INSECTICIDE RESISTANCE IN *HELICOVERPA ARMIGERA* (HÜBNER): STATUS AND PROSPECTS FOR ITS MANAGEMENT IN INDIA

N. J. ARMES[1], D. R. JADHAV[2] & P. A. LONERGAN[3]

1 - Natural Resources Institute, Chatham Maritime, Kent, U.K.
2 - International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, INDIA
3 - c/o Insecticide Resistance Action Committee of Groupement International des Associations Nationales de Fabricants de Produits Agrochimiques, Brussels, BELGIUM

Abstract

Insecticide resistance and concomitant field failures to control the cotton bollworm, *Helicoverpa armigera* (Hübner) were first recorded in south India in 1987. During the 1992/93 cropping season a discriminating dose technique was used to routinely monitor resistance in four major cotton and pulse growing areas of Andhra Pradesh State. Very high levels of resistance to pyrethroids and significant endosulfan and organophosphate resistance were a feature of all regions monitored - the intensity of expression being determined by local selection pressure and mixing of populations by windborne migration against a changing background of insecticide use across seasons. Levels of piperonyl butoxide insensitive pyrethroid resistance were higher in the more intensive insecticide use regions. Farmers are applying more frequent and higher doses of insecticides, often as mixtures, in an attempt to control resistant *H. armigera*, but field failures and economic losses are common. Wide-scale implementation of insecticide resistance management (IRM) rationale, resulting in greater control over the use of insecticides is urgently needed to reduce the resistance selection pressure on conventional insecticides and to conserve susceptibility to newer insecticides and biorationals with novel modes of action. Constraints and prospects for IRM implementation in India are discussed.

Introduction

Insecticide resistant cotton bollworm, *Helicoverpa* (=*Heliothis*) *armigera* (Hübner), populations were first reported in India in September 1987, when farmers in the coastal districts of Andhra Pradesh were unable to control the very high populations of *H. armigera* on their cotton crops with conventional insecticides; many farmers applied over 30 insecticide sprays but were unable to contain the pest. Later in the season, pigeonpea and chickpea crops were also badly attacked and insecticides were mostly ineffective against *H. armigera*, even in inland regions 200-300 km remote from the coastal cotton belt (Sawicki, 1989). High levels of resistance to the synthetic pyrethroids were subsequently confirmed by Dhingra *et al.* (1988) and McCaffery *et al.* (1989) as a major cause of control failures. In economic terms, resistant *H. armigera* caused an estimated loss of 15% of the total 1987/88 season income of Andhra Pradesh State, equivalent to some US$150 million (Kishor, 1992). In human terms, over 20 farmers committed suicide in the major Andhra Pradesh cotton growing districts of Guntur, Krishna and Prakasam during 1987/88 because of financial difficulties arising from loss of income and inability to repay agricultural loans. Since 1988, cotton farmers have largely been coping with poor control of *H. armigera* by applying more frequent insecticide applications, generally at higher than recommended rates, and as mixtures of 2-4 insecticides. Spray failures have become a way of life and casual labour is employed to 'hand-pick' large larvae. Recent resistance monitoring has shown that pyrethroid resistance is now widespread in south and central India and appreciable levels of cyclodiene, organophosphate and carbamate resistance are present in many regions (Armes *et al*., 1992; Armes, unpublished data).

Fortunately there has not been a recurrence of the disastrous situation of the 1987/88 and 1988/89 seasons, where severe *H. armigera* attack coupled with drought, provided little scope for cotton plants to compensate for early season damage. However, no significant changes in cotton agronomy and pest management have taken place in the intervening years, and it is likely that it is only a matter of time before a similar scenario occurs, unless strategies for management of resistant *H. armigera* are put into place.

Since 1990, the Natural Resources Institute (NRI), U.K., and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, have been collaborating on the identification of insecticide resistance management (IRM) options for *H. armigera* control in India. In the short term, there was an urgent need to determine the extent and severity of resistance to insecticides commonly used for bollworm control, and if feasible, to provide recommendations to limit its spread. In the longer term, practical IRM strategies need to be evaluated and implemented. The agrochemical organisation, the Insecticide Resistance Action Committee (IRAC), of Groupement International des Associations Nationales de Fabricants de Produits Agrochimiques, became concerned by the loss of susceptibility of *H. armigera* to conventional insecticides in the Indian subcontinent and the possible threat to newer insecticides with novel modes of action. During the 1992/93 cropping season they supported the research program by providing finance for P. A. Lonergan to join the research team at ICRISAT to monitor resistance in the coastal Andhra Pradesh cotton belt.

This paper describes the results of the 1992/93 season's monitoring studies and highlights some of the more immediate constraints to rapid implementation of *H. armigera* IRM programs in India.

Resistance Monitoring Program

During the 1992/93 cropping season, pyrethroid and endosulfan resistance were monitored at four locations in Andhra Pradesh (Fig. 1):

- ICRISAT Centre, Medak District - a cereal and legume cropping system with moderate insecticide use; spray decisions for *H. armigera* control are based on threshold counts of eggs and larvae.

- Rangareddi District - a mixed cropping region, traditionally cereals and legumes but an increasing area for cash crops, cotton in particular; insecticide use in this region is intensifying with the expanding area under cotton.

- Krishna District - a cotton-pigeonpea strip cropping area; moderate insecticide use.

- Guntur District - a traditional cash crop growing region, where cotton, chillies and tobacco are the major crops grown as monocultures on large (by India standards), 1-6 ha fields. Farmers are risk-averse and rely heavily on insecticides.

From October 1992, the organophosphate (OP) insecticide, quinalphos, was added to the monitoring program and assayed against samples from ICRISAT and Guntur. Quinalphos is second only to monocrotophos as the most widely used OP compound for bollworm control on cotton in India. It was chosen as the representative OP in preference to monocrotophos, because bioassay of these two chemicals against laboratory susceptible strains showed that log dose probit line slopes were significantly higher for quinalphos (3-4.5) (Armes *et al*., 1992), than monocrotophos (1-2) (Armes, unpublished data). The latter was therefore less suitable for confident determination of a discriminating dose under our bioassay conditions.

The monitoring technique was based on that in use in the Australian *H. armigera* IRM program (Forrester and Cahill, 1987; Forrester *et al.,* 1993). Eggs were collected weekly (except Rangareddi District where sampling was fortnightly) from host plants in the field. The areas surveyed at each location varied over the cropping season, depending upon availability of host plants at a susceptible stage for *H. armigera* oviposition. Typically, the first eggs of the season (June-August), were collected from wild hosts, after which they were collected from crops (late August onwards). The major crop hosts for *H. armigera* in Andhra Pradesh are tomato, sorghum, cotton, pigeonpea, sunflower, chickpea, tobacco and groundnut. In addition there are many other minor hosts which support low density populations, allowing for continuous breeding throughout the year (Fig. 2). In the laboratory, eggs were removed from the plant parts with a brush and placed individually onto the side wall of a 7.5 ml cell in a 12 well tissue culture plate (Linbro, ICN Flow Ltd.) containing a chickpea-based artificial diet.

The resulting 3rd-4th instar larvae in the weight range 30-40 mg, were randomly assigned to one of the following discriminating dose screens (these five or six treatments were undertaken weekly unless egg numbers were low):

- Cypermethrin 0.1 μg/μl - Approximate LD_{99} for homozygous pyrethroid susceptible *H. armigera* from Australia (Gunning *et al*., 1984) and the Sudan (Armes *et al.,* 1992)
- Cypermethrin 1.0 μg/μl - Precise kill of heterozygotes or homozygotes is unknown, but this dose was introduced as a "twin" cypermethrin dose because of the very high survival at the 0.1 μg discriminating dose.
- Cypermethrin 0.1 μg + Pbo 50.0 μg/μl - The amount of suppression of cypermethrin resistance by piperonyl butoxide (Pbo) is an indicator of the significance of metabolic detoxification in pyrethroid resistance.
- Fenvalerate 0.2 μg/μl - LD_{99} for pyrethroid susceptible *H. armigera* calibrated in Australia (Forrester and Cahill, 1987).
- Endosulfan 10.0 μg/μl - Approximate LD_{99} for endosulfan susceptible *H. armigera* calibrated in Australia (Forrester *et al.,* 1993).
- Quinalphos 0.75 μg/μl - LD_{99} for homozygous organophosphate susceptible *H. armigera* calibrated against a laboratory susceptible strain maintained in the UK (Armes *et al.,* 1992), and recently confirmed against OP susceptible field strains from Nepal (Armes, unpublished data).

One microlitre of insecticide solution (technical insecticide dissolved in acetone at the required discriminating dose), was applied to the thoracic dorsum of larvae with a Hamilton repeating dispenser. End point mortality was assessed at six days after treatment. A larva was considered dead if it was unable to move in a co-ordinated manner when prodded. Periodically, control groups of larvae were dosed with 1.0 μl of acetone alone. No control mortality was observed throughout the season (egg-larval parasitoids were found in some larvae after dosing, but these could easily be distinguished and were removed from the assay prior to final mortality assessment). All rearing and insecticide assays were conducted at 25 $\pm$ 2°C under natural photo period (approximately 12h light : 12h dark).

Pesticide Use Profile

Nearly all farmers in south India use pesticides on cotton and pulse crops and those that do not, do so for economic reasons rather than for a preference towards natural ("do nothing") control. As a result, farmers with enough cash or credit worthiness are willing to invest heavily in chemical control and 25-30% or more of a farmer's monetary inputs into cotton growing are spent on pesticides and their application (Kishor, 1992). The majority of farmers lack knowledge about pests and their control and spray decisions are frequently ill-founded. This is compounded by an ever increasing range of insecticide products/brand names and absence of reliable and specific pest control recommendations. Insecticide resistance is a difficult concept for most farmers to perceive and often the initial reaction to spray failures is that the products they purchased were sub-standard. In an attempt to improve control, many farmers mix chemicals and mixtures of two, three or four insecticides of different brands are not uncommon. Selection of chemicals for mixtures is haphazard; sometimes different brands of the same active ingredient or insecticide group are unwittingly mixed. Rarely is any allowance made for adjusting the concentrations accordingly and higher than recommended rates are applied. This aside, even at ICRISAT Centre where spray decisions for *H. armigera* control are based on threshold counts of eggs and larvae, insecticide use was high during the 1992/93 season because of very high pest pressure and poor control of resistant larvae. The estimated average number of sprays applied to a succession of host plants at ICRISAT over the season was ten and the maximum was about 15 (Fig. 3). In farmers fields close to ICRISAT (Rangareddi District), cotton crops alone received 9-13 applications. Fewer farmers sprayed their pigeonpea crops that flowered after cotton had matured, despite heavy *H. armigera* damage, because most of their cash/credit limit had been spent on pesticides for cotton. In coastal Andhra Pradesh and Guntur District in particular, heavier insecticide inputs are used. Insecticide application starts on 15-25 day old cotton, initially for aphid (mainly *Aphis gossypii* Glover) and jassid (*Amrasca devestans* (Distant)) control and later for *H. armigera*, regardless of whether or not pests are present. Farmers prefer prophylactic treatment of cotton, perceiving that insecticides provide insurance against pest attack. Weekly application (often of mixtures) is common with some more wealthy farmers applying insecticide every three days during peak flowering and squaring of cotton. In 1992/93 the average number of applications to cotton in the Guntur region was probably close to 25 (Fig. 3).

Pyrethroid resistance

Cypermethrin 0.1 μg (Fig. 4) - At ICRISAT Centre, early season pyrethroid resistance in populations from unsprayed wild hosts from June to August was prevalent with 70-80% survival of individuals at the discriminating dose. Resistance frequencies rose steadily over the cropping season, reaching 100% by mid November. The situations in Rangareddi and Krishna Districts were similar; pyrethroid resistance was already prevalent (80% survival) at the start of the respective cropping seasons in early August and September. Over 90% survival was attained by mid November and remained more or less at this level for the remainder of the cropping season. Guntur District showed the most severe resistance levels at this discriminating dose. Early season resistance frequencies in September were over 80% and 100% levels were attained by mid October for the remainder of the season.

Cypermethrin 0.1 μg + Pbo 50 μg (Fig. 4) - At ICRISAT Centre, frequencies of cypermethrin + Pbo resistant phenotypes increased steadily over the cropping season from August (at a low of 29% survival) to February (peak of 91% survival). The slight decrease in resistance frequencies between mid July to late August (29-41% survival), most probably occurred because the major *H. armigera* hosts at the start of the rainy season in June-July are wild plants, where no insecticide selection is operating. By early August, local farmers started applying insecticides to field crops and this correlates with a steady rise in frequency of Pbo insensitive resistance from early September on. In Rangareddi District, Pbo suppression was less, with resistance frequencies ranging from 52-80%. Samples from Krishna District were only sufficiently large during the October-November period to assay for Pbo suppression. Over the 7 week period, Pbo insensitive resistance frequencies ranged from 36-73%. Of the four locations, Guntur District samples exhibited the least Pbo suppression. Resistance frequencies increased steadily over the cropping season from 46% in September to 92% by January. The data clearly indicates that the frequencies of Pbo insensitive pyrethroid resistance are higher in the more intensive insecticide use districts of Krishna and Guntur and this is concomitant with lower Pbo suppression in the same areas (Table 1).

Cypermethrin 1.0 μg (Fig. 5) - Data have been collected for two seasons at ICRISAT Centre and some interesting trends are starting to appear. Early season resistance frequencies were higher in 1991/92 compared to 1992/93 (50% versus 30%). Resistance increased steadily over each season reaching a peak in egg collections from chickpea in March (approximately 90% frequency) in both years. Chickpea is the last crop of the season before the onset of the summer when no crops are grown on the ICRISAT farm. In both years, subsequent egg collections during April were from isolated patches of wild hosts growing on soils with residual moisture after sporadic summer thunderstorms. In 1992, resistance frequency declined from 81% in late March to 37% in late April, and in 1993, from 90% in mid March to 55% in mid April. In Rangareddi District, resistance frequency started at 30% in August, rising to 50% by January. From early February there was a marked increase in frequency, peaking at 93% survival by the end of the cropping season in late March. The resistance profiles for Krishna and Guntur were similar. Both exhibited a rapid increase in pyrethroid resistance frequency from September (16-27% survival) to November (78-82% survival), during which time spray applications on cotton were maximum. Far fewer farmers sprayed cotton after December and this correlates with a decrease in resistance from late December onwards.

Although the coastal Andhra Pradesh region has historically been considered to have a more severe *H. armigera* pyrethroid resistance problem, the end of season resistance frequencies at ICRISAT and Rangareddi were higher (approximately 90% versus 80%). A possible reason for this is that the cropping season in the inland areas is longer than coastal regions because small farmers continue to grow a patchwork of irrigated vegetable crops (invariably treated with insecticides), during the post rainy and summer seasons. This extends the availability of host plants which may augment selection for resistance over more generations. In the coastal sampling areas, far fewer farmers grow summer vegetables and increasing areas of land become fallow from February until the start of the next monsoon in June.

The utility of "twin" discriminating doses in situations where insecticide resistance is very high, has been demonstrated in this work. Had only the cypermethrin 0.1 μg dose (approximately LD_{99} for susceptible *H. armigera*), been used for monitoring pyrethroid resistance, much information on seasonal changes in resistance would have been lost because of the rapid attainment of full resistance to cypermethrin 0.1 μg within a few weeks of the start of the cropping season - particularly in the intensively sprayed cotton areas.

Fenvalerate 0.2 μg (Fig. 6) - The fenvalerate profiles were similar to cypermethrin 0.1 μg, which is probably not surprising because both doses are approximations to their respective LD_{99}'s for pyrethroid susceptible *H. armigera*. At all four monitoring locations, fenvalerate resistance frequencies were on average 5-9% lower than for cypermethrin, but differences were not statistically significant (X^2, P>0.05). The main reason for including fenvalerate in the monitoring program is to provide a comparison of the severity of pyrethroid resistance in India with that in eastern Australia where an effective IRM program is in operation (Forrester and Cahill, 1987; Forrester *et al.,* 1993).

Endosulfan resistance

Endosulfan 10.0 μg (Fig. 7) - The seasonal picture of changes in resistance and maximum resistance frequencies (up to 70-85% survival) were similar at all four locations. The rate of increase of resistance in the more intensive insecticide use areas of Krishna and Guntur were greater than at ICRISAT and Rangareddi, over the period August to December when insecticide selection pressure was at its peak. Similarly, *H. armigera* at all locations showed some reversion towards lower resistance at the end of the cropping season. This was more obvious in the Krishna and Guntur samples where cotton was the main source for *H. armigera,* and few farmers sprayed this crop after mid December.

Organophosphate resistance

Quinalphos 0.75 μg (Fig. 8) - Resistance to quinalphos was monitored from mid October onwards. At ICRISAT Centre, resistance frequencies ranged from 27-59% (average approx. 40% survival), but with no obvious seasonal trend. In Guntur, resistance frequencies started at over 60% in October, peaked at 77% in late December and on the basis of a single assay in late January, declined to a low of 46%.

Status of Insecticide Resistance

Clearly, the data for all four monitoring locations indicate that south India has a serious *H. armigera* insecticide resistance problem, with pyrethroid resistance being the worst of the three chemical groups assayed. Putting this into a global perspective, comparable data for the Namoi/Gwydir region of Australia show that pyrethroid resistance in Guntur District was on average 25% higher (based on survival at fenvalerate 0.2 μg) in the same year (N. Forrester, pers. comm.). This is despite the fact that *H. armigera* in Australia developed pyrethroid resistance four years before India (Gunning *et al.,* 1984). At all sampling locations, pyrethroid resistance started at a high level at the commencement of the rainy season (70-85% survival at fenvalerate 0.2 μg). This differs from the Namoi/Gwydir situation where early season resistance frequencies in most seasons starts at only 10-30% (at fenvalerate 0.2 μg). This difference is probably attributable to the fact that insecticide selection on *H. armigera* populations differs between the two countries. In south India there is little evidence for diapause over the summer period (Jadhav and Armes, pers. comm.), and the small areas of irrigated vegetables and summer grown cotton which harbour residual *H. armigera* populations at this time, are intensively sprayed and therefore selection pressure is continuous throughout the year. In eastern Australia, fewer generations are completed each year as a result of pupal diapause during the winter period (Fitt and Daly, 1990), and therefore resistance selection is over a much shorter period.

Endosulfan resistance frequencies were high at all locations and increased over the season with increasing selection pressure. Compared to the situation in Australia, India is experiencing a worse endosulfan resistance problem, with on average 27% higher resistance levels than the Namoi/Gwydir (N. Forrester, pers. comm.) At all monitoring locations there was slight recovery of susceptibility towards the end of the cropping season, by which time insecticide application to field crops had declined. This indicates some instability in endosulfan resistance, which could arise through immigration of susceptible moths breeding with local populations thereby reducing the frequency of resistant homozygotes, and/or because of fitness costs associated with specific cyclodiene resistance mechanisms. The former seems unlikely in view of the apparent ubiquity of endosulfan resistance in *H. armigera* in south India (Armes *et al.,* 1992; Armes *et al.,* unpublished data), making the likelihood of large influxes of susceptible moths unlikely. Fitness deficits are plausible, but not researched for Indian *H. armigera*. Forrester *et al*. (1993) found that in Australia endosulfan resistant *H. armigera* larvae were slower to develop, but it has not been shown that this contributes to fitness disadvantage under field conditions. In mosquitoes however, there is good evidence that the nerve insensitivity resistance mechanism confers reduced male mating success in HCH/dieldrin resistant strains (Rowland, 1991).

Compared to ICRISAT Centre, organophosphate resistance levels were higher in Guntur District. From the limited data available for Guntur there were indications of a decline in resistance toward the end of the season when most farmers had ceased spraying field crops and cotton in particular. The mechanisms of OP resistance are unknown at this stage, but the possibility of cross resistance with endosulfan needs to be looked at because of the potential role of glutathione s-transferase in both OP (Dautermann, 1985) and endosulfan (Kern *et al.*, 1991) resistance.

A very interesting result from the study is that at ICRISAT Centre, pyrethroid resistance was as severe as in farmers fields in Rangareddi District, approximately 50 km remote from ICRISAT, even though pyrethroids were little used on the ICRISAT farm for *H. armigera* control. Widespread mixing of populations through migration is a common feature of *H. armigera* (Daly and Gregg, 1985; Farrow and Daly, 1987; Riley *et al*., 1992), and this clearly highlights that it is only feasible to manage resistance and demonstrate impact of an IRM strategy if the majority of farmers over large areas take collective action. If only a few farmers co-operate then their efforts will be swamped by the overwhelming immigration of insecticide selected moths from crops where farmers have not adopted IRM practices.

The end of season drop in resistance frequencies more or less apparent for all chemical groups, is significant as it indicates that resistance, or at least some of the mechanisms involved in resistance, may exhibit a competitive disadvantage in the absence of insecticide selection pressure. Dilution of resistance by immigration of susceptibles at the tail-end of the cropping season seems remote in view of the widespread occurrence of pyrethroid and endosulfan and possibly also OP resistance in south India (Armes *et al*., 1992; Armes *et al.,* unpublished data). If this is the case, then at least partial management of resistance should be feasible simply by a reduction in selection pressure through more judicious use of insecticides on cotton and pulse crops. That is not to say that IRM will bring about reversion to susceptibility, but at least lower, and possibly 'stable' levels of resistance will allow for greater predictability of control and hopefully reduce resistance selection pressures on newer insecticide groups.

IRM Constraints

There is clearly an urgent need for implementation of curative IRM for *H. armigera*. However, despite resistance first being detected in 1987, workable IRM strategies have yet to be demonstrated in India. Some of the major constraints to rapid implementation posed at the farmer, researcher and extension level are highlighted.

Lack of community action

In India, farms are small and farmers individualistic and generally poorly educated. As mentioned earlier, IRM can only be successful through group action. At present no mechanism exists to co-ordinate the actions of farmers to bring about a collective responsibility for reducing insecticide use.

Education/extension

These two areas are the key to effective IRM programs. Dissemination of research results to farmers should be undertaken by well-trained extension officers. In general, linkages between research scientists and extension officers are weak and as a result soundly researched pest control practices are slow to reach farmers, if at all, and may not be passed on accurately to extension staff. Perhaps even more of a constraint is the lack of resources and support for extension officers to do their jobs effectively, engendering low morale and limiting the number of farmers with whom extension departments can interface.

No commitment to long term cotton production

As most cotton in south India is grown under rainfed conditions and nearly all farm operations are done by manual labour, farmers have no investment in expensive machinery. It is therefore comparatively easy for farmers to switch to growing different crops if cotton becomes uneconomic. Farmers will put up with one or two seasons of low returns, but thereafter they are quick to change to growing alternatives. A re-visit in 1992 to some of the villages in Krishna District which suffered serious cotton failures in 1987, revealed that in subsequent seasons the land area planted to cotton had reduced by 80-90%. Farmers were no longer prepared to accept the risks of economic yield losses due to poor control of *H. armigera*, preferring to grow oilseeds (groundnut and sunflower), which required less insecticide inputs and generally provided assured yields. Farmers could well decide that IRM is too difficult a course to follow, preferring to continue their old practices until it is no longer viable to grow cotton and then move to alternatives.

Past conditioning

In the 1970's to early 1980's farmers were encouraged by industry and agriculture departments to adopt calendar-based pesticide application. Up until the development of insecticide resistance and resurgence of sucking pests, this was largely successful for cotton pest control and most farmers and extension workers still favour such technology as it is simple to use. However, with the advent of resistance in *H. armigera,* calendar-based applications are no longer effective, and in recent years we have seen many cases of indiscriminate pesticide use leading to larger pest-related yield losses in cotton than not applying pesticides at all. What resistance has done is to reduce the effective window for insecticides to achieve economic control of *H. armigera* (Daly *et al.*, 1988), and correct application timing is imperative if an insecticide is to be at all useful. Badly timed sprays (say against large resistant larvae) at recommended rates will have little or no effect on the primary pest but will destroy its natural enemies and increase the likelihood of outbreaks of secondary pests. Integrated pest management (IPM) is very much in vogue with agriculture departments, and to some extent industry in India, but despite much research and demonstration trials, adoption by farmers has largely been poor. This is probably because IPM requires a sound knowledge and decision making approach largely unavailable to all but a minority of progressive, well educated farmers. Uncertainty about IPM could be tackled by education and training, but at present, funding constraints on research, extension and farmer education are hampering the required rapid adoption of IPM/IRM principles.

Role of pesticide dealers

The first line contact for most farmers to obtain advice on pest control is the pesticide dealer, of which there are over 86,500 in India (Matthews, 1993). Dealers are rarely impartial and will invariably advise a farmer to purchase pesticide even when none is required. Further, now that chemical control against resistant *H. armigera* is less effective, dealers are encouraging the use of *ad hoc* mixtures of insecticides for bollworm control. Resource poor farmers are also financially dependent on dealers for credit to buy insecticides and this limits their ability to question the choice, quantity and quality of insecticide products. Farmers settle their debts to the dealer at harvest time, and it is often only then that they realise that purchase (often excessive) of insecticide has resulted in financial loss.

Low cost of insecticides

It is estimated that in India there is almost one pesticide formulation plant for every 1.5 million people (Sugavanam, 1993). This has resulted in an overwhelming number of brand name products available in the market place. Partly as a result of stiff competition, pesticide prices are relatively low. Compared to Australia for example, costs per hectare for formulations from reputable companies with equivalent active ingredients for application on cotton at locally recommended rates, are at least half the price in India (Australia data from Forrester *et al*., 1993; N. Forrester, pers. comm.). Products from back-street formulators are often marketed at even lower prices by reducing the quantity of the active ingredient and using low grade sticker and spreader adjuvants. Laboratory analysis of insecticide samples from a random survey of pesticide shops in Karnataka State in 1992, identified 21 products (6% of samples analysed) with below specified concentrations of active ingredient (Office of the Principal Agricultural Officer, Gulbarga, pers. comm.) As a consequence, not only is there a tendency to overuse and over-depend on insecticides, but also use of the cheaper, often sub-standard insecticides is augmenting resistance selection through inadvertent application of low rates.

Variable crop planting dates

Cotton and pulses, the major crop host plants of *H. armigera* in India, are largely rainfed crops planted on the first monsoon rains. As rainfall in the semi-arid tropics of south India is characteristically erratic, even over distances of a few kilometres, there is no synchrony in timing of cultural management practices. Even in irrigated cotton areas, farmers take up sowing at different times depending upon farmer preferences, seed and labour availability, and access to credit. Asynchrony in planting times favours pest build-up via a succession of hosts at a suitable developmental stage for oviposition, and makes it impractical to define parameters for a community action window based pesticide use strategy (e.g. Forrester, 1990) in nearly all regions, perhaps with the exception of the irrigated tracts of the Punjab.

Varietal preferences

In south India, most farmers prefer to grow long maturing varieties, partly because historically they have shown good compensatory ability providing insurance against early season pest attack and drought, and partly because such varieties tend to produce long and extra long staple cotton, which fetches premium market prices. These varieties are notoriously pest susceptible, often growing to unmanageable heights and their long duration allows for multiple pest generations. It is not surprising therefore that high insecticide inputs are needed. Despite repeated crop failures, most farmers in the region are loath to grow shorter staple length/shorter duration varieties/hybrids and this makes IRM implementation problematic in such regions.

IRM Prospects

Having listed the most immediate practical constraints to IRM, it is pertinent to ask the question: "is it feasible to implement IRM in a developing country like India where knowledge, expertise and infrastructure are lacking because of inadequate and under financed research and extension operations?" There has been a reluctance in some quarters to accept insecticide resistance as a problem; control difficulties being attributed to weather factors and sub-standard insecticides, and this has hampered research and development into IRM initiatives by national institutes. However, this attitude is changing and an awareness of the need for IRM in cotton in particular, is reaching senior decision makers. Also at the other end of the spectrum, farmers are starting to question the role of insecticides in pest management. In Maharashtra and Tamil Nadu in particular, farmers are becoming increasingly receptive to the concepts of IPM and many are realising the financial benefits of reduced conventional insecticide inputs. The industry sector concerned over loss of susceptibility to their products and attendant decline in sales, is also emphasising the role of IPM and promoting more "environmentally friendly" pest management options and diversification into biorationals.

On the plant breeding side, a lot of emphasis in national agricultural research stations in recent years has been placed on developing cotton varieties and hybrids with many of the desirable traits for improved management of bollworms: pest and disease tolerance, pest damage compensation, shorter duration (less insecticide inputs), stature (more efficient insecticide application), reduced fertiliser requirements etc.

Whether or not curative IRM succeeds in India will largely depend upon whether research and extension workers can meet the challenge to develop practically based resistance management protocols, with options appropriate to a range of agroclimatic conditions and economic backgrounds. Clearly a classical IRM strategy involving restriction of use of chemicals to certain times in the season and reliance on voluntary compliance (Forrester, 1990), would not be practical here. More immediate benefit could be achieved from implementation of crop management packages including improvements in cotton agronomy and cotton varieties/hybrids, pest scouting systems and robust need-based insecticide use schedules. Indian farmers are shrewd and once they are convinced of the benefits through demonstrations and training, there is no question that uptake of IRM techniques in cotton will take-off - convincing the politicians will have to come later!

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Table 1. Average resistance frequencies to cypermethrin and cypermethrin + piperonyl butoxide and percentage of cypermethrin resistance suppressible by Pbo in *H. armigera* collected in concurrent weeks at the four sampling locations during the 1992/93 cropping season.

First analysis: Five coincident weeks data between mid October and late November 1993 for three sampling locations	ICRISAT	Krishna	Guntur
Average survival at cypermethrin 0.1 µg discriminating dose	91.3%	94.7%	96.4%
Average survival at cypermethrin 0.1 µg + Pbo 50 µg discriminating dose	49.9%	66.6%	72.7%
Average suppression of cypermethrin resistance by Pbo	45.3%	29.7%	24.6%
Second analysis: Eight coincident weeks data between mid September 1992 and mid January 1993 for three sampling locations	ICRISAT	Rangareddi	Guntur
Average survival at cypermethrin 0.1 µg discriminating dose	87.6%	90.1%	95.4%
Average survival at cypermethrin 0.1 µg + Pbo 50 µg discriminating dose	53.8%	57.6%	72.5%
Average suppression of cypermethrin resistance by Pbo	38.6%	36.1%	24.0%

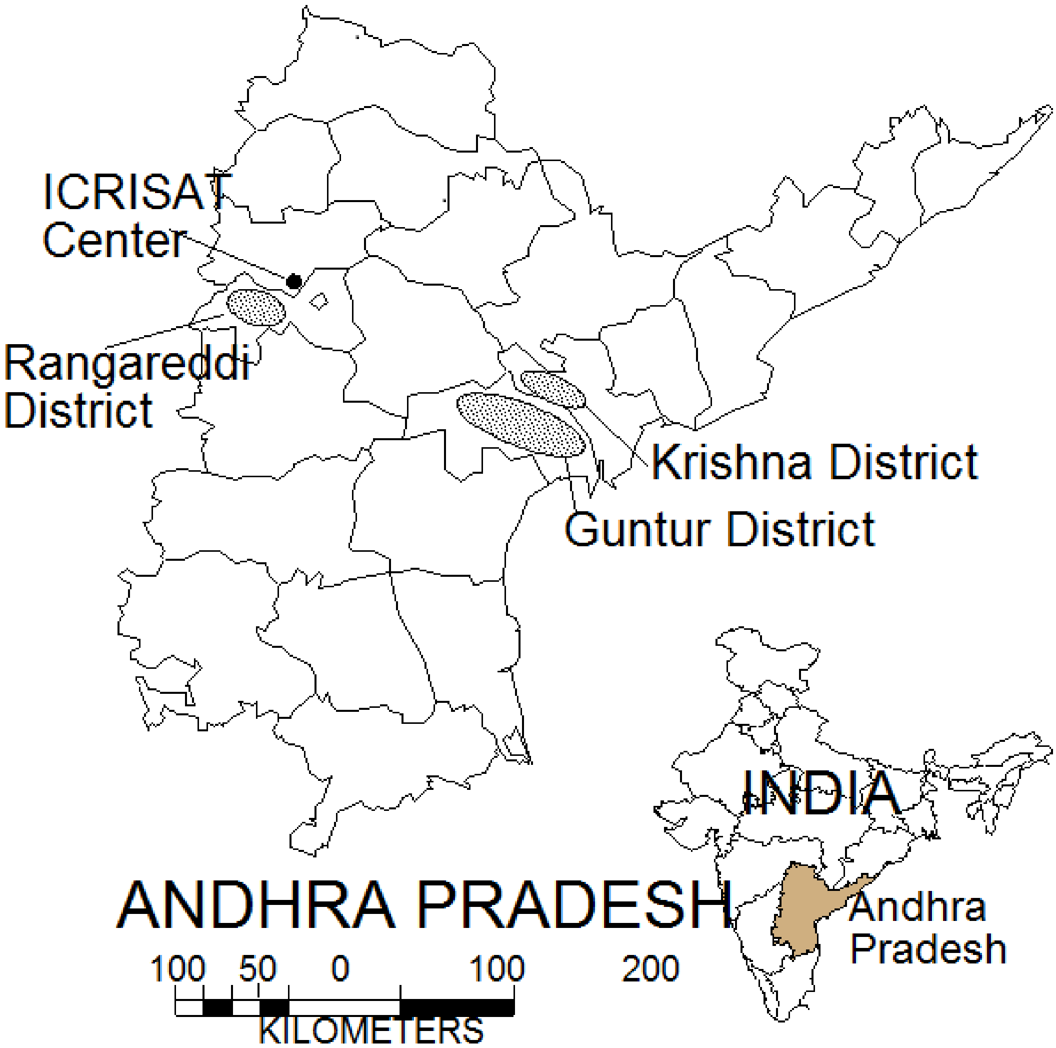

Figure 1. Arm et al.

Figure 1. Locations sampled for *H. armigera* eggs in Andhra Pradesh State during the 1992/93 cropping season.

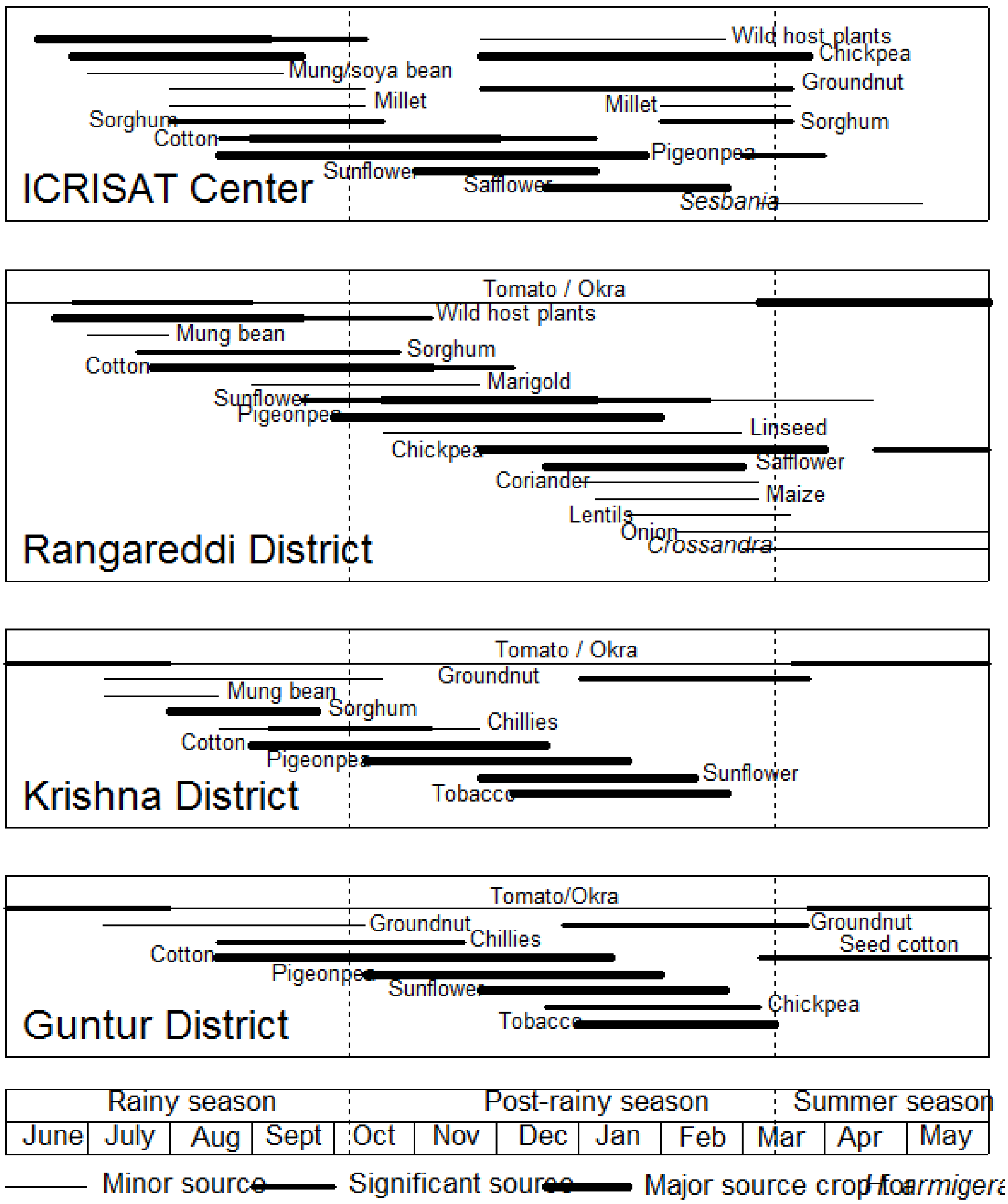

Figure 2. Armes *et al.*

Figure 2. Host plant profiles showing approximate timings of plant susceptibility to *H. armigera* infestation at the four monitoring locations during the 1992/93 cropping season.

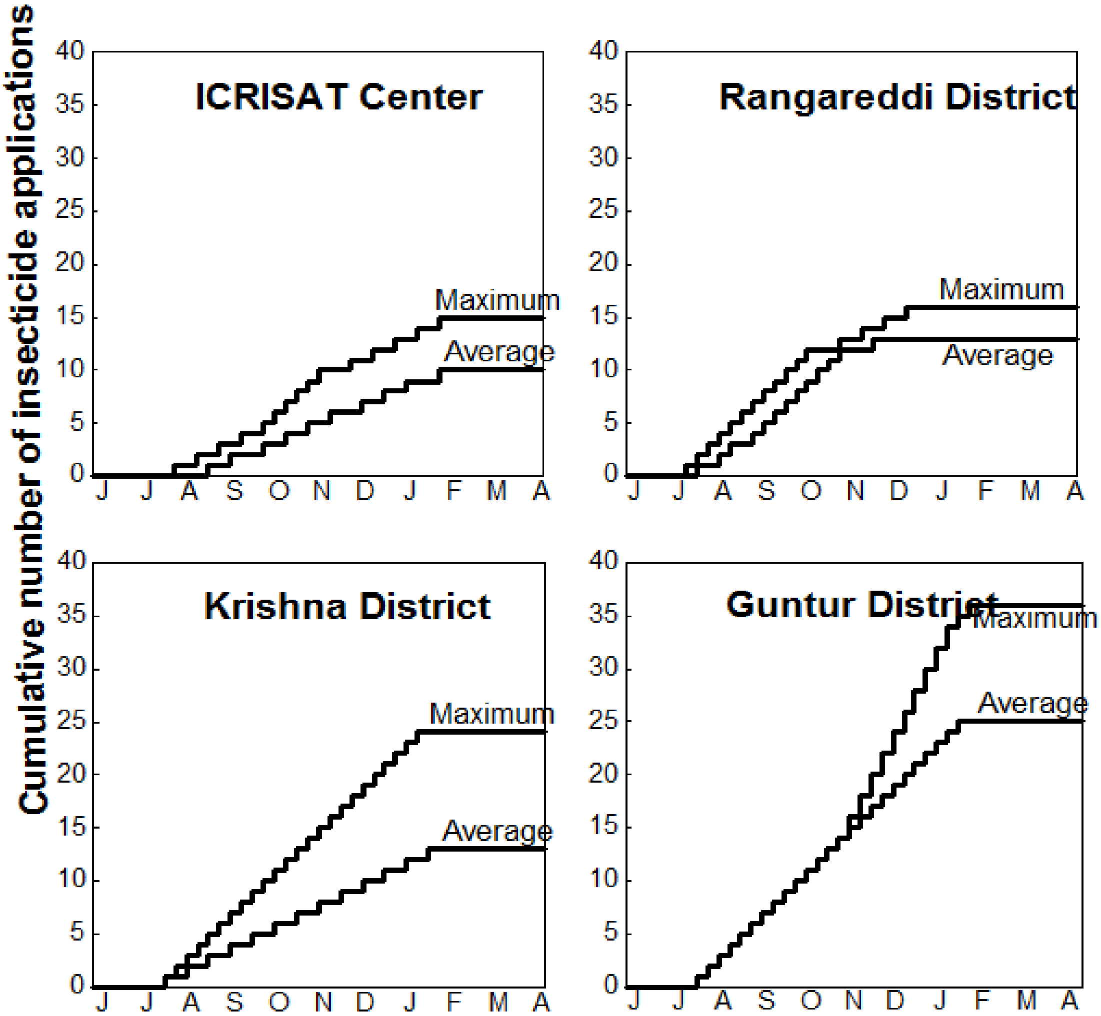

Figure 3. Armes *et al*

Figure 3. Approximate cumulative number of insecticide applications to a succession of field crops at the four monitoring locations during the 1992/93 cropping season.

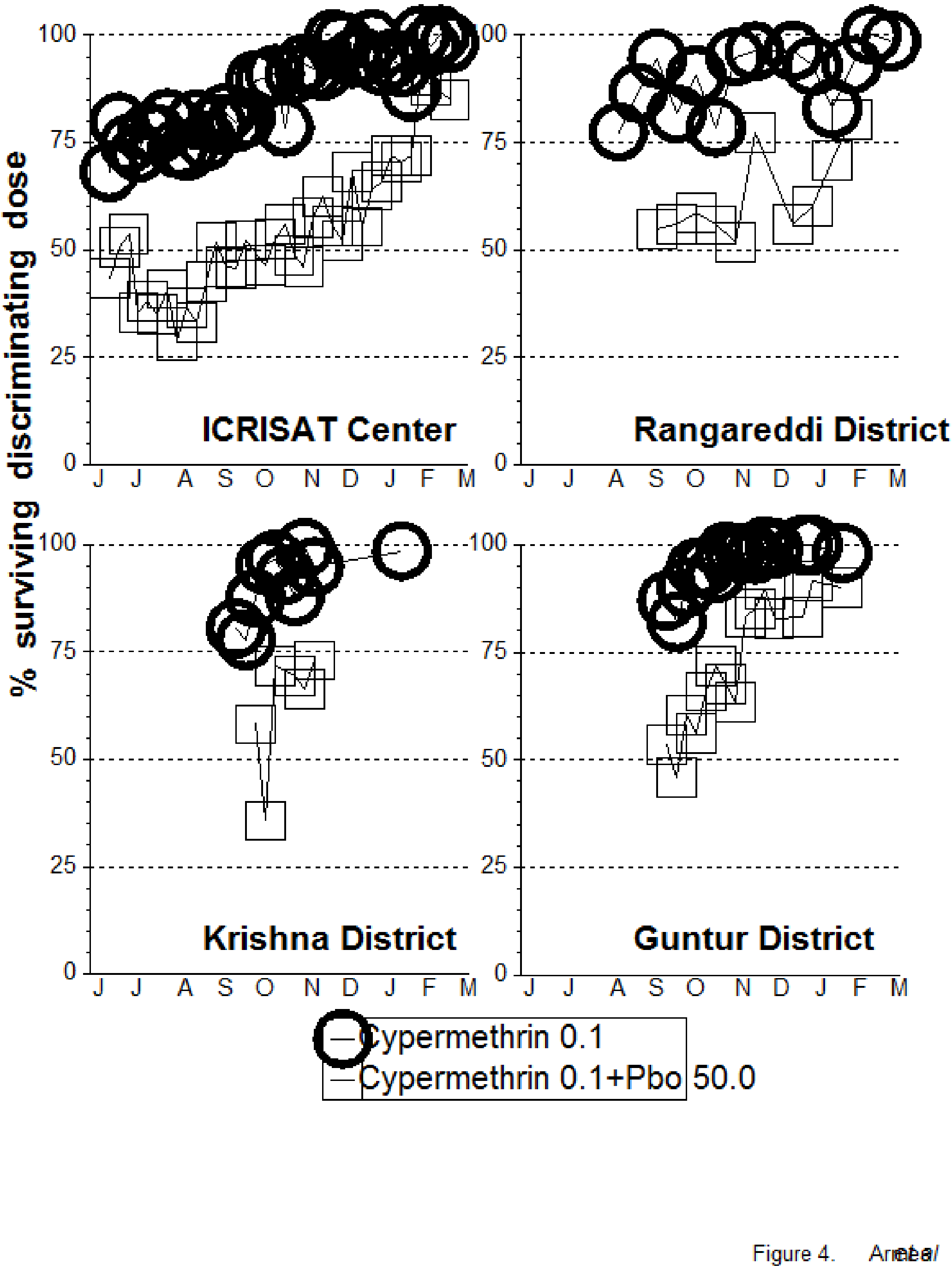

Figure 4. Average weekly pyrethroid resistance frequencies and effect of piperonyl butoxide on suppression of pyrethroid resistance in *H. armigera* at the four monitoring locations during the 1992/93 cropping season (based on % of 30-40 mg larvae surviving the cypermethrin 0.1 µg and cypermethrin 0.1 µg + Pbo 50 µg discriminating doses).

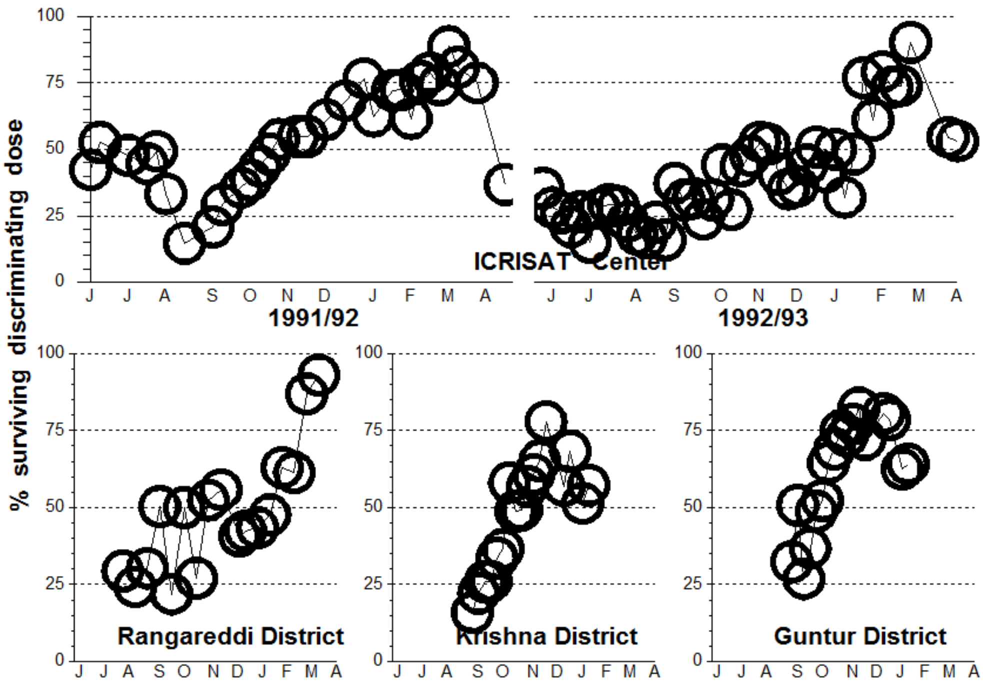

Figure 5. Armes et al

Figure 5. Average weekly pyrethroid resistance frequencies in *H. armigera* at the four monitoring locations during the 1992/93 (and 1991/92 at ICRISAT Centre) cropping season (based on % of 30-40 mg larvae surviving the cypermethrin 1.0 µg 'high' discriminating dose).

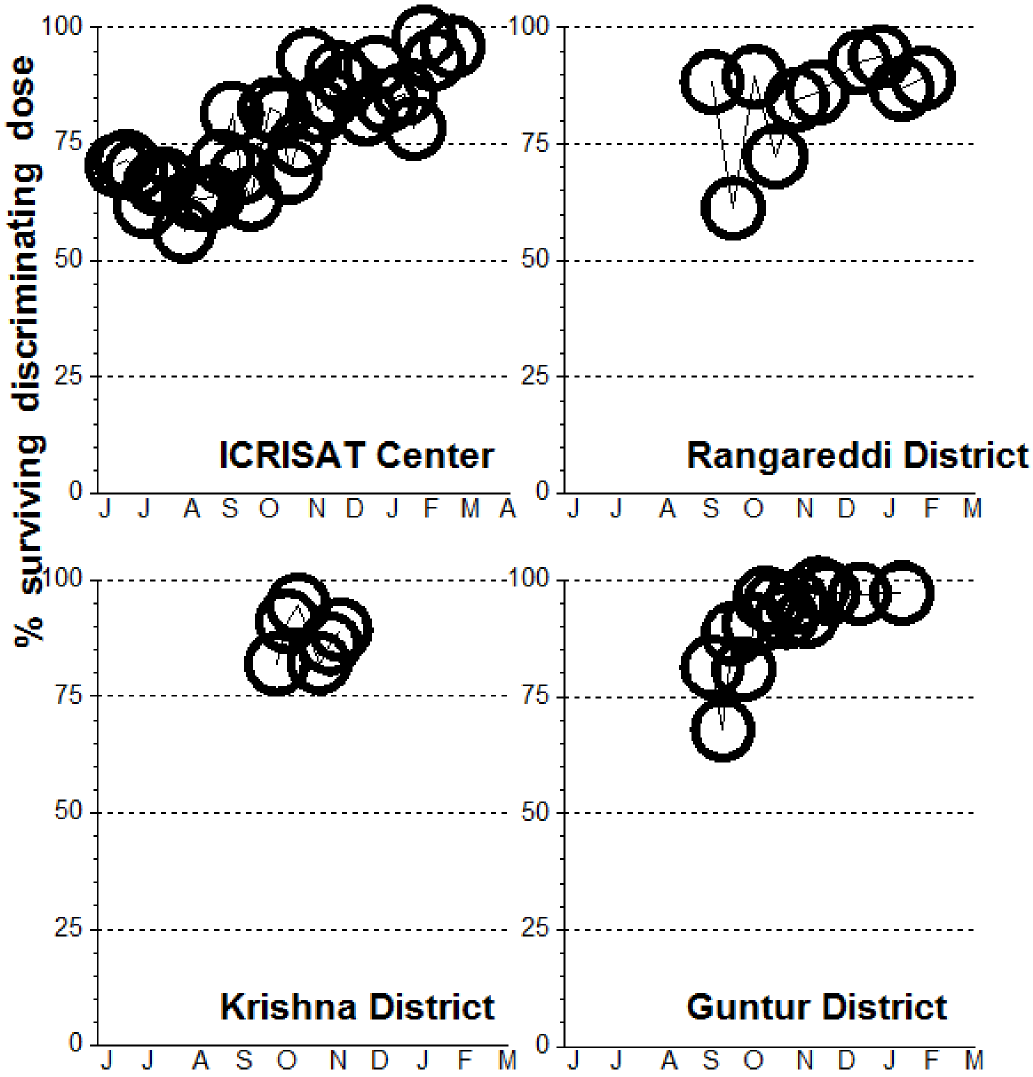

Figure 6. Armes *et al.*

Figure 6. Average weekly pyrethroid resistance frequencies in *H. armigera* at the four monitoring locations during the 1992/93 cropping season (based on % of 30-40 mg larvae surviving the fenvalerate 0.2 µg discriminating dose).

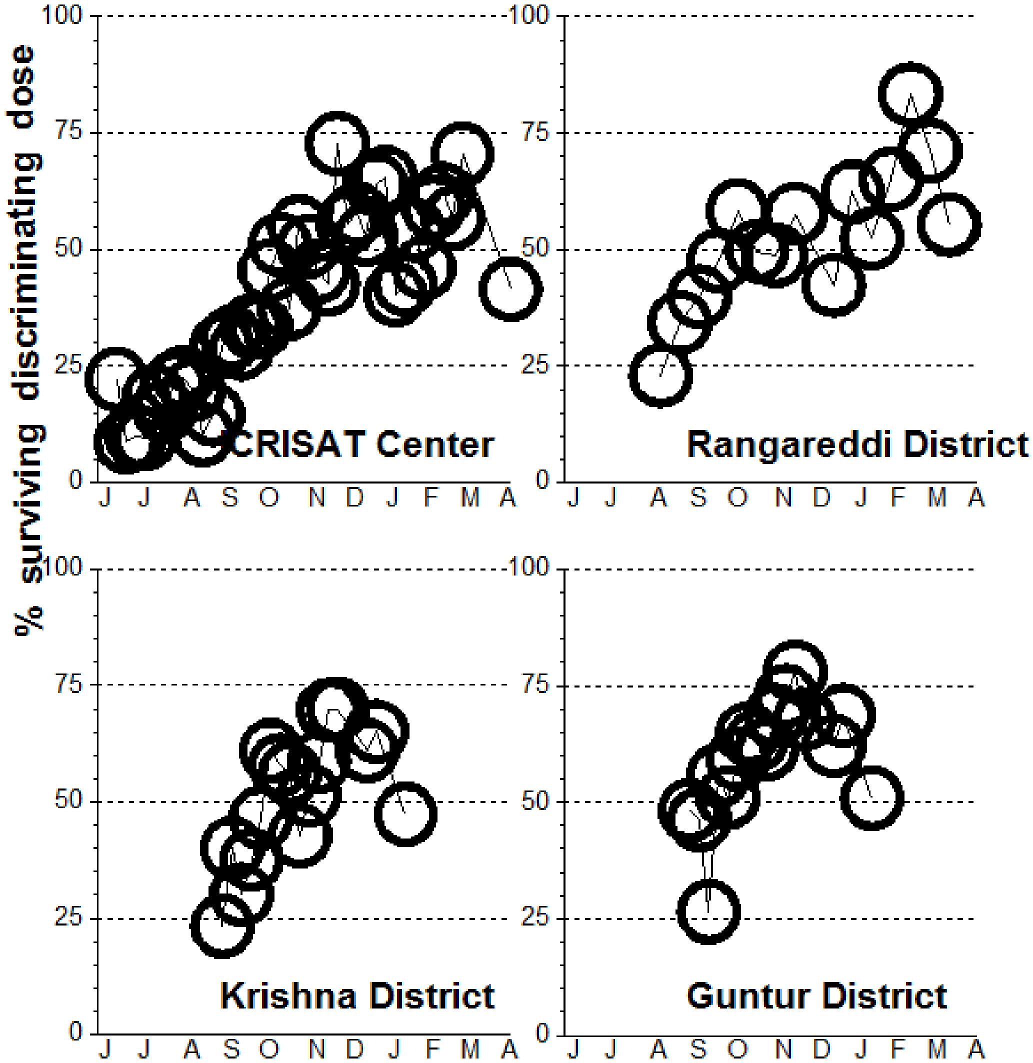

Figure 7. Armes *et al*

Figure 7. Average weekly endosulfan resistance frequencies in *H. armigera* at the four monitoring locations during the 1992/93 cropping season (based on % of 30-40 mg larvae surviving the endosulfan 10.0 µg discriminating dose).

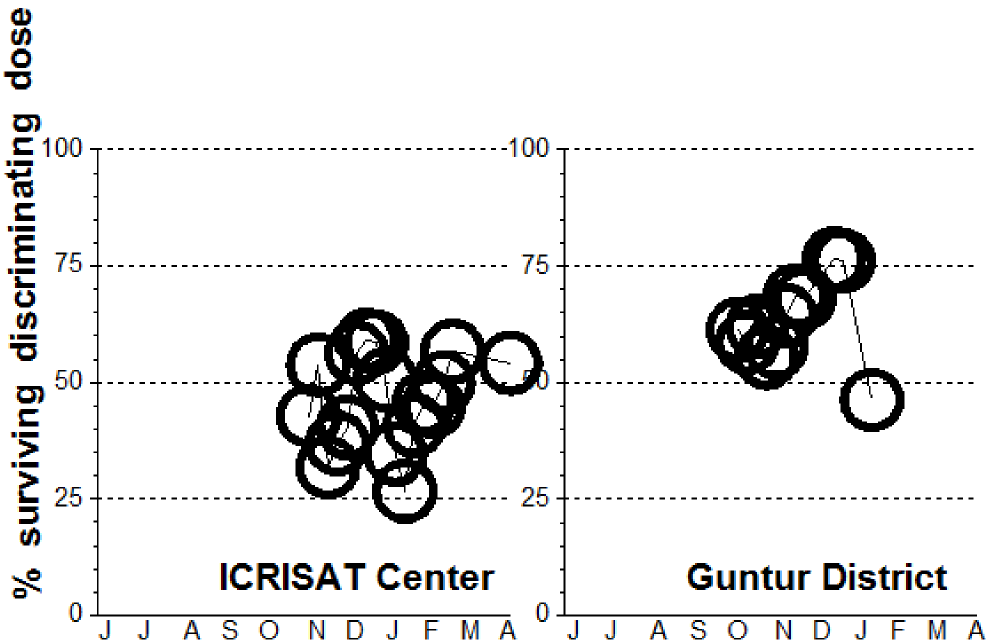

Figure 8. Armes et al

Figure 8. Average weekly quinalphos resistance frequencies in *H. armigera* at two of the four monitoring locations during the 1992/93 cropping season (based on % of 30-40 mg larvae surviving the quinalphos 0.75 µg discriminating dose).