factors recorded from other locations were low (0 5 4-fold Table 2) In general the highest levels of pyrethroid resistance were recorded in samples from Guntur and Prakasam districts High resistance factors were also recorded from chick pea at Pasamure (24-fold) and Ongole (29 fold) both of these crops had been sprayed, but it was not possible to ascertain the types of insecticides used

At ICRISAT in both seasons there was temporal variation in tolerance to cypermethrin In 1989 90 resistance peaked in mid November on sprayed pigeon pea while in 1990 91 tolerance levels increased from November to March Overall it is evident that pyrethroid resistance levels in Andhra Pradesh increased with the progression of the 1990 91 post-rainy season

3 1 2 Foliar residue bioassay

All field strains recorded higher tolerance of first instar larvae to cypermethrin residues than the Sim Sim laboratory strain (Table 3) First instar larvae of the

TABLE 3

Toxicity of Foliar Residues of a Cypermethrin EC to First Instar Larvae of Indian Field Strains and a Laboratory Strain of *H armigera*

Collection site	*Collection date*	*Parental host*	*n*	LC_{50} (95% *FL*) (mg litre^{-1})	LC_{90} (95% *FL*) (mg litre^{-1})	*Slope* (± *SE*)	*RF*[a]
Sim Sim	Sept Oct 89	Artificial	330	0 37 (19 61)	30 (19 61)	1 40 (+0 14)	
ICRISAT	17 23 Nov 89	Pigeon pea	320	13 (9 2 17)	119 (77 225)	1 32 (+0 15)	35
Guntur	24 Nov 89	Cotton	370	9 4 (6 3 13)	181 (114 382)	0 99 (±0 11)	25
Coimbatore	29 Nov 89	Cotton	320	18 (14 24)	136 (89 249)	1 47 (+0 16)	50

[a] Resistance Factor relative to Sim Sim strain

TABLE 4

Toxicity of Topically Applied Quinalphos to 30 50 mg Larvae of Indian Field Strains and Laboratory Strains of *H armigera*

Collection site	*Collection date*	*Parental host*	*n*	LD_{50} (95% *FL*) (μg larva^{-1})	LD_{90} (95% *FL*) (μg larva^{-1})	*Slope* (± *SE*)	*RF*[a]
	1989 90 season						
Sim Sim	Sept Oct 89	Artificial	240	0 13 (0 12 0 15)	0 25 (0 21 0 33)	4 54 (±0 59)	
ICRISAT	25 Sept 5 Oct 89	Pigeon pea	208	0 32 (0 24 0 43)	1 9 (1 1 6 6)	1 68 (±0 35)	2
ICRISAT	17 23 Nov 89	Pigeon pea	280	0 58 (0 38 0 82)	6 4 (4 0 13)	1 23 (+0 16)	4
ICRISAT	16 20 Nov 89	Chick pea	142	0 41 (0 021 0 73)	7 3 (2 9 57)	1 03 (+0 22)	3
ICRISAT	14 16 Mar 90	Pigeon pea	208	0 32 (0 22 0 43)	2 5 (1 5 5 8)	1 45 (±0 23)	2
Coimbatore	29 Nov 89	Cotton	242	0 42 (0 27 0 59)	3 5 (2 2 7 3)	1 39 (±0 20)	3
	1990 91 season						
Sim Sim	Sept 90	Artificial	218	0 19 (0 16 0 23)	0 46 (0 37 0 64)	3 40 (+0 40)	
Delhi	Nov 90	Artificial	180	0 21 (0 17 0 27)	0 79 (0 58 1 3)	2 26 (±0 31)	
ICRISAT	11 15 Mar 91	Pigeon pea	280	1 7 (1 3 2 2)	7 8 (5 4 13)	1 91 (±0 19)	9
Shankarpalli	20 Mar 91	Chick pea	240	1 3 (1 0 1 8)	6 9 (4 7 12)	1 80 (+0 20)	7
Guntur	28 Nov 90	Pigeon pea	249	1 1 (0 85 1 5)	5 3 (3 3 12)	1 90 (±0 30)	6
Tadikonda	23 Jan 91	Chick pea	201	1 1 (0 6 1 7)	13 (7 2 41)	1 23 (+0 25)	6

[a] Resistance factor relative to Sim Sim strain

TABLE 5

Toxicity of Topically Applied Endosulfan to 30–50-mg Larvae of Indian Field Strains and a Laboratory Strain of *H. armigera*

Collection site	*Collection date*	*Parental host*	*n*	LD_1 (95% FL) (μg larva^{-1})	LD_{50} (95% FL) (μg larva^{-1})	Slope (±SE)	RF*
Delhi	Nov 90	Artificial	242	3.5 (2.3–4.7)	23 (16–41)	1.84 (±0.21)	
ICRISAT	11–15 Mar 91	Pigeon pea	320	23 (15–33)	494 (243–1564)	0.96 (±0.13)	7
Tadikonda	23 Jan 91	Chick pea	250	7.6 (5.3–10)	79 (46–194)	1.26 (±0.18)	2
Vriddhachalam	26 Feb 91	Groundnut	306	15 (9.8–30)	697 (207–8200)	0.78 (±0.14)	4

*Resistance factor relative to Delhi strain

Coimbatore strain recorded the highest tolerance (50-fold). The slope of the ldp line obtained from the Guntur strain was considerably lower than that recorded for the other strains, indicating heterogeneity with respect to cypermethrin tolerance.

3.2 Quinalphos

The Sim Sim strain was slightly more tolerant to quinalphos in 1990 than in 1989 (comparative RF = 1.5) and the ldp line slope was lower in 1990 (Table 4). The Delhi strain was tested only in 1990, however tolerance at LD_{50} was similar to the Sim Sim strain, so the latter was used as the reference in both seasons.

All the field strains were more tolerant of quinalphos than was the Sim Sim strain and there was an indication that tolerance had increased slightly in 1990–91, with resistance factors ranging from 2 to 4 in 1989–90 and 5 to 9 in 1990–91. Heterogeneity was not significant (Heterogeneity χ^2, $P > 0.05$) for any of the strains tested.

3.3 Endosulfan

Bioassays with endosulfan were conducted only in 1990–91 (Table 5). The Delhi strain was used as the reference as insufficient Sim Sim insects were available at the time of testing. The slope of the ldp line obtained from the Delhi strain was low for a susceptible and may therefore not have been truly homogeneous with respect to endosulfan resistance. However, all field strains were more tolerant of endosulfan and recorded even lower slopes, but there was no indication from any of the ldp lines of systematic curvilinearity and heterogeneity was not significant (Heterogeneity χ^2, $P > 0.05$).

3.4 Methomyl

Insufficient insects were available to bioassay the Delhi strain with methomyl, so resistance factors have been computed with respect to the Sim Sim strain (Table 6). All the field strains showed tolerance to methomyl with resistance factors ranging from 6 to 30. Ldp line slopes were particularly shallow in 1990–91 (0.9–1.0) suggesting that the strains comprised mixed resistant and susceptible genotypes. Heterogeneity was significant for the ICRISAT (Heterogeneity χ^2, $P < 0.001$) and Shankerpalli (Heterogeneity χ^2, $P < 0.05$) strains and the ldp lines indicated segregation of phenotypes.

TABLE 6

Toxicity of Topically Applied Methomyl to 30–50-mg Larvae of Indian Field Strains and a Laboratory Strain of *H. armigera*

Collection site	*Collection date*	*Parental host*	*n*	LD_{10} (95% FL) (μg larva^{-1})	LD_{50} (95% FL) (μg larva^{-1})	Slope (±SE)	RF*
1989–90 season							
Sim Sim	Sept–Oct 89	Artificial	280	0.12 (0.09–0.16)	0.55 (0.35–1.2)	1.94 (±0.29)	
ICRISAT	17–23 Nov 89	Pigeon pea	240	1.0 (0.69–1.4)	10 (5.3–37)	1.27 (±0.22)	8
1990–91 season							
Sim Sim	Sept 90	Artificial	291	0.30 (0.24–0.38)	1.2 (0.85–2.2)	2.09 (±0.28)	
ICRISAT†	11–15 Mar 91	Pigeon pea	365	2.4 (1.5–3.6)	71 (38–175)	0.87 (±0.10)	8
Shankarpalli	20 Mar 91	Chick pea	280	1.8 (1.2–2.7)	32 (16–91)	1.02 (±0.13)	6
Guntur	28 Nov 90	Pigeon pea	250	8.9 (5.3–25)	243 (61–6972)	0.89 (±0.20)	30

*Resistance factor relative to Sim Sim strain
†Heterogeneity χ^2 significant at $P < 0.001$
‡Heterogeneity χ^2 significant at $P < 0.05$

4 DISCUSSION

4.1 Measurement of resistance

Although ldp assays do not give an estimate of the frequency of resistant genotypes in a population and are considered to give a less precise measure of field resistance than discriminating dose tests they can be adequate for assessing high levels of resistance[3] as is now the case for pyrethroid resistance in *H. armigera* in South India. One major problem has been to find a suitable local susceptible strain essential to the calibration of a discriminating dose. The presence of some tolerance to pyrethroids in the Delhi strain the most susceptible Indian strain available to date would suggest that either gene flow through the subcontinent has been sufficiently widespread to have contaminated most populations with resistant genotypes or resistance has developed independently over large areas. In the absence of selection experiments to rear a homozygous susceptible strain the use of the Delhi strain as a baseline would seem to be justified on the basis that pyrethroids were not used locally to any great extent and where used they were considered to give effective field control of *H. armigera* larvae (K. N. Mehrotra 1990 pers. comm.). Further ldp lines for the Delhi strain gave consistently higher slopes than all but one of the South Indian field strains tested.

The foliar residue test was less efficient at detecting resistance. As found in an earlier study[3] the RFs recorded in the residue bioassays were lower than those from the topical tests. There was no evident correlation between the computed resistance factors of the two test methods however the number of strains tested by the residue method was low.

4.2 Spread of pyrethroid resistance

The survey results indicate that pyrethroid resistant *H. armigera* populations are probably present throughout Andhra Pradesh as only two of the strains bioassayed were more susceptible to cypermethrin than the Delhi strain. Even those which recorded low LD_{50} values and corresponding RFs generally had low slopes indicating variable levels of heterogeneity. The presence of high tolerance to cypermethrin in the two strains collected in Tamil Nadu, from cotton (in 1989) and groundnut (in 1991) suggests that resistance to pyrethroids is widespread and could feature throughout South India. As this is the first study where extensive sampling of field populations has been carried out in India there is no measure of the extent to which the situation may have changed from that in previous years.

As the development of pyrethroid resistance in the cotton belt of Andhra Pradesh was rapid[3] and *H. armigera* has high migratory potential[11] (and I. R. Riley *et al.* unpublished) the spread of resistant genotypes outside the coastal cotton-growing region was probably inevitable. The farming landscape in Andhra Pradesh is characterised by mostly small farms and mixed cropping. There is a heavy dependence on insecticides[12] which are applied on most field crops with the exception of sorghum. Because of often poor coverage, bad timing and sub-lethal doses farmers are inadvertently applying very high selection pressure for resistant genotypes. Areas of unsprayed crops may often be too small or too close to sprayed crops to provide significant refugia for susceptible populations. In Australia, the management of pyrethroid resistant *H. armigera* in cotton has relied on dilution and subsequent inter-breeding with immigrant susceptible populations from large areas of unsprayed crops[13] but unsprayed refugia were soon contaminated by resistant *H. armigera*[14] and the declining source of susceptibles for dilution has resulted in steadily increasing resistance levels in populations on cotton[15].

4.3 Seasonal variation in pyrethroid resistance

Pyrethroid resistance in *H. armigera* at ICRISAT and in the cotton belt varied substantially between years. In the rainy season (June–September) of 1986 there was no evidence of tolerance to pyrethroids but by the post-rainy season of 1987 32-fold resistance to cypermethrin was recorded from a population collected from cotton in Krishna district and 780-fold resistance from pigeon pea at ICRISAT[3]. By 1988 larvae collected from rainy-season crops were susceptible and resistance in the cotton belt during the post-rainy season had fallen to between 30- and 60-fold[5]. With reference to the Sim Sim strain data presented in this paper show that RFs were very high during the 1989–90 season and intermediate during 1990–91 (Table 2). At ICRISAT, for example, insects collected from pigeon pea in mid-November showed tolerances of 929-fold in 1989, compared to 41-fold in 1990. Similarly in Guntur district a strain collected from cotton in 1989 recorded 2100-fold resistance the highest yet recorded whereas the highest resistance recorded there in 1990–91 was 830-fold from pigeon pea. At field level, the highly resistant 1989–90 populations went largely unnoticed as pest pressure was low and despite poor control, damage was tolerable.

Seasonal variation in pyrethroid-resistance levels (based on percentage of larvae surviving a discriminating dose) has also been shown to occur in Australia[16]. There the proportion of resistant genotypes in a population is believed to depend largely upon the extent of immigration of susceptible moths at the beginning of the season, which dilute the local resistant populations derived from overwintering pupae[19].

4.4 Dynamics of pyrethroid resistance

The lower resistance levels recorded during the rainy season each year can probably be attributed to the fact that the major crop at this time, sorghum is unsprayed so that insecticide selection pressure is not operating for at least the first one or two *H. armigera* generations of the season. It has been demonstrated that migration of *H. armigera* can occur during August–September when winds are consistently from between NW and SW.[9] This could result in an influx of predominantly susceptible moths emerging from large areas of sorghum in Maharashtra and Karnataka thereby diluting residual resistant populations downwind in Andhra Pradesh.

In Andhra Pradesh it is likely that the major source of inoculum of pyrethroid-resistant *H. armigera* is derived from populations on cotton where pyrethroid consumption[1-] and therefore selection pressure is highest. There is evidence that long distance downwind dispersal of resistant moths from the coastal cotton-growing region to the Hyderabad area, some 250 km distant, may take place on the prevailing winds between October and December.[-0] This is supported by the fact that in the two seasons of this survey and between 1987 and 1988[1] pyrethroid resistance levels recorded at ICRISAT effectively mirrored those in the cotton belt.

During this and an earlier study[1] it has been demonstrated that, at ICRISAT, tolerance to pyrethroids increases as the season progresses. These increases may be attributed in part to local selection for resistant genotypes resulting from applications of pyrethroids. For example, in 1989 strains collected from pigeon pea sprayed at least once with fenvalerate and from unsprayed chick pea, separated by only about 1 km and collected at the same time, showed a 4-fold difference in tolerance. This is comparable to the 5-fold increase in tolerance recorded in north India in a field population following two sprays of pyrethroids during a single larval generation.[1] And in Australia it has been shown that selective survival of resistant larvae and moths accounts for the increase in resistance frequency when pyrethroids are applied to field crops.[10,22]

From the evidence we have to date, it seems likely that the geographic and temporal variations in levels of pyrethroid resistance recorded in *H. armigera* in Andhra Pradesh arise because of dynamic interactions between local selection pressure and immigration of resistant and susceptible moths at certain times of the year.

4.5 Summer season carry-over

In the Namoi–Gwydir region of Australia, diapause pupae constitute the major source for carry-over of resistant *H. armigera* across seasons,[19] as over 70% of pupae enter diapause at the onset of winter.[23] In South India less than 2% of pupae enter diapause (D. R. Jadhav and A. B. S. King, unpublished) and in this study < 0.5% of *H. armigera* collected from field crops in March had extended pupal periods of 57–64 days when kept in the laboratory. It is likely therefore that the major source of carry-over is from the many small populations surviving on crops and weed hosts growing under irrigation or on residual moisture in receding ponds and other wet areas (D. R. Jadhav unpublished). The small percentage of diapause pupae may however be more important sources of carry-over in drought years when few crops are grown under irrigation.

4.6 Resistance to quinalphos, endosulfan and methomyl

Resistance to the organophosphate quinalphos was low although tolerance had increased in 1990–91 (6·9-fold) over that in 1989–90 (2·4-fold). These results are consistent with data for 1986–88 where there was no evidence for significant resistance to monocrotophos.[18] Perceived problems in controlling *H. armigera* with organophosphate insecticides were more likely to be due to targeting the wrong life stage (i.e. large larvae rather than eggs and first instars) and poor application technique.

Resistance to endosulfan was not particularly high but showed some increase over the 1986–87 data.[1] In Australia control problems with endosulfan occurred in *H. armigera* populations recording 21-fold resistance.[24] However control difficulties with endosulfan sprayed on pigeon pea were experienced at ICRISAT during 1990–91 when only 7-fold resistance was recorded. Similarly, in 1987 control failures were reported in India when endosulfan tolerance ranged between 2- and 13-fold.[1]

The 1990–91 season was the first time that evidence for carbamate resistance has been recorded for *H. armigera* in India. The 30-fold tolerance to methomyl recorded in the strain from Guntur was surprising in view of the fact that this insecticide has only recently become available to farmers in India. However, in the past up to 80% of carbaryl consumption was on cotton[1] so that residual cross- or multiple resistance to carbamates could be responsible.

4.7 Future implications

Clearly the *H. armigera* insecticide resistance issue in India is becoming ever more acute. Pyrethroid resistance is widespread in populations in Andhra Pradesh and it is likely that few refugia of susceptible populations remain to dilute the build up of resistant populations. Tolerance to endosulfan has increased and this is the first season in which carbamate resistance has been recorded from the cotton belt. Selection pressure for resistance in *H. armigera* is most probably driven by spraying cotton, as this crop accounts for 41% of pesticides used in India, whereas pulses account for only < 4%.[2] Resistance