Management of the Development of Insecticide Resistance by Sensible Use of Insecticide, Operational Methods

Bu-Keun Chung¹ and Chung Gyoo Park*

Institute of Agriculture and Life Sciences (BK 21 Program), Gyeongsang National University, Jinju 660-701, Republic of Korea

¹Gyeongnam Agricultural Research and Extension Services, Jinju 660-370

실행방식 측면에서 살충제의 신중한 사용에 의한 저항성 발달의 관리

정부근¹ · 박정규*

경남 진주시 가좌동 경상대학교 농업생명과학연구원 (BK21 Program), ¹경남 진주시 초전동 경남농업기술원 친환경연구과

ABSTRACT : An attempt was made to stimulate future research by providing exemplary information, which would integrate published knowledge to solve specific pest problem caused by resistance. This review was directed to find a way for delaying resistance development with consideration of chemical(s) nature, of mixture, rotation, or mosaics, and of insecticide(s) compatible with the biological agents in integrated pest management (IPM). The application frequency, related to the resistance development, was influenced by insecticide activity from potentiation, residual period, and the vulnerability to resistance development of chemical, with secondary pest. Chemical affected feeding, locomotion, flight, mating, and predator avoidance. Insecticides with negative cross-resistance by the difference of target sites and mode of action would be adapted to mixture, rotation and mosaic. Mixtures for delaying resistance depend on each component killing very high percentage of the insects, considering allele dominance, cross-resistance, and immigration and fitness disadvantage. Potential disadvantages associated with mixtures include disruption of biological control, resistance in secondary pests, selecting very resistant population, and extending cross-resistance range. The rotation would use insecticides in high and low doses, or with different metabolic mechanisms. Mosaic apply insecticides to the different sectors of a grid for highly mobile insects, spray unrelated insecticides to sedentary aphids in different areas, or mix plots of insecticide-treated and untreated rows. On the evolution of pest resistance, selectivity and resistance of parasitoids and predator decreased the number of generations in which pesticide treatment is required and they could be complementary to refuges from pesticides. To enhance the viability of parasitoids, the terms on the insecticides selectivity and factors affecting to the selectivity in field were examined. For establishment of resistant parasitoid, migration, survivorship, refuge, alternative pesticides were considered. To use parasitoids under the pressure of pesticides, resistant or tolerant parasitoids were tested, collected, and/or selected. A parasitoid parasitized more successfully in the susceptible host than the resistant. Factors affecting to selective toxicity of predator are mixing mineral oil, application method, insecticide contaminated prey, trait of individual insecticide, sub-lethal doses, and the developmental stage of predators. To improve the predator/prey ratio in field, application time, method, and formulation of pesticide, reducing dose rate, using mulches and weeds, multicropping and managing of surroundings are suggested. Plant resistance, predator activity, selective insect growth regulator, and alternative prey positively contributed to the increase of the ratio. Using selective insecticides or insecticide resistant predator controlled its phytophagous prey mites, kept them below an economic level, increased yield, and reduced the spray number and fruits damaged.

KEY WORDS : Resistance management, Insecticide, Mixture, Rotation, Mosaics, Predator, Parasitoid

*Corresponding author. E-mail: parkcg@gnu.ac.kr

초 록 : 해충의 저항성발달로 야기되는 문제를 해결하기 위한 정보를 제공함으로써 향후연구를 촉진시키고자 하였다. 농약사용이 지속되는 한 저항성 발달은 필연적이라는 생각으로, 저항성발달을 지연시키기 위해 재배자가 활용할 수 있는 약제성질에 근거를 둔 약종선택, 혼용, 교호, 모자이크 처리 등 약제살포법과, 천적과 양립할 수 있는 선택성 살충제와 저항성 천적의 이용을 중심으로 한 병해충 종합관리(IPM)에 대해 고찰하였다. 저항성관리에 약종의 성질을 이용할 경우 약종별로 작용점과 mode of action(작용방식)이 같거나 다를 수 있고, 2차 해충과 함께 살충제의 활성, 잔류기간, 약제 저항성 발달에 대한 취약성도 다르다. 약제는 섭식, locomotion(거동), 비행, 교미, 포식자 회피 등에도 영향을 미치므로 종합적으로 고려하여 역교차저항성을 나타내는 살충제의 사용이 바람직하다. 농약혼용은 실제 많이 이루어지고 있고 앞으로도 그러하겠지만, 진정한 의미에서 저항성 발달 지연을 위한 혼용, 교호, 모자이크 처리법은 대립유전자의 우성도, 교차저항성, 유입(immigration), fitness 불이익 등과 함께 살충제의 작용방식과 작용점들의 차이에서 구성약제가 매우 높은 비율로 충을 죽이는 부의 교차저항성을 가진 살충제들의 채택에 대하여 논의하였다. 저항성 관리에 약제혼용의 대표적인 사례 22가지와 교호처리 사례 27가지를 표로 제시하였다. 혼용처리의 잠재적 불이익은 생물적 방제의 와해, 이차해충의 저항성발달, 고도의 저항성 개체군 선발, 다양한 살충제에 대한 교차저항성 범위 확대를 내포하고 있다. 교호처리는 살포약량을 높이거나 낮추고, 다른 대사기구를 가진 살충제를 사용하는 것도 고려되었다. 모자이크 처리는 진딧물 같이 정주성 해충인 경우에 연관없는 살충제를 교호로 다른 구역에 처리하거나, 살충제 처리한 열(列)과 그렇지 않은 것을 혼합 배치하여 저항성 발달을 지연시키거나 피해를 감소시킬 수 있다. 해충의 저항성 진화 측면에서 볼 때, 기생자와 포식자의 저항성과 선택성은 농약처리를 요하는 세대 수를 감소시키고 농약으로부터 피난처의 상보적 역할을 수행할 수 있다. 작물별, 기주별, 기생자와 포식자에게 선택성을 보이는 약제를 별도의 표로 요약하여 제시하였다. 기생자의 생존력 향상을 위해 살충제의 선택성과 선택성에 영향을 주는 내·외적 요인에 대하여 검토하였다. 농약사용 하에서 기생자를 사용하기 위해 농약에 대해 저항성이거나 내성이 있는 기생자를 검정, 채집 혹은 선발하는 것을 논의하였다. 포식자에 대한 선택독성에 영향을 미치는 요인들로 농약의 선택성, 선택성의 포장적용과 그에 미치는 요인, 포식자와 기주의 균형, 선택성을 도외시한 방제법의 문제점, 천적과 농약의 양립성 등에 대하여 논의하였다.

검색어 : 저항성관리, 혼용, 교호, 모자이크, 살충제, 포식자, 기생자

1. Introduction

Management of the resistance development that conceived by Georgiou and Taylor (1977) was adopted in this review as a main theme. Their strategy was exploiting the use of genetic and biological information of the specific insect pest for the control of it in the version of operator's way of practical implementation, an operational method. Before applying insecticide, an operator would consider the chemical nature, its relationship to earlier used one and persistence of residue for the control of or for the management of resistant insect pest(s). Tabashnik (1989) proposed similar idea to them, namely sequential, mixture, rotational, and mosaics use of insecticides. As mentioned by him, sequential use is the manner of application of insecticides repeatedly until resistance occurs to one insecticide (A),

then the use of another pesticide (B); mixture is using each of compound simultaneously to the individuals; rotation is treating insecticides alternately, ABABA or any other ways; and mosaics is applying different pesticides simultaneously to adjacent areas.

The dynamics of economic thresholds on resistance evolution by the dynamics of alleles might have important implications for pesticide management strategies in a single-field model. The time to resistance was affected by the growth rate of the population, the selection pressure on the resistant allele, and migration in the regional model where migration, refuges, and crop rotation under different management strategies were considered (Peck and Ellner, 1997). In this respect, insecticides compatible with the biological agents, predators and parasitoid is very important in fields. Many excellent reviews were contributed by the Motoyama and

Dauterman (1992), Croft (1993), Palumbo *et al.* (2001), and Ellsworth and Martinez-Carrillo (2001) in this respect. Although biogenic insecticide is nowadays very popular to the agricultural practitioners, it was not considered in this review. Reviews on *Bacillus thuringiensis* (Bt) were presented by the Ferre and van Rie (2002) and Frutos *et al.* (1999).

The objective of this review was focused on taking advantage of the nature of chemical to delay the development of insecticide resistance by using either method of insecticide use, mixture, rotation, or mosaics, with particular emphasis on insecticide(s) in the frame of IPM. Furthermore, it is highly expected to stimulate future research in resistance management by providing exemplary information. This review deals with the publications mostly before 2000.

2. Selecting chemical(s) for resistance management

It is highly recommended to use an insecticide or a combination of insecticides against resistant population with different target sites or mode of actions to the insect pests. The target sites listed by Casida and Quistad (2000) are acetylcholinesterase (AChE) for organophosphates (OP) and methylcarbamates, nicotinic acetylcholine for neonicotinoids, GABA receptor-chloride channel for fipronil, Na⁺ channel for DDT and deltamethrin, NADH: ubiquinone oxidoreductase uncouplers for fenazaquine, juvenile hormone receptor for methoprene, ecdyson receptor for tebufenozide, chitin for diflubenzuron, and gut for Bt- δ -endotoxin and GM crop.

Strategies to prevent the development of resistance are careful choice and appropriate use of selective insecticides, according to the mode of action at which the target species are most vulnerable, and a progressive reduction in the pressure of chemical selection (Cravedi, 1997). Alteration of insecticides across generations, non-persistent formulations, and the use of pesticides conferring only low magnitudes of resistance seem to be promising tactics for general use in resistance management (Roush, 1989).

Depending upon the nature of individual insecticides, the number of applications that are related to the evolution

of resistance in the pest population was different in cucumber where *Trialeurodes vaporariorum* is an important pest and *Lyriomyza trifolii* and *Aphis gossypii* as secondary pests. On the viewpoints of growers, an insecticide was reliable as far as the application period not shortened drastically. Spraying furathiocarb, a carbamate, compared with other OP or pyrethroid (Pyr) insecticides had reduced the number of spray through the potentiation process to carbofuran, longer residual activity, and lower level of resistance development against the whitefly, compared with others from OP and Pyr. Among the group of the insecticides that belong to OP, the resistance to methion was not developed to *T. vaporariorum* but residual activity was too short to be practical. In addition, fenitrothion and profenofos treated for the control of secondary pests, *L. trifolii* and *A. gossypii*, respectively were initially effective in controlling *T. vaporariorum* but yield to the resistance development. When susceptibility was checked to each insecticide during the process of insecticide treatment, significant resistance was observed to the Pyr, deltamethrin and zetacypermethrin to the recommended dose (Chung and Son, 2001).

Chemical nature affected the behavior on feeding and locomotion in *Heliothis virescens* (Benedict *et al.*, 1992), and the pattern of flight activity, mating competition, and predator avoidance of *Anopheles* (Rowland, 1991). Chlordimeform caused increase in the locomotion of a Pyr-susceptible (S) and resistant (R) larvae but cypermethrin increased resting of S larvae on plants compared with Pyr-R larvae, both chlordimeform and cypermethrin reduced feeding, though, when third-instar larvae were placed on the flower budding of cotton plants 1 h after spraying. Since chlordimeform could alter the larval behavior on plants treated with cypermethrin, damage by the larvae could be reduced and larval acquisition of insecticide residues would be increased (Benedict *et al.*, 1992).

Negatively correlated cross-resistance (Kato *et al.*, 1999) to the strains selected with other(s), in which the level of cross-resistance or resistance developed, conditions of experiment conducted, and the species tested were quite

various. For the management of insecticide resistant population it is recommended to use insecticides showing negatively correlated cross-resistance with different mode of action in implementing the management strategy of sequence, mixture, rotation, and mosaics, which will be dealt later.

3. Mixture

3.1. Control of resistant insects by synergistic mixture

For the control of resistant population, intensive researches were conducted to find out synergistic combinations in the laboratory and field to the early nineties in Korea because of decreased rate of new insecticide registration.

Most of the works done to find best combinations of synergistic mixtures were not directly led to commercialized formulations, because activity tested in the laboratory and interests of the local pesticide companies could not be complied. However, the approaches to solve the pest control problem by using mixture were substantially accepted by the companies. Mixture items listed in Pesticide Handbook of Korea by the Association of Korea Pesticide Companies in 2005 took 56% among the total 704 pesticides, excluding plant growth regulators and other non-pesticides. In case of insecticides, 94 items, taking 42%, were used in mixture formulations among the 223 kinds, though it was not known to exactly the portions in the market share. The practice of mixture use would be widely accepted to the agricultural practitioners, if we were taking the portions of using tank mixture.

However, the mixture, either a formulated mixture with active ingredients or a mixture of formulations in a tank, is not always directed to control of the insecticide resistant populations. Mixture is used various way for extending its activity range to pests (Song, 1985), not only insect pests but also other organisms, fungi and weeds. As far as insect pests they have been used also for increasing the insecticide activity, for controlling unprecedented pests immigrated from oversea at

emergency, and for marketing policy to extend an effective life of old or new chemicals.

Now, the importance to find out a synergistic mixture have no longer sound ground in government funded research communities in Korea, though its use in practice would increase further in coming future. This consequence have been arisen from various causes: 1) private companies have well done in finding excellent combinations to the urgency of the growers, 2) several potent insecticides were introduced at proper time in the market with different mode of action from the conventional insecticides.

3.2. Delaying resistant development by mixture

3.2.1. Theoretical background of using mixture

Several simulation models were presented for the comparison of the rate of development of insecticide resistance under rotation, mixture, or checkerboards (Holloway and McCaffery, 1988; Caprio, 1998; Li and Chang, 1990).

For effectively delaying the resistance development by using mixture strategy, Holloway and McCaffery (1988) emphasized the low frequency of initial R allele on the assumption that resistance is due to the inheritance of a single semi-dominant allele and there is no cross-resistance. The prospects for successful use of a mixture depend on each component killing a very high percentage of the exposed insects, which are genetically susceptible to it (Curtis *et al.*, 1993; Argentine *et al.*, 1994). When resistance to both components of the mixture is likely to be rare, the double resistance combination would be so rare as to be dwarfed in numbers by those insects which avoid exposure altogether (Curtis *et al.*, 1993). Argentine *et al.* (1994) pointed out that the mixture strategy was more effective in reducing resistance development at the 97% level of control, particularly if coupled with immigration of susceptible beetles, *L. decemlineata* into treated areas or if relative fitness disadvantage associated with the resistance alleles was increased.

Caprio (1998) considered that the use of 5 resistance management strategies in the presence and absence of

external refuges was in a stochastic model. The full-rate mixtures provided for better insect control but resulted in resistance to both toxins in approximately the same time it took resistance to develop to the 1st toxin in the sequential use strategy. In the absence of refuges and an IPM strategy, the full-rate mixture strategy resulted in the most rapid resistance development among the 5 strategies, which were sequential introduction of 2 toxins, rotations and mosaics of toxins, and half- and full-rate mixtures of the toxins. Half-rate mixtures were less effective than full-rate mixtures under ideal conditions. Resistance took 2.2 times longer to evolve in the polygenic simulations in the presence of a refuge (Caprio, 1998). Results of a comparison of rational mixtures with rotation and 'checkerboard' systems (Li and Chang, 1990) showed that the mixture strategy was same as the rotation under favorable or better than the other 2 methods under unfavorable conditions caused by a high original frequency of the resistance gene, low dilution action, etc.

When cross-resistance is absent, a sequence of 2 insecticides is expected to be more durable than a mixture unless the population's heritability (h^2) of resistance to the mixture is less than half of the mean of the population's h^2 of resistance to the 2 individual components of the mixture (Tabashnik and McGaughey, 1994).

However, there was little or no advantage gained by using mixture or rotation strategies at the 90% level of control in a computer simulation model with level of dominance and fitness, immigration and control parameters (Argentine *et al.*, 1994). Holloway and McCaffery (1988) indicated that rotation becomes the better strategy, when the frequency of R exceeds about 0.02.

The computer simulation for an artificial population of *Plutella xylostella* indicated that the effect of rotating and mixing fenvalerate and methylpo mainly depended on factors including the fitness value of the resistant genotype and the mode of action of the pesticide mixture (Mo *et al.*, 1999). However, potential disadvantages associated with mixtures include disruption of biological control, promotion of resistance in secondary pests, and intense selection for cross-resistance (Tabashnik, 1989).

3.2.2. Delaying resistance development by mixture

Table 1 shows summary of using mixture for delaying insecticide resistance development. Explanations on this table will be appeared in the following text.

a. In the laboratory

The selection of N-methylcarbamates resistant *Nephotettix cincticeps* Uhler (RN-4 strain) with the structurally a little bit different mixture of MTMC (N-methylcarbamate) and compound Z (N-propylcarbamate) delayed effectively the development of resistance, so that resistance was almost unchanged at 20th generation, with 1.1x to BPMC, 1.4x to MTMC, 1.4x to MTMC+Z, and 1.7x to Z. The RN-4 strain in which LD₅₀ (microgram/g) was 166 to BPMC, 66 to MTMC, 22 to MTMC + Z and 58 to Z were selected for 21-27 generations with one thousand last instars male and female larvae for each selection, with selection pressure of 60-80% mortality (Yamamoto *et al.*, 1993). These results implied that the use of mixture would be prospective as strategies for future resistance management. The development of insecticide resistance in *Helicoverpa armigera* was also much slower when selected by synergistic insecticide mixtures than by Pyr alone. The delayed resistance was related to the delayed penetration of Pyr, by the 14C-labeled radio assay method, and the decreased nerve sensitivity to Pyr in the larvae by the electrophysiological method (Wei *et al.*, 1996).

b. In the field

The rate of resistance development was significantly reduced by rotations and mixtures of insecticides, compared with single, continuous insecticide selections in the greenhouse (Prabhaker *et al.*, 1998). A field population of *Bemisia argentifolii* from cotton in California was subjected to selective pressure with 5 insecticide regimens: continuous applications of bifenthrin, endosulfan, chlorpyrifos; bifenthrin-endosulfan-chlorpyrifos rotation; and a bifenthrin (2) + endosulfan (1) mixture. The magnitude of resistance ranged from highs of 752-, 36-, 47-fold for the single, to lows of 16-, 5-, 7-fold for rotational use of bifenthrin, endosulfan, and chlorpyrifos, respectively around 27th generation, and to a low of 17-fold

Table 1. Management of the resistance development to insecticide by applying in mixture

Species	Combinations	Comment	Resistance	Field or Lab.	Ref
<i>Aphis gossypii</i>	Fenvalerate + omethoate (8:1)	Cotton fields	Delayed	Lab.	Mu <i>et al.</i> , 1988
<i>Bemisia argentifolii</i>	Bifenthrin + endosulfan (1:2)	Cotton field origin	Delayed	Lab.	Prabhaker <i>et al.</i> , 1998
<i>B. tabaci</i>	Dimethoate+ endosulfan	Cotton field origin/survey	Delayed	Field	Ahmed <i>et al.</i> , 1987
<i>Blattella germanica</i>	λ -Cyhalothrin + pb +pyriproxyfen (6) → λ -cyhalothrin + pyriproxyfen (5)	Formulated; catches reduced	Effective	Field	Scharf <i>et al.</i> , 1997
<i>Culex pipiens pallens</i>	Deltamethrin + fenthion	Lab.	Delayed	Lab.	Zhou <i>et al.</i> , 2001
<i>C. pipiens pallens</i>	Malathion + trichlorfon	-	Delayed	-	Tang <i>et al.</i> , 1988
<i>Haematobia irritans</i>	Permethrin + diazinon (1:2)	Lab. susceptible	Delayed	Lab.	McKenzie and Byford, 1993
<i>H. irritans</i>	Permethrin + diazinon (1:2)	Up to 12 G.	Delayed	Lab.	Byford <i>et al.</i> , 1999
<i>H. irritans</i>	Cyhalothrin + PBO + DEF Cypermethrin + PBO + chlorpy-rifos	Acceptable control	R-developed	Field	Cilek and Knapp, 1993
<i>Heliothis virescens</i>	Permethrin + chlordimeform (1:1 wt/wt)	-	Delayed	Lab.	Bohmann <i>et al.</i> , 1988
<i>Helicoverpa armigera</i>	Insecticide mixtures (Pyrethroids)	-	Delayed	-	Wei <i>et al.</i> , 1996
<i>Lipaphis erysimi</i>	Fenvalerate + malathion	-	Delayed	-	Ru <i>et al.</i> , 1998
<i>H. armigera</i>	Cyhalothrin + parathion-methyl + methomyl	-	-	-	-
<i>Musca domestica</i>	Permethrin, cypermethrin (1:9)	-	Delayed	Lab.	Smirnova <i>et al.</i> , 1994
<i>M. domestica vicuña</i>	Deltamethrin + phonic	Checked at 18 G. selection	Delayed	Lab.	Zhang <i>et al.</i> , 1995
<i>M. domestica</i>	(Fenitrothion & tetramethrin) + prothiofos	RR to prothiofos 1.6-5.2	-	Field	Yasutomi <i>et al.</i> , 1988
<i>Myzus persicae</i>	Deltamethrin/heptenophos	-	Accelerated	Field	ffrench-Constant <i>et al.</i> , 1986, '87
<i>M. persicae</i>	Cypermethrin, oil and pirimicarb	Potatoes	R-developed	-	ffrench-Constant <i>et al.</i> , 1988
<i>Nephotettix cincticeps</i>	N-methyl- + N-propylcarbamate N-methylcarbamate + metoxadiazone	-	No further R-developed	Lab.	Yamamoto <i>et al.</i> , 1993
<i>Plutella xylostella</i>	Fenvalerate + methylpo	Lab/ artificial population	Delayed	Lab.	Mo <i>et al.</i> , 1999
<i>P. xylostella</i>	Strains of Bt. + deltamethrin	Resistant pest controlled	-	Field	Yeh <i>et al.</i> , 1986
<i>P. xylostella</i>	Bt. + (phenthoate or prothiofos)	Highly resistant population	Effective	Field	Horikiri and Makino, 1987
<i>Spodoptera littoralis</i>	Monocrotophos-methoprene	Resistance increased at 10 G.	Delayed	-	El-Guindy <i>et al.</i> , 1990

for the bifenthrin + endosulfan mixture at 23rd generations. For all insecticide-selection regimens, slopes of regression lines increased over many generations. The whitefly population treated with the bifenthrin + endosulfan mixture generated the steepest lines, as suggested by Caprio (1998).

However, selection over 16 generations using a monocrotophos-methoprene mixture against the noctuid *Spodoptera littoralis* was the most effective in delaying resistance to either compound, followed by alternate selection for 1 generation with monocrotophos followed by selection with diflubenzuron. Under all test regimes, a significant rise in resistance was observed in the 10th generation of selection, which suggested that different selection regimes might retard, but not prevent, resistance to each compound (El-Guindy *et al.*, 1990).

To study the effects of an insecticide mixture on an insecticide-resistant field population of *Blattella germanica* from Muncie, Indiana, USA, a formulated lambda-cyhalothrin (Pyr) + PBO (excluded from the 2nd mo) + pyriproxyfen (JHA) were treated monthly (first 6 mo in total) and monitored for 12 months. Sticky trap catches of cockroaches were reduced from 27.9 to 2.6 trapped per apartment at the beginning and end of the study, increased in the percentage of trapped adults having twisted wings (an indicator of JHA-induced sterility), and reduced ratios of nymphs: adults and gravid: non-gravid females. Biochemical assays of hydrolytic and oxidative enzymes indicated increases in 1-naphthyl acetate and 2-naphthyl acetate hydrolysis, and in total cytochrome P450 content, but no change in

p-nitrophenyl acetate hydrolysis. This is a substantially successful case of controlling insecticide resistant population of cockroach by using mixture, though it was limited to mixture because single treatment could not be adopted to the human dwellings (Scharf *et al.*, 1997).

c. Problems in using mixture

For delaying the development of insecticide resistance in using mixture have faced several problems by selecting very resistant population more rapidly in *Myzus persicae* (ffrench-Constant *et al.*, 1987) and *Haematobia irritans* (Cilek and Knapp, 1993), by decreased susceptibility of *P. xylostella*, yearly or by locality (Kimura, 1989) and of *S. littoralis* (Keddis *et al.*, 1986), and by extending cross-resistance range in *B. argentifolii* (Sivasupramaniam *et al.*, 1997).

In mixture treated, rapid increase of very resistant clones of *M. persicae* (R2) with enhanced nymph production resulted in a smaller reduction in numbers than was achieved by the single treatments, pirimicarb (carbamate) or demeton-S-methyl (OP), after spraying aphids in field cages enclosing single rows of potatoes. The resistance genotype frequencies were determined individually by an immunoplate assay, which measures the amount of the carboxylesterase E4, the enzyme conferring resistance (ffrench-Constant *et al.*, 1987). After ear tags impregnated mixture of cyhalothrin-PBO-DEF or cypermethrin-PBO-chlorpyrifos treated to the Pyr-resistant *H. irritans* on cattle in Kentucky, the frequency of Pyr-resistant individuals remaining in each of the treated fly populations was 100%. Resistance developed to the mixture was 2-33 times greater after 14 weeks exposure, compared with values before treatment, although acceptable control of horn flies (average >92%) was generally achieved on treated animals (Cilek and Knapp, 1993).

Kimura (1989) suggested the importance of monitoring susceptibility of *P. xylostella* when using mixture like other insecticides as well. The insect population showed highly resistant to OP but susceptible to a mixture of fenvalerate and dimethoate by a leaf-dipping method to autumn generations during 1982-85 and 1987. A slight

decrease in susceptibility to the mixture was observed during 1985 and local differences to both OP and Pyr revealed in 1987. Keddis *et al.* (1986) also observed that the mixtures in 1983 were effective against *S. littoralis* in most areas, but some strains by 1985 were highly resistant to some of the mixtures.

A mixture selection with fenpropathrin + acephate for six generations to a mixed colony of whitefly, *B. argentifolii* that collected in November 1995 from the Gila River Basin (highly resistant) and the Yuma (relatively susceptible) areas of Arizona in a 1: 4 ratio resulted in statistically significant reductions in susceptibility to profenofos, methomyl, methamidophos and amitraz. It was determined that resistance to fenpropathrin + acephate confers cross-resistance to esfenvalerate, bifenthrin, fenpropathrin, deltamethrin, deltamethrin + acephate and lambda-cyhalothrin (Sivasupramaniam *et al.*, 1997).

3.3. Further research in mixture use

Along with emphasizing the importance of delaying resistant development of mixture, further researches are requested in the field on 1) understanding what is synergistic mechanisms, 2) what is the impact of mixture use to agricultural insect populations – resurgence and resistance development (or delay) of the target and secondary pests, pollinators, natural enemies (Elzen *et al.*, 1987), 3) what consequences to the cross-resistance by using mixture, and 4) economically what is substantial benefits to the growers - by reducing spray frequency and yield increase, by widening its activity range of insecticide, and by increasing the range of cross-resistance (Archer *et al.*, 1999). As a conclusion it would be a wonderful example of mixture use against fenvalerate resistant Lembang strain *P. xylostella* in Indonesia. Applications of the Pyr in combination with *B. thuringiensis* in West Sumatra brought out significantly higher yields than when the Pyr were applied alone or when quinalphos was applied as a standard check and a less adverse effect on *Diadegma eucerophaga*, a parasite of *P. xylostella* (Iman *et al.*, 1986).

4. Rotation

When resistance is assumed to be due to the inheritance of a single semi-dominant allele (R) and the frequency of R exceeds about 0.02, rotational strategy may delay the development of resistance better than the mixture (Holloway and McCaffery, 1988). Resistance evolution was delayed most if 2 pesticides were applied alternatively at every 2 applications, compared with successive or mixture treatments, when an artificial population of *P. xylostella* contains an initial frequency of resistant individuals of 0.01. The computer simulation indicated that the effect of rotating and mixing mainly depended on factors including the fitness value of the resistant genotype and the mode of action of the pesticide mixture (Mo *et al.*, 1999). Li and Chang (1990), however, drawn up results that the effectiveness of a rational mixture is the same as that of rotation under favorable condition ($P(0)=0.01$) and the rational mixture strategy is obviously better than rotation and 'checkerboard' systems under unfavorable conditions caused by a high original frequency ($P(0)=0.1$) of the resistance gene, low dilution action, etc.

Countermeasures by insecticide rotation to the resistance was reviewed on *P. xylostella* by Cheng (1988) in South East Asia and by Saito *et al* (1992), and on resistance to agricultural pests in China by Tang *et al* (1988). Mixtures, rotation or alternation of malathion and trichlorfon can delay the build-up of resistance in *Culex pipiens pallens* when these 2 insecticides were used together (Tang *et al.*, 1988). Based upon the characteristics of multifunctional oxidases, Cheng (1988) has stressed that cross-resistance relationships among traditional insecticides are mostly known and so alternate spraying schedules may be used with insecticides conferring minimum cross-resistance. Saito *et al* (1992) suggested that resistance could be controlled by monitoring using a leaf-dip method, use of selective insecticides and rotation of insecticide use, and forecasting and partial control with yellow sticky traps.

Rotation of low (near lethal) doses, causing quantitative changes, alternated with high doses (above LD_{99}) selecting for monogenic resistance could delay the

evolution of resistance longer than by applying a constant dose (either low or high) in every treatment and suppress pest populations longer and require less pesticide (or drug) than successive constant doses (Gardner *et al.* 1998). They suggest this dosage rotation strategy for situations in which crops and alternative pesticides or drugs cannot be rotated, and suggest that it can be used in conjunction with other methods of control (biocontrol, IPM) to further delay resistance. The rotations of azinphosmethyl with other control materials that are not primarily metabolized by esterase are suggested as a resistance management strategy in *Choristoneura rosaceana* in which azinphosmethyl resistance coupled with the apparent involvement of esterases (Smirle *et al.*, 1998). A regime which Pyr use and maximized rotation of chemical classes resulted in delayed onset of insecticide resistance in *B. tabaci*, compared to a regime of Pyr-OP mixtures only (Ellsworth *et al.*, 1996). Malinowski (1993) suggest that rotation of Pyr with other insecticides (e.g. acylureas) is necessary to delay the build up of Pyr resistance since use of a single Pyr to houseflies induced cross-resistance to all Pyr tested, natural pyrethrins, DDT and methoxychlor, but not to lindane, propoxur or OP.

4.1. Results conducted in the laboratory or in the field

4.1.1. Laboratory results

The rate of resistance development in a field population of *B. argentifolii* from cotton was significantly reduced by rotations and mixtures of a 1:2 bifenthrin + endosulfan, compared with single, continuous insecticide selections in the greenhouse. Continuous selection with bifenthrin, chlorpyrifos or endosulfan resulted in resistance development to 752-, 47- or 36-fold to the respective insecticides by generation F27. Rotational selection with the bifenthrin-endosulfan-chlorpyrifos delayed resistance development to only 10- and 16-fold after 20 and 27 generations, compared with the 173- and 752-fold resistance level for the continuous selection by bifenthrin treatment. The onset of resistance to endosulfan (5-fold) and chlorpyrifos (7-fold) was delayed until generations

25 and 26, respectively (Prabhaker *et al.*, 1998). Similar results of delaying resistance development were also obtained in *P. xylostella* against fenvalerate after rotational treatments of fenvalerate and methylo over 8 generations selected from initial frequency of resistant individuals of 0.01 (Mo *et al.*, 1999), in housefly against cypermethrin after rotational selection with bromfeninfos and cypermethrin (Korczynski *et al.*, 1992), and in *Aedes aegypti* selected with malathion and cypermethrin in the laboratory with minimal level of resistance to each insecticide (Shajahan, 1996).

4.1.2. Field results

a. Rotation with cross-resistance

Control measures should consist of alternate treatments with dimethoate and methamidophos to the dimethoate resistant German populations of *M. persicae* with normal susceptibility to methamidophos in field of sugar beet seed crop (Muer *et al.*, 1987). To Pyr resistant horn fly, *H. irritans* in selected counties in New Mexico, organophosphorus resistance was not detected. The 20% diazinon ear tags alone provided effective control (>80%) of horn flies for 17 weeks. Diazinon ear tags rotated with ivermectin topical pour-on also provided adequate fly control evaluated on a ranch in De Baca County (Crosby *et al.*, 1991).

A resistance management strategy for *Bemisia* which showed >100-fold resistant to fenpropathrin + acephate and cross-resistant to esfenvalerate, bifenthrin, and lambda-cyhalothrin was evaluated in a cotton-producing areas of Arizona. The strategy was diversifying the insecticides used. Contrasts of rotation strategy with a more conventional (less diverse) regime showed that rotation with mixture of the more diversified components of insecticides slowed but did not prevent resistance from developing. By the end of the season, both treatments had high, comparable levels of resistance to fenpropathrin + acephate. The large shift to lower susceptibility took place as few as 3 insecticide treatments (Dennehy *et al.*, 1996). The simultaneous resistance to several classes of insecticides in the populations of codling moth, *Cydia pomonella*, suggests that the implementation of a rotation program to delay resistance development will be difficult

(Sauphanor *et al.*, 1998).

b. Delaying resistance development by rotation

Alternate use of insecticides significantly reduced the onset and degree of resistance development of *H. irritans* in environmentally controlled room (McKenzie and Byford, 1993), *Scirtothrips citri* in a citrus field trial (Immaraju *et al.*, 1990), and *S. littoralis* from cotton field strains in Egypt (Kansouh *et al.*, 1987), compared with single continuous insecticide selections. Resistance to permethrin in *H. irritans* selected with permethrin-diazinon or permethrin-ivermectin rotations resulted in 269- and 248-fold, compared with 1,470-fold resistance to continuous permethrin selection around 45 generations. Rotational selection with permethrin- ivermectin delayed resistance to ivermectin with 2.58- fold, compared with continuous ivermectin selection with 6.18-fold after 49 generations. Selection with permethrin- diazinon rotation had low resistance level to diazinon similar with diazinon continuous selection (McKenzie and Byford, 1993). Three fluvalinate treatments interspaced with 2 formetanate treatments performed best in retarding the development of resistance of the citrus thrips, *S. citri* in a field trial over the season, while sequential use of either insecticide resulted in the development of resistance and mild cross-resistance (< 8-fold) to the other insecticide (Immaraju *et al.*, 1990).

In table 2) are the cases in use of rotation to delay the resistance development summarized.

c. Importance of the choice of insecticide and substantial benefits in rotation.

A single applications or rotations ending with endrin increased the tolerance to endrin, but the susceptibility of these strains ending with mephosfolan or methomyl did not cause tolerance to either insecticide, when the susceptibility of the 4th instars *S. littoralis* was investigated over 2 successive cotton seasons to F₁ individuals which was reared from strains that collected from the field before and after 3 applications of each insecticide in rotation (Kansouh *et al.*, 1987). In a practical sense the rotational application of chlorfluazuron (1)-dimehypo (2)-Bt (2) with different mode of actions did not reduce the treatment

Table 2. Management of the resistance development to insecticide by applying in rotation

Species	Combinations	Comment	Resistance	Field or Lab.	Ref
<i>Bemisia argentifolii</i>	Bifenthrin-end-chlorpyrifos	Cotton field origin	Delayed	Lab.	Prabhaker <i>et al.</i> , 1998
<i>B. tabaci</i>	Pyriproxyfen-buprofezin		Delayed	Field	Horowitz <i>et al.</i> , 1994
<i>B. tabaci</i>	Pyriproxyfen-buprofezin	No resistance to Conventional	Suscept	Field	Horowitz <i>et al.</i> , 1994
<i>B. tabaci</i>	Rotation of chemical classes	-	Delayed	Field	Horowitz <i>et al.</i> , 1994
<i>Blattella germanica</i>	OP-carbamates-pyr-etc.	Low levels resistance	Delayed	Field	Robinson and Zhai, 1992
<i>Culex pipiens pallens</i>	Deltamethrin-fenthion	Lab population	Delayed	Lab.	Zhou <i>et al.</i> , 2001
<i>H. irritans</i>	Permethrin-diazinon	Lab. susceptible. Tolerant to diazinon	Delayed	Lab.	McKenzie & Byford, 1993
<i>H. irritans</i>	Permethrin-Ivermectin	Lab. susceptible. Tolerant to ivermectin	Delayed	Lab.	McKenzie & Byford, 1993
<i>H. irritans</i>	λ -Cyhalothrin-pirimiphos-methyl	Cattle Field. Effective life shortened.	Ineffect	Field	Barros <i>et al.</i> , 1999
<i>H. irritans</i>	Per-diazinon, per-ivermectin	Up to 12 G.	Delayed	Lab.	Byford <i>et al.</i> , 1999
<i>H. irritans</i>	Per-diazinon, per-ivermectin	Yearly alternate use.	Ineffect	Field	Byford <i>et al.</i> , 1999
<i>H. irritans</i>	Per-diazinon, per-ivermectin	2-Yr alternate. Partial rev. of pyr-R	Inconcl	Field	Byford <i>et al.</i> , 1999
<i>H. irritans</i>	Per-diazinon, per-ivermectin	Mosaic at 2 different locations.	Delayed	Field	Byford <i>et al.</i> , 1999
<i>Helicoverpa armigera</i>	(Del+mt+pxm)-(end+del+pxm)-(del+para+mt)	Multiple-R to mixtures	Delayed	Lab.	Yanchao <i>et al.</i> , 1995
<i>H. armigera</i>	(Del+mt+pxm)-(end+del+pxm)-(del+para+mt)	Mixture rotation	Delayed	Lab.	Yanchao <i>et al.</i> , 1995
<i>Lipaphis erysimi</i>	Dimethoate-fenvalerate	Mosaic rotation	Delayed	-	Tang <i>et al.</i> , 1988
<i>L. erysimi pseudobrassicae</i> , and others	Dimethoate-fenvalerate	Unrelated insecticides sprayed at first	Delayed	Field	Tang <i>et al.</i> , 1994
<i>Plutella xylostella</i>	Fenvalerate and methylpo	Artificial population	Delayed	Lab.	Mo <i>et al.</i> , 1999
<i>P. xylostella</i>	Chlorfluazuron -dimehypo -Bt	R to del, chl, dimehypo, Bt	Delayed	Field	Zhao <i>et al.</i> , 1996
<i>P. xylostella</i>	Chlorfluazuron -dimehypo -Bt	R to del, chl, dimehypo, Bt.	Delayed	Field	Zhao <i>et al.</i> , 1996
<i>P. xylostella</i>	Mevinphos-methamidophos-per	Low parasitism in treated plots	Delayed	Field	Taiwan, AVRDC, 1991
<i>Simulium squamosum</i>	Per-B.t. subsp. israelensis	Resistance to permethrin	Delayed	Field	Hougard <i>et al.</i> , 1992
<i>Spodoptera exigua</i>	Chlorpyrifos-permethrin	Methomyl resistance	Delayed	Lab.	Yoshida and Parrella, 1987
<i>S. littoralis</i>	Endrin-mephosfolan-methomyl	F1 individuals from the field.	Delayed	Field	Kansouh <i>et al.</i> , 1987
<i>Scirtothrips citri</i>	3 Fluvalinate-2 formetanate	Moderate R to Formetanate	Delayed	Field	Immaraju <i>et al.</i> , 1990
<i>Simulium damnosum s.l.</i>	B. t. israelensis - (chlorphoxim-carbosulfan-per)-te mephos	-	Partly success	Field	WHO. 1988
<i>Thrips tabaci</i>	OP-cypermethrin	R to dimethoate, phosalone, trichlorfon.	R-controlled	Field	Deryabin, 1991

Chl: chlorfluazuron del: deltamethrin; end: endosulfan; mt: methomyl; para: parathion; per: permethrin; pxm: phoxim; pyr: pyrethroid; R: resistance

frequency, compared with 3 times treatments only when chlorfluazuron was used singly. However, this rotational treatments regimes had still sound background in the insecticide efficacy, yield, and net profit, compared with the rotational application of fenvalerate and dimethoate mixture (3)-Bt (2) for delaying development of resistance in *P. xylostella* (Zhao *et al.*, 1996). In contrast to the positive role of chlorfluazuron, Ellsworth *et al.* (1996)

delayed Pyr use and maximized rotation of chemical classes in their insecticide resistance management program. The results in conjunction with the threshold of 5 *B. tabaci* adults per leaf on cotton in Arizona realized 3 to 5 less sprays than 3 or 1 adult(s) per leaf, and brought in a relative slowing of the progression toward resistance. However, statistically less yield was produced in the 5 per leaf ($P=0.051$), mainly due to secondary pest and

poor performance of one set of treatment. In cotton and seed lucerne rotation system, a scheme in which lucerne was sprayed with an OP at the beginning of bud-formation and with a Pyr before flowering, or vice-versa, increased seed quality and yield, and reduced injuriousness of *Thrips tabaci* which was resistant to dimethoate, phosalone, and trichlorfon, but not to cypermethrin in cotton (Deryabin, 1991).

4.2. Mosaics

4.2.1. Fast moving insects

The use of a mosaic in which insecticides are applied in different sectors of a grid pattern may delay resistance in highly mobile insects with relatively specific requirements for host or habitat. The mechanism by which resistance is managed is similar to the action of insecticide mixtures if there is extensive movement between treated sectors within a generation. Resistance is delayed by a process analogous to insecticide rotations if movement between treated sectors occurs between generations. Current evidence indicates that newly emerged adults are primarily responsible for dispersal so that a mosaic would function principally as a rotation of insecticides (Byford *et al.*, 1987).

Field studies in Louisiana, USA, demonstrated that use of a single class of insecticide ear tag during the horn-fly season resulted in product failure within 3-4 years for Pyr and OP, respectively. In field studies, yearly alternated use of Pyr and OP did not slow or reverse Pyr resistance, while a 2-year alternated use with OP resulted in partial reversion of Pyr resistance. When Pyr and OP ear tags were used in a mosaic strategy at 2 different locations, efficacy of products did not change during a 3-year period (Byford *et al.*, 1999).

4.2.2. Sedentary insects

Mosaic rotation of dimethoate and fenvalerate delayed the onset of resistance in the brassica pest *Lipaphis erysimi* (Tang *et al.*, 1988). Mosaic control with insecticides seems to be unsuitable for insects such as aphids, which reproduce by parthenogenesis and have low mobility in apterous form. Another strategy was

adopted by spraying unrelated insecticides at first and then exchanging or rotating the spraying in different areas at the next application. For the control of aphids, *L. erysimi pseudobrassicae*, *M. persicae* and *Cavariella salicicola*, mosaic rotation of dimethoate and fenvalerate was found to delay the development of insecticide resistance in the above three species of aphids, compared with continued use of dimethoate followed by continued use of fenvalerate to the point where control was impaired by resistance (Tang *et al.*, 1994), based on bioassays and determination of alpha-Na esterase activity in single aphids.

4.2.3. Patches with treated and untreated

Treated and untreated plants in a field provide a refuge to pests to minimize resistance, while the high dose strategy may result in rapid pest adaptation. Plots of mixtures of imidacloprid-treated and untreated rows of potato cultivars were compared with plots of untreated and 100% treated rows to determine their effects on the Colorado potato beetle, *L. decemlineata*. By mixture of imidacloprid treated rows, first-generation populations and feeding injury were significantly reduced after releasing post-diapause adults along the edge of plots to simulate a typical colonization pattern. Densities of life stages and percentage defoliation decreased as the proportion of imidacloprid-treated rows increased. The effectiveness of imidacloprid was greater than the additive effect based on the proportional contribution of the treated rows. Even when colonizing adults were introduced uniformly in row mixture plots, the treated rows trapped many dispersing adults and suppressed feeding injury on adjacent untreated rows (Dively *et al.*, 1998).

5. Resistance delay in IPM frame

Based on detailed understanding of tritrophic interactions, key ways to manipulate the crop environment was reviewed and identified to improve the control of insect pests. Verkerk *et al* (1998) gave attention to 1) the compatibility of partial plant resistance and biological control, 2) the use or effects of allelochemicals, refuges, intercropping, crop backgrounds, fertilization regimes,

parasitoid conditioning (by host plants) and transgenic crops, 3) use of selective insecticides which show compatibility with biological methods.

May and Hassell (1988) described a basic framework for examining the outcome of releasing natural enemies against a target pest population. The dynamics of host-parasitoid and host-pathogen interactions where insecticides are applied are discussed, with reference to the evolution of insecticide resistance. Based solely on the reduction of insecticide treatments, blue gum eucalyptus growers had had a benefit cost ratio ranging from at least 9:1 to 24:1, when *Psyllaephagus pilosus*, a parasitoid native to Australia was introduced in California to control *Ctenarytaina eucalypti* (Dahlsten *et al.*, 1998). Release of *Encarsia formosa* reduced the number of insecticide applications on poinsettia by 75%, but the cost of using *E. formosa* was 9.5 times that of insecticides alone. In the presence of *E. formosa*, survivorship of *B. argentifolii* to adult emergence was 14%, while that was 67% when *E. formosa* was excluded (Hoddle and van Driesche, 1996). The application rates of the insecticide for the control of *B. tabaci* and *T. vaporariorum* could be reduced by up to 80% compared to years when *E. formosa* was not used in greenhouse. However, neither of the 2 species of aleyrodid could be sufficiently controlled by *E. formosa*, when densities of 1 *Encarsia* per 1.5-4 plants and per 2-3 plants were applied at weekly intervals in 1991 and 1992, respectively (Ruisinger and Backhaus, 1994). Producers on release farms of *Muscidifurax raptor* made an average of 2.7 insecticide applications for housefly control compared with 14.7 insecticide applications on control farms (Geden *et al.*, 1992).

Computer simulations incorporated potential for the resistance evolution of diamondback moth to *B. thuringiensis* with B.t.-parasitoid *Cotesia plutellae* -pest interactions. In delaying the evolution of pesticide resistance, parasitoid decreased the number of generations in which pesticide treatment is required. Parasitoids could be complementary to refuges from pesticides, with parasitoids maintaining control of a pest while refuges slow the development of resistance to the pesticide by

the pest (Chilcutt and Tabashnik, 1999). On the introduction and establishment of a laboratory-selected azinphos-methyl resistant strain of *Trioxys pallidus*, a parasitoid of *Chromaphis juglandicola*, computer simulation was used to estimate the effects of biological and operational parameters. Establishment of the resistant strain was considered to increase by 1) the migration of the parasitoid between walnut orchards, 2) low survivorship of the susceptible strain when treated with insecticide, 3) minimal refuge from insecticide, 4) the available resistant parasitoids splitted into small groups and released the groups in separate orchards, 5) increasing the relative frequency of use of azinphos-methyl over alternative pesticides (Caprio *et al.*, 1991).

Jansen and Sabelis (1995) presented a simple tri-trophic model which can have two simultaneously stable states, one in which 3 species can coexist and one in which the predators are absent. The disturbance caused by the application of pesticides can therefore cause the predators to decrease and eventually to go extinct, leaving the pest to show sustained outbreaks. Resurging pests will trigger more pesticide treatments, leading to strong selection for resistance. The development of pesticide resistance in predator populations is discussed in relation to the tri-trophic model. Harper (1991) introduced a bioeconomic model involving three key species: a primary target pest, a secondary pest, and a natural enemy of the secondary pest. Optimal decision rules are derived and contrasted with myopic decision making which treats the predator-prey system as an externality. van de Baan and Croft (1990) suggested that fecundity and immigration explain resistance to azinphos-methyl and fenvalerate in *Cacopsylla pyricola* and the lack thereof in *Deraeocoris brevis* better than do detoxification attributes. Sensitivity analyses predicted that high fecundity and low immigration of susceptible individuals into populations selected by insecticides contributed greatly to the development of rapid resistance in *C. pyricola*. The use of an attractant was shown to increase the numbers of natural predators of *Heliothis* on cotton in Australia. This resulted in a decrease in the number of insecticide applications (Maples, 1998).

5.1. Parasitoid

5.1.1. Selective toxicity to parasitoids

a. Selecting pesticides to enhance the viability of parasitoids

Table 3. Selective toxicity to parasitoids

Biological agents	Host species	Compatible to parasitoid	Crop	Field or Lab.	Ref.
<i>Aphytis melinus</i>	<i>Aonidiella aurantii</i>	Carbaryl	Citrus	-	Rosenheim and Hoy, 1988
<i>A. melinus</i>	Lepidopteran pests	<i>B.t.</i> endotoxin, and others	Citrus	Field	Bellows <i>et al.</i> , 1993
<i>A. holoxanthus</i>	<i>Chrysomphalus aonidum</i>	Malathion	Citrus	-	Cohen <i>et al.</i> , 1987
<i>Anastatus bifasciatus</i> and others	<i>Thaumetopoea pityocampa</i>	<i>B.thuringiensis</i> , diflubenzuron	Pine	Field	Jamaa <i>et al.</i> , 1996
<i>Anisopteromalus calandrae</i>	<i>Sitophilus oryzae</i>	Malathion	Wheat	Field	Baker and Throne, 1995
<i>Aleochara bilineata</i>	<i>Delia radicum</i>	Carbofuran + isofenphos	Cabbage	Seed beds	Maisonnecuve <i>et al.</i> , 1996
<i>Bracon hebetor</i>	<i>Helicoverpa armigera</i>	Phosalonc	-	-	Zilbermints <i>et al.</i> , 1986
4 Coccinellid, braconids	<i>Cydia pomonella</i> & others	Teflubenzuron	Apple	Field	Ferrari, 1987
<i>Camptopletis chlorideae</i>	<i>H. armigera</i>	Diflubenzuron+(chlorpyri-fos or endosulfan)	Chickpeas	Field	Rav and Verma, 1997
<i>C. chlorideae</i>	<i>H. armigera</i>	Endosulfan	Chickpeas	Lab.	Ravi and Shashi, 1997
<i>Cardiochiles nigriceps</i>	<i>Anthonomus grandis</i>	Oxamyl	Cotton	Lab.	Tillman, 1995
<i>C. nigriceps</i>	<i>Heliothis virescens</i>	Thiodicarb and others	Cotton	Lab.	Tillman, 1995
<i>Corycyra cephalonica</i>	<i>Chelonus blackburni</i>	Endosulfan	-	Lab.	Latha <i>et al.</i> , 1998
<i>Cotesia marginiventris</i>	-	Tebufenozide	Cotton	Lab.	Pietrantonio & Benedict, 1999
<i>C. plutellae</i>	<i>P. xylostella</i>	Chlorfluazuron, and others	Vegetable	Lab.	Shi and Liu, 1998
<i>C. plutellae</i> and others	<i>P. xylostella</i>	<i>B.thuringiensis</i>	Cruciferous	Field	Uematsu & Yamashita, 1999
<i>Diadegma eucerocephala</i>	<i>P. xylostella</i>	Pyrethroids + <i>B.thuringiensis</i>	Cabbages	Lab./Field	Iman <i>et al.</i> , 1986
<i>D. semiclausum</i>	<i>P. xylostella</i>	<i>B.thuringiensis</i>	Cabbage	Field	Sastrosiswojo and Grey, 1996
<i>D. semiclausum</i>	<i>P. xylostella</i>	<i>B.thuringiensis</i> Berl	Crucifers	Field	Amend and Basedow, 1997
<i>D. semiclausum</i>	<i>P. xylostella</i>	Teflubenzuron, abamectin	-	Lab.	Iqbal and Wright, 1996
<i>D. semiclausum</i>	<i>P. xylostella</i>	Diafenthionuron	Cruciferous	-	Streibert and Kaeding, 1994
<i>Diadegma</i> sp.	<i>H. virescens</i>	<i>B.t.</i> subsp. <i>dendrolimus</i> , and others	Tobacco	Field	Jimenez and Fernandez, 1985
<i>Diglyphus</i> sp., <i>Opius</i> sp.	<i>Liriomyza huidobrensis</i>	Cyromazine	<i>Phaseolus vulgaris</i>	Field	Carballo <i>et al.</i> , 1990
<i>Eretmocerus mundus</i>	<i>Bemisia tabaci</i>	Amitraz, and others	Cotton	Lab.	Jones <i>et al.</i> , 1995
<i>E. orientalis</i>	<i>B. argentifolii</i>	Hexaflumuron, buprofezin	-	Lab.	Tzeng and Kao, 1999
<i>E. sp.</i> and others	<i>B. tabaci</i>	Buprofezin	Cotton	Lab.	Jones <i>et al.</i> , 1995
<i>Goniozus nephantidis</i>	<i>Opisina arenosella</i>	Methoprene	Coconut	Field	Jayaraj, 1989
<i>Glabromicroplitis croceipes</i>	<i>H. virescens</i>	Thiodicarb	Cotton	Lab.	Tillman, 1995
<i>Muscidifurax raptor</i>	<i>Musca domestica</i> , <i>Stomoxys calcitrans</i>	Pyrethrins, tralomethrin	-	Calf pens	Miller and Pickens, 1989
23 species of beneficials	-	Buprofezin	-	-	Hassan <i>et al.</i> , 1994
30 species of beneficials	<i>Pseudatomoscelis</i> & others	Lambda-cyhalothrin	Cotton	Field	Cole <i>et al.</i> , 1997
<i>Orius insidiosus</i>	-	Tebufenozide	Cotton	Lab.	Pietrantonio & Benedict, 1999
<i>Oxyopes salticus</i> , and others	<i>Tagosodes orizicolus</i>	Etofenprox and others	Rice	Field	Bastidas, 1996
<i>Sturmiopsis inferens</i>	Sugarcane moth borers	Deltamethrin	Sugarcane	Lab.	Easwaramoorthy <i>et al.</i> , 1990
Tachinid	<i>Dendrolimus punctatu</i>	Diflubenzuron	<i>Pinus massoniana</i>	Field	Liang, 1991
<i>Trichogramma brasiliense</i>	<i>Corycyra cephalonica</i>	Phosalone, fenvalerate	Cotton	Lab.	Varma and Singh, 1987
<i>T. cacaeciae</i>	<i>Cydia pomonella</i>	Imidacloprid	Orchards	-	Schuld and Schmuck, 1997
<i>T. chilonis</i>	<i>H. armigera</i>	Abamectin	Cotton	Field	Cai <i>et al.</i> , 1997
<i>T. demoraesi</i>	<i>Ephestia kuehniella</i>	Abamectin	-	Lab.	Souza <i>et al.</i> , 1987
<i>T. evanescens</i>	<i>Spodoptera littoralis</i>	Nuclear polyhedrosis virus	-	Lab.	Abbas, 1987
<i>T. pretiosum</i>	<i>Ephestia kuehniella</i>	Monocrotophos	-	Lab.	Hohmann, 1993
<i>T. pretiosum</i>	-	<i>B.thuringiensis</i>	-	Lab.	Castelo-Branco & Franca 1995
<i>Trichogrammatoidea</i>	<i>Cryptophlebia</i>	Deltamethrin	-	-	Malawi, Min. Agric., 1990
<i>T. bactrae</i> , <i>Microplitis demolitor</i>	-	<i>B. thuringiensis</i>	-	Lab.	Hassan and Graham-Smith, 1995
<i>Trissolcus basalis</i>	Pentatomids	Permethrin	Soyabean	Field	Orr <i>et al.</i> , 1989
<i>Trioxys pallidus</i>	<i>Chromaphis juglandicola</i>	Azinphos-methyl	Walnut	Field	Hoy <i>et al.</i> , 1989
<i>Typhlodromus occidentalis</i> and others	-	Fenoxycarb	Apple	Field	Nicholas <i>et al.</i> , 1999
<i>Urolepis rufipes</i> ,	Muscoid fly	Fenvalerate	-	Dairy	Rutz and Scott, 1990

b. Harmless pesticides to parasitoids

1) Conventional insecticides. Topical treatment of thiodicarb for cotton insect at field rates resulted in high survival of adults for each parasitoid species, *Glabromicroplitis croceipes* and *Cardiochiles nigriceps* (Tillman, 1995). The emulsifiable concentrates of endosulfan, cypermethrin, fenvalerate and deltamethrin against sugarcane moth borer caused little harm to the adult parasitoid *Sturmiopsis inferens* in the laboratory, when exposed to the chemicals for 6 h to impregnated filter paper or sugarcane shoot pieces. Soil applications and whorl applications of chlorpyrifos G and Sevidol G (carbaryl with lindane), recommended against the pyralid *Chilo infuscatellus*, had no harmful effects on the adults in pot cultures (Easwaramoorthy *et al.*, 1990). Endosulfan among six insecticides evaluated was found to be safest with the highest emergence of parasitoid *Chelonus blackburni* from insecticide-treated *Corcyra cephalonica* eggs, and the least persistent by a semi field study with an LT₅₀ value of 1.39 days. It is suggested that an endosulfan spray 3 days after parasitoid release could be used in the field (Latha *et al.*, 1998). Fenvalerate was the most selective insecticide to the parasitoid *Aphidius rhopalosiphii*, after checking on the terms of adult emergence from mummies, fertility and longevity of female, mortality by dried residues, host searching behavior, and mortality by direct application (Borgemeister *et al.*, 1993).

2) Insect growth regulators. Hexaflumuron and buprofezin among nine insecticides proved to be harmless (mortality <50%) to adults of parasitoid *Eretmocerus orientalis* of whitefly *B. argentifolii* at 1/2, 1/4 dosages of field (Tzeng and Kao, 1999). Exposure to *B. thuringiensis* and diflubenzuron used for *Thaumetopoea pityocampa*, a defoliator of cedar and pine, had no direct effect on the eggs of parasitoid, *Anastatus bifasciatus*, *Ooencyrtus pityocampae*, *Baryscapus servadeii* and *Trichogramma embryophagum* (Jamaa *et al.*, 1996). Residues of tebufenozide treated cotton leaves were nontoxic to adult parasitoid *C. plutellae* in the laboratory. Spinosad was less toxic than chlorfenapyr to *C. plutellae* and to *C. marginiventri* (Pietrantonio and Benedict, 1999). Buprofezin was not toxic to any of the 4 parasitoids of

B. tabaci, *Eretmocerus* sp. and *E. pergandiella* from Texas, *E. mundus* from Spain, and *E. formosa* from Greece. When caged on leaves sprayed 2 days previously, only amitraz of 8 insecticides allowed significant general parasitoid survival after 2 days. *E. mundus* exhibited the greatest overall tolerance to insecticides, amitraz, thiodicarb and cypermethrin (Jones *et al.*, 1995). The insecticide buprofezin, the fungicides triforine, procymidone, anilazine, triadimenol, hexaconazole, tridemorph and the herbicides tralkoxydim and bentazone tested by members of IOBC-WPRS were harmless to nearly all the beneficial organisms (Hassan *et al.*, 1994).

Dosages of 0.1, 0.2, 0.4 and 0.8 ml of abamectin 1.8% EC /litre did not affect the pre-imaginal development of the parasitoid *T. demoraesi* before its emergence from parasitized eggs of the pyralid *Ephesia kuehniella* (Souza *et al.*, 1987).

c. Pesticides effective to pests but safe to parasitoids

1) In laboratory. Phosalone and fenvalerate for the control of cotton bollworms *C. cephalonica* were considered to be relatively safe on the emergence of *T. brasiliense* from 1- and 7-day old parasitized host eggs tested (Varma and Singh, 1987). *G. croceipes* and *C. nigriceps*, parasitoids of *H. virescens*, were treated topically. Higher survival for *C. nigriceps* adults was obtained in thiodicarb, acephate, oxamyl, azinphos methyl, and cypermethrin. These 5 insecticides were less toxic to females than male *C. nigriceps*, except for treatment with acephate (Tillman, 1995). Application of monocrotophos to eggs of host *E. kuehniella* 0.5, 24 and 72 h before exposure to the adults of parasitoid *T. pretiosum* led to parasitization rates of 57, 61 and 71%. Parasitoid emergence was not affected by endosulfan, parathion-methyl or monocrotophos (Hohmann, 1993). Cyfluthrin and tebufenozide were more toxic to *Eoreuma loftini* a key pest of sugarcane than to its parasitoid *P. pyralophagus* (Legaspi *et al.*, 1999).

2) Development of resistance. A field strain of *Anisopteromalus calandrae* from near Bamberg, South Carolina was about 90-fold more resistant to malathion than the field strain of its host, *Sitophilus oryzae*. *A. calandrae* survived doses of malathion of 172 µg/vial

(Baker and Weaver, 1993). In laboratory and field experiments, *D. semiclausum*, a parasitoid of *P. xylostella*, is unaffected by the diafenthiuron. The insecticide was toxic to susceptible and insecticide-resistant strains of *P. xylostella*, *S. exigua*, *Pieris brassicae* and *P. rapae*. No cross-resistance to other insecticides was observed (Streibert and Kaeding, 1994).

3) In field. For the control of *C. pomonella* and *Leucoptera malifoliella* on the apple orchards in Italy, teflubenzuron gave positive results not only against the 2 species of Lepidoptera by the counts of pheromone traps and damaged apples, but also against *Ceratitis capitata*. No adverse effects were observed on a braconid parasitoid of the genus *Apanteles* or on 4 species of coccinellid predators (Ferrari, 1987). During the rabi seasons of 1992-94 in Delhi, mixtures of diflubenzuron with chlorpyrifos or endosulfan on chickpeas were recommended for the control of *H. armigera* and had little effect on the larval parasitoid *Campoletis chlorideae* (Ravi and Verma, 1997). Endosulfan at 2.4 kg/ha and 50% WP in tobacco fields was also innocuous to *Diadegma* sp, a parasitoid of *H. virescens* (Jimenez and Fernandez, 1985).

4) Comparison of selective toxicity between predator and parasitoid. Abamectin and tebufenozide are advantageous to protect the chief natural enemies for cotton (Cai *et al.*, 1997; Pietrantonio and Benedict, 1999). The corrected mortality in 72 h was 11% to the most effective parasitoid *T. chilonis* but 43.28% to populations of the principal predators *Coccinella septempunctata* in cotton fields in China, showing lower mortality to parasitoids than to the predator, when B1 component of abamectin at 40 mg/litre concentration is to control cotton bollworm *H. armiger* (Cai *et al.*, 1997). Tebufenozide and spinosad were less harmful than chlorfenapyr for the beneficials exposed for 24 or 48 h to fresh dried foliar residues. Mortality of the predaceous bug *Orius insidiosus* on tebufenozide and spinosad was low, killing 18%, and on chlorfenapyr was intermediate, killing 21-55%. To adult *C. plutellae*, residues of tebufenozide were non-toxic, however, spinosad and chlorfenapyr residues were toxic to *C. marginiventris* and to *C. plutella* (Pietrantonio and

Benedict, 1999).

d. Differences of selectivity by insecticide traits

1) Specificity in toxicity to parasitoids. Chlorpyrifos was highly toxic to the adult stage of *Aphelinus mali*, a parasitoid of the aphid. But both chlorpyrifos and azinphos-methyl were found to be harmless to the immature stages of the parasitoid under semi-field conditions (Cohen *et al.*, 1996). Cyfluthrin and tebufenozide were more toxic to *E. loftini* a key pest of sugarcane than to its parasitoid *Parallorhogas pyralophagus* (Legaspi *et al.*, 1999). At field doses of cartap, chlorfenapyr, emamectin benzoate, and permethrin, contact toxicity was selective against the *C. plutellae* cocoon but moderately to extremely toxic (80% to 100% lethal) against the wasp, a larval parasitoid of *P. xylostella*. Of oral toxicity of chlorfluazuron, flufenoxuron, and teflubenzuron on wasp stage were somewhat selective. While chlorfenapyr and emamectin benzoate were recorded slightly to be persistent (5-10 days) and permethrin seems to be short lived (< 5 days) (Haseeb and Amano, 2002).

In 4th-instar hosts of *P. xylostella*, teflubenzuron significantly reduced emergence of adult *D. semiclausum* but had no significant effect on *C. plutellae*. Similar differential toxicity was observed in 2nd-instar hosts, when parasitoids were eggs or early-instar larvae. Uptake experiments with radiolabelled teflubenzuron showed that accumulation of radioactivity was much greater in *D. semiclausum* than in *C. plutellae* (Furlong and Wright, 1993).

2) Influence on developmental stage. On activity to each stage of the aphid parasitoid *A. rhopalosiphii*, parathion and pirimicarb reduced adult hatching, dried residues of parathion killed females, direct application of demeton-S-methyl, parathion and pirimicarb caused high mortality to female, and demeton-S-methyl and fenvalerate affected the searching behavior (Borgemeister *et al.*, 1993). Methamidophos severely affected survival and longevity of emerged endoparasitoid *Diaeretiella rapae* individuals and of those within the mummified aphids *Brevicoryne brassicae*. Fenvalerate did not affect the adults survival of *D. rapae* emerged or those individuals still inside the mummies (Lankin *et al.*, 1997).

Feeding diflubenzuron or chlorpyrifos-methyl to the adult ectoparasite *Bracon brevicornis* reduced adult longevity, the number of eggs deposited, the rate of egg hatch and the number of pupae. Few adults parasitoid emerged when the host *S. exigua* was exposed to the chemicals. Effects of diflubenzuron were different: at 4.0 g/litre no adults emerged and at 0.5 g/litre some adults obtained were all male in the following generation (Zaki *et al.*, 1987).

e. Considering insecticide selectivity for practical application

1) Field conditions. Campbell *et al.*, (1991) suggested three factors, 1) species identification of predominant parasitoid complex and of primary parasitoids, 2) the compatibility of various insecticides with parasitism and parasitising avoidance of *Trichogramma* spp, and 3) evaluation of insecticides efficacy and of the level of parasitism because the treatment with the lowest level of parasitism had the lowest levels of fruit damage. Finding the best fit of a pesticide into an IPM program requires a consideration of its potential longevity, mode of delivery, or its toxicity to the target pest and direct study of effects on the aphelinid parasitoid, *E. citrina* of euonymus scale, *Unaspis euonymi* (Rebek and Sadof, 2003).

2) Traits of insecticides. (Selectivity) Avermectin, Bt, and a mixture of Bt and virus, diafenthiuron, and chlorfluazuron of 9 insecticides are recommended to have high mortality to the host, *P. xylostella* and low mortality to adult parasitoid *C. plutellae* (Shi, and Liu, 1998). Adults of the egg parasitoid *Trissolcus basal* were affected little by permethrin field applications, but parathion-methyl had an adverse but short-lived effect on parasitoid survival. High levels of adult parasitoid mortality were observed only within the first 6 h following parathion-methyl application (Orr *et al.*, 1989). Fresh residues of endosulfan were highly toxic at the 2 rates tested, but 2-day-old residues at the lower rate allowed 76.7% survival of *E. mundus* and 35% survival of *E. pergandiella* after 48 h (Jones *et al.*, 1995). Incorporation into the soil and sprinkling chlordimeform hydrochloride for the control of the yellow rice borer

S. incertulas on the field had a smaller influence on parasitism and emergence of the parasitoid *T. japonicum* (Hong, 1988).

3) Residual uptake by time. Residual uptake of radiolabelled diazinon by parasitoid *A. ervi* was dependent on the concentration of the residues and exposure time. The quantity of insecticide taken up via ingestion was positively correlated with time spent feeding. Diazinon penetration through the mummy case and into the immature parasitoid was dependent on time after insecticide application (Longley and Stark, 1996).

4) Factors of host environment. Emergence of parasitoids *T. cacaeciae* was significantly affected when host *C. pomonella* eggs treated were stored under greenhouse conditions, but no significant reduction of parasitoid emergence was recorded when they were subjected to field conditions (Schuld and Schmuck, 1997).

5) Place of egg mass in plants. The adults' mortality of the egg parasitoid *T. basalis* was affected by position of parasitized egg masses in the soyabean canopy (Orr *et al.*, 1989).

6) Direct or indirect exposure of mummies. After exposure of mummies to chlorpyrifos directly to the undersides of cotton leaves or indirectly to the upper surface of the leaves, adult emergence of parasitoid, *Lysiphlebus testaceipes* from *A. gossypii* was 21.0% or 79.1%, respectively, killing the parasitoids developing within the host mummy case and adult survival was 10.9% or 11.0%. However adult emergence by direct exposure of acephate was as high as 86.6% and by indirect exposure to phosphamidon was over 97.2%. And adult survival by direct exposure of to profenofos was 44.9% and by indirect exposure of mummies to endosulfan was over 70.5% (Hardee *et al.*, 1990).

f. Factors related to parasitoid biology

1) Parasitoid development. The degree of adult mortality of the egg parasitoid *T. basalis* was affected by parasitoid development stage at time of insecticide application (Orr *et al.*, 1989). In field studies conducted in New Zealand, chlorpyrifos was applied to field lucerne at a rate (0.3 kg/ha) recommended to control the curculionid *Sitona discoides*. Where parasitoid *Microctonus*

aethiopoides was sufficiently advanced in the host, larvae of late-instars emerged and successfully pupated from cadavers up to 18 h following host mortality (McNeill *et al.*, 1996). For the control of the yellow rice borer *S. incertulas* on the field, spraying chlordimeform hydrochloride on the 2nd day after oviposition resulted in the lowest rate of parasitism (0.53%) by *T. japonicum*, while spraying on the 4th resulted in 18.91% parasitism. Insecticide treatment on the 6th day had the greatest influence on parasitoid emergence, with a mortality of 35.99%, (Hong, 1988). It was also shown that adult parasitoids were most sensitive to the insecticide (Hong, 1988).

2) Gender of parasitoid and host. The degree of adult mortality of the egg parasitoid *T. basalis* was affected by parasitoid gender (Orr *et al.*, 1989). The gender of *S. discoideus*, a host of *M. aethiopoides* was a significant factor influencing mortality (McNeill *et al.*, 1996).

3) Protection mechanism. Cyhalothrin and endosulfan had little impact on the emergence of parasitoid *T. pretiosus* in the laboratory when host eggs were directly treated. The survival of the parasitoids after treatment was not significantly influenced within the host egg by the host species (*H. virescens* or *H. zea*) and by development stage of the parasitoid. However, residues of both insecticides were highly toxic to emerging adult parasitoids for 5 days after treatment (Kring and Smith, 1995). Neither permethrin nor parathion-methyl affected emergence of egg parasitoids *T. basalis* from their host eggs, suggesting that pentatomid eggs provided a barrier to insecticide penetration. However, parasitoids apparently contacted insecticide residues when chewing through the shell of host egg to emerge, resulting in some mortality after emergence, caused by parathion-methyl (Orr *et al.*, 1989).

4) Parasitoids protection by host resistance from insecticide. The mortality of unparasitized host *S. discoideus* was significantly greater than that of the hosts parasitized by *M. aethiopoides* (McNeill *et al.*, 1996). Host resistance to insecticides can confer protection to endo-larval parasitoids, *C. plutellae* and *D. semiclausum* (Furlong and Wright, 1993). Teflubenzuron had no significant effect against *D. semiclausum* at rates up to

the LC₄₀ value irrespective of the host's resistance status and where application rates differed by up to 3 orders of magnitude. A teflubenzuron-resistant host population of *P. xylostella* also conferred some protection to the parasitoid against abamectin (Iqbal and Wright, 1996).

5) Insecticide pressure on host and parasitoid. When the host *D. melanogaster* was under the pressure of chlorpyrifos, its parasitoid *Leptopilina boulardi* infested more host larvae (the degree of infestation was increased by 11-16%), the development of the parasitoid was improved (the rate of successful parasitism was increased by 10-21%) and no significant effect was found on the host's capacity to encapsulate the parasitoid's eggs.

6) Parasitoid. When the parasitoid was under insecticide pressure, it infested fewer host larvae (the degree of infestation was decreased by 16%) and no significant effect on the development of the parasitoid was found, but encapsulation of the parasitoid's eggs was increased 3-fold; the longevity of surviving parasitoids was decreased (Delpuech and Tekinel-Ozalp, 1991).

5.1.2. Exploitation of insecticide resistant parasitoid

a. Selection of insecticide resistant parasite

1) Endoparasitoid. Parasitoids with insecticide resistant or tolerant were tested, collected from field, and/or selected, which were *C. juglandicola* for walnuts (Hoy and Cave 1988), *Aphytis melinus* for citrus (Rosenheim and Hoy, 1988), *A. holoxanthus* for citrus (Havron *et al.*, 1991), and *Ganaspidium utilis* (Rathman *et al.*, 1995). They were better survived (Hoy and Cave 1988; Rosenheim and Hoy, 1988), produced more progeny (Hoy and Cave 1988), and performed as a biological agent and dispersed to nearby orchard blocks (Hoy *et al.*, 1989).

Populations of the aphelinid *A. holoxanthus*, a parasitoid of the diaspitid *Chrysomphalus aonidum*, were collected from 7 citrus orchards and selected for increased resistance in the laboratory. Two field populations showed relatively high levels of azinphos-methyl tolerance, which were further increased by selection to 24-48 times that of a susceptible laboratory population (Havron *et al.*, 1991). Populations of *A. melinus*, a parasitoid of the citrus pest *A. aurantii*, were selected in the laboratory for increased

tolerance to 5 insecticides. LC_{50} s for carbaryl increased to > 5 times that of the original field population from California and approximately 20 times that of a susceptible natural population. Two-leaf bioassays of carbaryl residues revealed > 50% survival of the carbaryl-selected strain as early as 18 days after treatment, whereas the unselected colony continued to suffer > 86% mortality on 75-day-old residues (Rosenheim and Hoy, 1988). Maximum resistance ratios of four field populations of leafminers parasitoid *G. utilis* at the LC_{50} were 3 for methomyl, 2 for oxamyl, 3 for fenvalerate, 12 for permethrin and 9 for malathion, compared with the susceptible laboratory populations. LC_{50} s for some populations were higher than the recommended field rates for permethrin and fenvalerate (Rathman *et al.*, 1995).

A strain of the braconid *T. pallidus*, a parasitoid of *C. juglandicola* on walnuts, was selected with to azinphos-methyl. This resulted in an LC_{50} 7.5 times as high as that of the strain, which was selected 3 times. A clip cage assay indicated that 26% of the resistant strain survived for at least 72 h on treated foliage, compared to <6% survival of the susceptible strain. Females of the selected strain also produced 6.7 times more progeny than susceptible females on treated walnut trees (Hoy *et al.*, 1988). The improved strain performed well as a biological control agent after release in commercial walnut orchards in California in 1988, persisting in 4 of the 5 release sites and, at 2 sites, dispersing to nearby walnut blocks (Hoy *et al.*, 1989).

2) No increase in resistance by selection. However, LC_{50} s of 7 insecticides, parathion-methyl, methamidophos, phosphamidon, isoprocarb, dimehypo, fenvalerate and deltamethrin were not increased more than 2.5 times in the parasitoid *T. japonicum* after 10-14 selection for resistance in the egg, pupa, or adult for 16-43 generations (Hsiu *et al.*, 1988).

3) Ectoparasite. The possibilities for selecting out resistant races of ectoparasitoid to insecticides are very considerable not least because of its very rapid rate of reproduction in the laboratory. Initial two selections with *Bracon hebetor*, the most active ectoparasitoid of older larvae of *H. armigera*, increased phosalone resistance of 25-fold (Zil'bermints *et al.*, 1986).

Both an increase in expression of carboxylesterase and a modified gene structure may be responsible for the high level of resistance found in beneficial parasitoid, *A. calandreae*. Malathion-specific carboxylesterase (MCE) activity, determined by using 2,3- ^{14}C -malathion as substrate, was 10- to 30-fold higher in malathion-resistant (R) compared with that in malathion-susceptible (S) strains of the parasitoid (Baker *et al.*, 1998). The level of the carboxylesterase-like enzyme mRNA in adult *A. calandreae* is approximately 30-fold higher in the resistant strain relative to that in the susceptible by northern blot analyses (Zhu *et al.*, 1999b).

b. Considering factors for field application

1) Interaction of resistant parasitoid and host. Interaction of a resistant Bamberg strain *A. calandreae* and a curculionid host *S. oryzae* on malathion treated wheat had no significant effect on longevity, fecundity, or the effectiveness of the strain of *A. calandreae* parasitizing *S. oryzae*. The strain of *A. calandreae* was more successful parasitizing the Savannah laboratory strain of *S. oryzae* compared with the Bamberg strain of *S. oryzae*, possibly because of the larger size of the former (Baker and Throne, 1995).

2) Viability. Pesticides resistance developed in the parasitoid *A. calandreae* and in its associated host lacked significant resistant in a stored grain ecosystem. A field strain of *A. calandreae* collected near Bamberg, South Carolina survived at doses of 172 μ g malathion /vial, was about 90-fold more resistant to malathion than the field strain of its host *S. oryzae* (Baker and Weaver, 1993). However, LD_{50} s of the malathion-resistant field strain of parasitoid *A. calandreae* were 0.36 μ g/vial for deltamethrin and 1.52 μ g/vial for cyfluthrin, while LD_{50} s of *S. oryzae* were 0.51 μ g/vial for deltamethrin and 1.51 μ g/vial for cyfluthrin (Baker, 1994). Populations of *D. begini*, a parasitoid of *Liriomyza* spp., showed resistance to oxamyl, methomyl, fenvalerate and permethrin. Parasitoids from a heavily sprayed tomato greenhouse on the island of Hawaii had 10 and 29 times higher LC_{50} s to permethrin and fenvalerate, respectively, than the field rate. Populations resistant to oxamyl and methomyl had LC_{50} s 2- and 6-fold below the field rate, respectively (Rathman *et al.*, 1990). Four field populations of a

parasitoid of agromyzid leafminers, *G. utilis* were significantly less susceptible than a laboratory population. LC₅₀s for some populations were higher than the recommended field rates for permethrin and fenvalerate (Rathman *et al.*, 1995). The persistence of resistance on *D. begini* may be especially valuable in IPM programs that use Pyr intermittently. The resistance to fenvalerate in *D. begini*, a major parasitoid of *Liriomyza* spp., remained and showed low mortality at concentration equivalent to field-recommended application rates

(Spollen *et al.*, 1995). Stability of the resistances in *A. calandreae* will facilitate the incorporation of these parasitoid strains into integrated biological-chemical control programmes for stored-product insect pests. Malathion resistance of *A. calandreae* collected near Bamberg, South Carolina, was stable after 23 generations of laboratory rearing with no selection pressure. The progeny F23 of this parasitoid strain were 200-fold more tolerant of malathion than the field strain of the insect host *S. oryzae* with which they were collected (Baker, 1995).

5.2. Predator

5.2.1. Selective toxicity of predator

a. Selective insecticides to predators

Table 4. Selective toxicity of predators (1)

Biological agents	Host species	Toxic to predator	Favorable to predator	Crop	Field or Lab.	Ref
<i>Achaearanea veruculata</i> and others	<i>Tetranychus urticae</i>	Dimethoate, thiodicarb, Methomyl	Amitraz	Cotton	Field	Wilson <i>et al.</i> , 1998
<i>Amblyseius andersoni</i> , <i>Typhlodromus phialatus</i>	<i>P. ulmi</i>	Dimethoate	Parathion-methyl	Vineyards	Field	Grande & Ingrassia, 1988
<i>A. longispinosus</i>	-	Fenprothrin , perm EC	Permethrin Wp.	Tea	Field	Mochizuki, 1992
<i>A. womersleyi</i>	<i>T. urticae</i>	-	Fenpyroximate	-	-	Paik and Kim, 1996
<i>A. womersleyi</i>	<i>T. urticae</i> , <i>T. kanzawai</i>	-	Flufenoxuron	-	Lab.	Paik <i>et al.</i> , 1996
Aphidopathogenic fungi	<i>Apis gossypii</i>	-	Sulprofos	Cotton	Field	Kerns and Gaylor, 1993
<i>Brachygastra lecheguana</i>	<i>Tuta absoluta</i>	Permethrin	Abamectin, cartap	Tomato	Lab.	Leite <i>et al.</i> , 1998
<i>Chauliognathus lugubris</i>	<i>Chrysophtharta bimaculata</i>	B.t. subsp. <i>tenebrionis</i>	-	<i>T. eucalypt</i>	Lab.	Greener and Candy, 1994
<i>C. lugubris</i>	<i>C. bimaculata</i>	-	B.t. var. <i>tenebrionis</i>	<i>T. eucalyptus</i>	Lab.	Beveridge and Elek, 1999
<i>Chilocorus bijugus</i> , <i>Pharoscyrmus flexibilis</i>	<i>Pseudaulacaspis</i> sp.	Monocrotophos	Dormant mis. spray oil	Apple	Field	Gupta and Bhalla, 1993
<i>Chrysoperla carnea</i>	-	Deltamethrin	Kelthane-S	-	-	El-Maghraby <i>et al.</i> , 1994
<i>C. carnea</i>	-	Triazophos, and others	Endosulfan, and others	Cotton	-	Kapadia and Puri, 1991
<i>Coccinella septempunctata</i>	<i>Brevicoryne brassicae</i>	Mtrithion, and others	Endosulfan, toxaphen	-	-	Sharma and Adlakha, 1986
<i>C. septempunctata</i>	<i>A. gossypii</i>	-	Fluvalinate, esfenvalerate	Cotton	-	Kovalenkova & Tyurina, 1993
<i>C. septempunctata</i>	<i>Uroleucon carthami</i>	-	Endosulfan	-	Lab.	Singh <i>et al.</i> , 1995
<i>C. septempunctata</i> , <i>Chrysopa carnea</i>	<i>A. fabae</i>	-	DSC 24300 (IGR)	<i>Vicia faba</i>	Lab.	Yakti and Poehling, 1988
<i>C. septempunctata</i> , <i>Propylea japonica</i>	<i>A. gossypii</i>	Cyhalothrin	Endosulfan	-	Field	Zhu <i>et al.</i> , 1998
<i>C. septempunctata</i> , and others	<i>A. craccivora</i>	Dimethoate Dimethoate, mono Monocrotophos	Fenvalerate Cyber, endosulfan Endosulfan	<i>L. sativus</i> Lentil, Chickpeas	Field	Sharma <i>et al.</i> , 1991
<i>Curinus coeruleus</i>	<i>Heteropsylla cubana</i>	Cyhalothrin, and others	-	Leucaena	Field	Sudarmadji, 1988
<i>Cyrtorhinus lividipennis</i>	<i>Nilaparvata lugens</i>	-	Buprofezin	-	-	Choi <i>et al.</i> , 1996
<i>Cryptolaemus montrouzieri</i>	<i>Maconellicoccus hirsutus</i>	Pyrethroids, dicofol	Dichlorvos	Grapevines	Lab.	Babu and Azam, 1987
<i>Doru luteipes</i>	<i>Spodoptera frugiperda</i>	Carbaryl, malathion	Perm, deltamethrin	Maize	Lab.	Faleiro <i>et al.</i> , 1995
<i>Diaeretiella rapae</i> , and others	<i>Diuraphis noxia</i>	Malathion	Acephate	-	Lab.	Bayoun <i>et al.</i> , 1995
<i>Forficula auricularia</i>	<i>Cydia pomonella</i>	Diflubenzuron	-	Pears	Field/Lab.	Sauphanor <i>et al.</i> , 1993

Table 4. Selective toxicity of predators (2)

Biological agents	Host species	Toxic to predator	Favorable to predator	Crop	Field or Lab.	Ref
<i>Geocoris punctipes</i>	<i>Anticarsia gemmatilis</i>	-	Thiodicarb	Soyabeans	Field	Chandler & Sumner, 1993
<i>G. spp.</i> and others	-	Methamido-phos	Endosulfan	Soyabean	Field	Avila, 1997
<i>Harmonia octomaculata</i> , and others	<i>A. gossypii</i> , <i>Creontiades dilutus</i>	-	Spinosad	Cotton	Field	Murray and Lloyd, 1997
<i>Microplitis croceipes</i>	<i>Heliothis virescens</i> , <i>H. zea</i>	Acephate, methomyl	Fenvalerate, and others	Cotton	Lab.	Elzen <i>et al.</i> , 1987
<i>Neoseiulus californicus</i>	<i>P. ulmi</i>	Fenpyroximate	Azinphos-methyl	Apple	Field	Muther, 1998
<i>N. fallacis</i>	<i>T. urticae</i>	-	Propargite	Mint	Field	Morris <i>et al.</i> , 1999
<i>N. longispinosus</i>	-	Fenpropathrin, perm (EC)	Methidathion and others	Tea	Field	Mochizuki, 1992
<i>Orius</i> sp.	<i>Thrips palmi</i>	Fenthion	-	Eggplant	Lab	Nagai <i>et al.</i> , 1988
<i>O. sp</i>	-	λ -Cyhalothrin, bifenthrin	Chlorfenapyr	-	Field	Mau <i>et al.</i> , 1999
<i>O. insidiosus</i>	<i>Frankliniella occidentalis</i>	-	Spinosad	Peppers	Field	Funderburk <i>et al.</i> , 1998
<i>O. laevigatus</i>	-	Imidacloprid	Pyriproxyfen	-	Lab.	Delbeke <i>et al.</i> , 1997
<i>Pardosa amentata</i>	-	-	Dimethoate, cyper	-	Lab.	Toft and Jensen, 1998
<i>Podisus nigrispinus</i>	<i>Blera</i> sp. and others	-	Perm, deltamethrin	Eucalyptus grandis	Lab.	Suinaga <i>et al.</i> , 1996
<i>P. nigrispinus</i>	<i>S. frugiperda</i>	-	Deltamethrin	-	Lab.	Batalha <i>et al.</i> , 1997
Polyphagous predators	<i>Phorodon humuli</i> , <i>Brachycaudus helichrysi</i>	-	Pirimicarb	Plum	Lab.	Hartfield and Campbell, 1996
Predatory arthropods	-	Pyrethroid, and others	IGR, spinosad	Cotton	Field	Duffie <i>et al.</i> , 1998
Spiders, lacewings, <i>Stethorus</i> spp.	<i>Cydia pomonella</i> , and others	-	Tebufozide	Apple	Field	Gurr <i>et al.</i> , 1999
<i>S. punctum</i>	-	Fenoxycarb, and others	Tebufozide, OP tolerant	-	Lab.	Biddinger and Hull, 1995
<i>S. punctum</i>	-	-	Tebufozide, OPs	-	Field/Lab.	Biddinger and Hull, 1995
<i>T. pyri</i>	-	Triamiphos, and others	-	Apple	Field	Blommers <i>et al.</i> , 1986
<i>T. pyri</i>	<i>P. ulmi</i>	Trichlorfon, fenvalerate	Fenb-o, parathion	Vineyards	Field	Maixner, 1990
<i>T. pyri</i>	<i>P. ulmi</i>	Cyper, pirimi-m	Carbaryl, chlorpyrifos	Apple	Field	Cross and Berrie, 1994
<i>T. pyri</i>	<i>P. ulmi</i> , and others	-	Cyper, azin-m	Apple	Field	Hardman <i>et al.</i> , 1997
<i>Xylocoris flavipes</i>	<i>Tribolium castaneum</i>	-	Malathion	Maize	Lab.	Baker and Arbogast, 1995

Azin-m: azinphos-methyl; cyper: cypermethrin; fenb-o: fenbutatin oxide; L.: Lathyrus; mono: monocrotophos; pirimi-m: pirimiphos-methyl; perm: permethrin; T.: Tasmanianb. Selecting selective insecticides to predators

b. Selecting selective insecticides to predators

1) **Safe insecticides to predators.** Endosulfan was the safest insecticides to the coccinellid predator *Cheilomenes sexmaculata* (Babu, 1988), to *C. septempunctata* (Singh *et al.*, 1995; Zanzwar and Jadhav, 1998) when insecticide-treated cabbage aphid, *B. brassicae* were supplied (Sharma and 1986.), and to the predator *Rhynocoris kumarii* at the recommended field concentration (George and Ambrose, 1998). The least toxic insecticide to the predator, *Podisus nigrispinus*, was permethrin at the dosages tested caused 90% mortality of larvae of *Ascia monuste orseis* in the laboratory (Picanco *et al.*, 1997). Pyriproxyfen was harmless to 5th-instar *O. laevigatus* by the exposure of ingestion and residual contact (Delbeke *et al.*, 1997). In

laboratory tests of the nontarget effects of 7 insecticides, 2 acaricides and a fungicide, 5 were classified as harmless to the OP resistant predatory mite *Phytoseiulus persimilis* from Austria according to IOBC/WPRS categories (Stolz, 1990). In commercial apple orchards, repeated sprays of the several fungicides, carbaryl, or chlorpyrifos, did not significantly affect the numbers of OP-resistant strains of the orchard predatory mite *Typhlodromus pyri* (Cross and Berrie, 1994). No detrimental effects were found for the growth regulators or feeding substances when trials conducted on the effects on the *T. pyri* in apple (Blommers *et al.*, 1986). Dichlorvos at 0.1% was found to be the safest insecticide to the coccinellid *Cryptolaemus montrouzieri* against *Maconellicoccus hirsutus* on

grapevines (Babu and Azam, 1987).

2) Effective insecticides to predators. Demeton-methyl 0.025% spray was the most effective insecticides against *A. craccivora* on cowpea and hyacinth bean in the field in India (Babu, 1988). Permethrin and deltamethrin were the most selective insecticides to the predator, *Podisus nigrispinus*, of Eucalyptus lepidopteran defoliators (Suinaga *et al.*, 1996), and to the predator, *Doru luteipes* which were exposed to insecticide treated maize leaves causing 99% mortality to *S. frugiperda* (Faleiro *et al.*, 1995). Deltamethrin was the more selective insecticide to the predator *P. nigrispinus* than to its prey, *S. frugiperda*, exposed to insecticides impregnated leaves (Batalha *et al.*, 1997). Abamectin and cartap were the most selective insecticides favouring *Brachygastra lecheguana* (Hymenoptera: Vespidae) compared with tomato pest *Tuta absoluta*, with differential selectivity indexes (DSIs) (LC_{50} predator, LC_{50} pest) of 9.5 and 8.6, respectively (Leite *et al.*, 1998). Endosulfan is recommended for the control of resistant *A. gossypii* with *C. septempunctata*, with selective toxicity index of 4.9 (Zhu *et al.*, 1998). Bifenazate, acequinocyl, chlorfenapyr, flufenoxuron and fenbutatin oxide were much less toxic to adult females and immatures predatory mite, *P. persimilis* than to those of *Tetranychus urticae*, and adult female predators treated with these acaricides produced $84 \pm 96\%$ as many eggs as did control females in laboratory (Kim and Yoo, 2002). LC_{50} s of alpha-cypermethrin and deltamethrin of the 4th-instar larvae of *Toxorhynchites splendens* were 53 and 12, and 14 and 5 times higher than the values of *C. quinquefasciatus* and *A. aegypti*, respectively (Amalraj and Das, 1996). Malathion sensitivity of adult warehouse pirate bug, *Xylocoris flavipes* were estimated to be higher LD_{50} s of 51.4 ng a.i./filter for males and 45.9 ng a.i./filter for females than LD_{50} s of its prey, larvae of *Tribolium castaneum*, 15.0 ng a.i./filter, indicating higher selectivity to the predator (Baker and Arbogast, 1995). In field trials cypermethrin was the most effective insecticide against bean aphid, *A. craccivora* on all 3 crops, sativus, lentils and chickpeas with coccinellid predator complex. Fenvalerate, followed by endosulfan applied to sativus, cypermethrin and endosulfan (applied to lentils), and

endosulfan (applied to chickpeas) were considered the most selective insecticides for aphid control (Sharma *et al.*, 1991).

c. Increasing or decreasing selectivity by chemical specificity

1) Treatment method. Pyriproxyfen by exposure of ingestion and residual contact was harmless to *O. laevigatus* nymphs. Diafenthiuron did not cause significant mortality to fifth-instar nymphs and adults via ingestion but was toxic by residual contact with LC_{50} -values of 329.4 mg a.i./l and 125.9 mg a.i./l for nymphs and adults, respectively (Delbeke *et al.*, 1997).

2) Specificity to development stage. The larvae of aphid predator, *Episyrphus balteatus* were exposed until pupation to cereal aphicides residues at recommended field rate in the laboratory. Six compounds were classified 'harmful' for the larvae in beneficial capacity reduction: cyfluthrin, cypermethrin, phosalone and pirimicarb caused 100% larval mortality, few pupae harvested but failed to emerge to adults after treatment with deltamethrin, and eggs from the adults emerged was not hatched by lambda-cyhalothrin. Bifenthrin and esfenvalerate were slightly harmful, giving much lower mortality rates with reduced the fertility of females. Fluvalinate had no effect on reproductive performance of the *E. balteatus* adults (Jansen, 1998)

3) Effect of insecticide concentration. When abamectin was applied directly at doses of 0.1-0.4 ml/l water, the incubation period of the eggs of the predator *Chrysoperla externa* was reduced and the duration of larval instars was affected, although development was normal. Doses greater than 0.4 ml/l applied to the eggs reduced larval survival (Ribeiro *et al.*, 1988).

4) Additives to insecticide formulations. Fourth-instar *C. septempunctata* larvae were innately more sensitive to azadirachtin (AZA), the active ingredient in Neemix, with LC_{50} value of 520 ppm than 1st instar with 1120 ppm. These values were much higher than the recommended rates for control of aphids (3 weekly applications of 20 ppm), suggesting that Neemix might be used in IPM programs (Banken and Stark, 1997). Significantly more predatory mite, *P. persimilis* and

Neoseiulus cucumeris, were found on untreated disks than those treated. *N. cucumeris* females that contacted leaf disks and prey treated with AZA laid fewer eggs than those on the untreated. Greater mortality was observed when adults of *Aphidoletes aphidimyza* exposed to the residues and when first- and 3rd-instar acquired the neem from foliage contact or aphids ingestion (Spollen and Isman, 1996). The differential selectivity indexes (DSIs), LC_{50} of adults predator, *B. lecheguana*, over LC_{50} of the larvae of *T. absoluta*, the main tomato pest, of abamectin, cartap, and permethrin were 9.5, 8.6, and 0.002, respectively, without mineral oil but DSIs with 0.5% (v/v) mineral oil increased to 83.67, 38.32 and 0.02, respectively, in favour of *B. lecheguana*. Phenthoate with mineral oil had a strong negative effect to *B. lecheguana* on selectivity (Leite *et al.*, 1998).

5) Field results. In field trials, fenvalerate followed by endosulfan applied to sativus, cypermethrin and endosulfan to lentils, and endosulfan to chickpeas were considered to be the most selective insecticides for the control of bean aphid, *A. craccivora* (Sharma *et al.*, 1991). Repeated sprays of carbaryl or chlorpyrifos, did not significantly affect the numbers of OP-resistant strains of the predatory mite *T. pyri* in apple orchards (Cross and Berrie, 1994). On cucumbers in Egypt, ethiofencarb equally provided effective control of *A. gossypii* and conserved predators, *C. carnea*, *C. septempunctata* and *Syrphus* spp. Prothiofos and chlorpyrifos-methyl kept aphid numbers below those in untreated plots and caused a smaller reduction in the combined population of insect predators (El-Sayed and El-Ghar, 1992).

d. Application of insecticide selectivity to field

1) Major factors to insecticide selectivity. Control of budmoth (*Platynota idaeusalis*), a key pest in Pennsylvania apple, is closely tied to the management of spider mites and the conservation of the mite predator *Stethorus punctum*. Knight and Hull (1987) reviewed and discussed choice of insecticides, and spray interval, volume/acre, and timing. It is suggested that the predator/prey ratio can be improved by application time,

method and formulation, by reducing the dose rate of the insecticide, by using mulches and weeds, and by multicropping and management of surroundings (Wratten and Goulding, 1991). The effects of plant resistance and predator activity could be increased strongly by a combination of both factors with selective insect growth regulator. Predation on *A. fabae* by larvae of *C. septempunctata* and *C. carnea* in the laboratory was higher on the resistant variety Bolero of *Vicia faba* than on the more susceptible Diana. After treatment of aphids and host plants with the insect growth regulator DSC 24300 I (JHA), only a very low initial aphid mortality but a slow-acting inhibition of aphid fecundity could be detected if the young stages were contaminated (Yakti and Poehling, 1988).

e. Factors affecting to selective toxicity

1) Mixing mineral oil. The differential selectivity indexes LC_{50} s of predator *B. lecheguana* over its prey, *T. absoluta* increased or decreased, depending upon the kinds of insecticides used and the addition of mineral oil (Leite *et al.*, 1998).

2) Application method. The effect of cyhalothrin, monocrotophos and dimethoate, on the coccinellid *Curinus coeruleus*, a predator of *Heteropsylla cubana* on Leucaena, was tested. All 3 insecticides were toxic to the predators. However, application of the systemic insecticides, monocrotophos and dimethoate, to trees by painting did not affect the predator (Sudarmadji, 1988). Fly management efforts have used sanitation, insecticide-treated baits, and releases of *Spalangia endius*, *S. cameroni*, *Muscidifurax* raptor, and *Creophilus erythrocephalus* to control the populations of *Musca domestica*, *Fannia* sp. and other filth flies breeding in cattle, horse and poultry manure. A bait of sugar treated with 1% dichlorvos was found to be an effective means of controlling flies and was far less detrimental to the beneficial fauna than dichlorvos applied as a spray (Ripa, 1986).

3) Feeding on insecticide-contaminated prey. Direct treatments of oxydemeton-methy (0.1% a.i.) to predaceous coccinellid *C. montrouzieri* caused 85%, 50%, and 8% mortality in eggs and young larvae, in adults, and in 15-day-old larvae, respectively, in laboratory. In the case

of indirect treatment, where the insecticide was applied to the food source of its prey *Planococcus citri* at 0.1 and 0.025%, the mortality of 4-day-old predator larvae and adults was 95% and 100%, respectively, while mortality of 15-day-old larvae was 44% at 0.1% and 28% at 0.025% (Castaner *et al.*, 1987). Predation by either beetles of immature *Tchyporus hypnorum* or mature *Agonum dorsale* was not affected by oxydemeton-methyl sprayed loamy soil in a laboratory trial, while nymphs of the aphid *Metopolophium dirhodum* were offered as prey. However, mortality of 30% in the predator *Platynus dorsalis* resulted in within 10 days when oxydemeton-methyl sprayed aphid nymphs were offered to 48 h starved adults of *P. dorsalis* (Forster, 1990). The developmental duration of predator, *T. splendens* was not affected by any of the insecticides tested, 6 larvicides and 5 adulticides. However, the predation rate of *T. splendens* was lowered when larvae of *A. aegypti* previously exposed to fenthion and temephos were offered as prey. Alpha-cypermethrin and hexaflumuron did not affect the feeding rate of the predator. There was a significant reduction in the pupal weight and pupation as result of the predator feeding on the insecticide-treated prey (Amalraj and Das, 1996).

4) Traits of individual insecticides. In a season-long trial on cotton, *Helicoverpa* spp in the spinosad-treated plot was well managed. *A. gossypii* populations were controlled by beneficials under the spinosad programme, though spinosad had no effect on *Creontiades dilutus* and *A. gossypii*. Non-disruptive nature of spinosad was observed on 3 key predator groups, *Harmonia octomaculata* and other Coccinellidae, true bugs, and spiders. There was an indication that Hymenoptera densities were reduced in both the spinosad-treated and conventional plots, compared with the unsprayed. Predator populations in the conventional treatment were substantially reduced (Murray and Lloyd, 1997). Broad-spectrum OP insecticide azinphos-methyl and IGR tebufenozide and fenoxycarb were equally effective in controlling the lepidopteran pests, *C. pomonella*, *Epiphyas postvittana*, and predominantly *H. punctigera*. Azinphos-methyl treatment significantly lowered populations of various natural enemies (spiders, lacewings and the

specialist mite predator *Stethorus* spp. adults and larvae) than either of the two IGR treatments and had most numerous *T. urticae* in a replicated apple field. After azinphos-methyl use halted, a tebufenozide treatment assumed the levels of populations of polyphagous natural enemies broadly equivalent to those observed under IGR treatments the previous year. Results indicate that tebufenozide provides good control of lepidopteran pests, while allowing the rapid build-up of natural enemies, which contribute to control of other pests (Gurr *et al.*, 1999).

5) Sub-lethal effects on the predation activity. A high proportion of surviving spiders, *Pardosa amentata* at sublethal doses (LD₅₀ and LD₁₀) of dimethoate and cypermethrin suffered paralysis for 1-2 days, but no negative effects on prey capture, feeding and rate of development of the surviving individuals were observed in laboratory experiments. With very low doses of cypermethrin particularly, killing rate and feeding of females in the period between the final molt and egg-sac deposition were increased compared to untreated controls (Toft and Jensen, 1998). As sublethal effect on biocontrol potential the developmental duration of predator, *T. splendens*, was not affected by any of the insecticides tested, 6 larvicides such as fenthion, temephos, malathion, deltamethrin, alpha-cypermethrin and hexaflumuron and 5 adulticides such as malathion, fenitrothion, propoxur, deltamethrin and permethrin. Alpha-cypermethrin and hexaflumuron did not affect the feeding rate of the predator for vector mosquitos (Amalraj and Das, 1996).

6) Resurgence of thrips by broad-spectrum insecticides. *O. insidiosus* significantly suppressed populations of *Frankliniella occidentalis*, *F. tritici* and *F. bispinosa* in pepper fields. In treatments of fenpropathrin or acephate, exclusion of *O. insidiosus* resulted in greatly increased densities of thrips compared to untreated plots, while spinosad reduced prey density without significant effects on predator populations, and this resulted in more rapid extinction of *F. occidentalis* (Funderburk *et al.*, 1998).

7) Developmental stage of predator. Etoxazole did not seriously affect the survival and reproduction of female predators but caused high mortality rates in eggs and larvae of *P. persimilis*. However, no differences were

observed in the predator-prey selectivities between female and immature of *P. persimilis* in which bifentazate, acequinocyl, chlorfenapyr, flufenoxuron and fenbutatin oxide were much less toxic to the predator than to those of *T. urticae*, and milbemectin and fenazaquin were very toxic to the predator (Kim and Yoo, 2002). Selectivity of malathion, carbaryl, permethrin and deltamethrin to a predator, *P. nigrispinus* and its lepidopterous prey *S. frugiperda* was evaluated using leaves impregnated with the insecticides. Deltamethrin was the most selective insecticide in favor of *P. nigrispinus*. The 3rd- and the 5th-instar nymphs and adults of *P. nigrispinus* showed high tolerance to deltamethrin. But for permethrin, 5th-instar and adults of *P. nigrispinus* were more tolerant than 3rd-instar nymphs (Batalha *et al.*, 1997).

f. On the balance of predator and prey

1) Insecticide. Dimethoate, parathion-methyl EC and microencapsulated parathion-methyl used for the control of the tortricid *Lobesia botrana* had different effects on the balance of the populations of *Panonychus ulmi* and its predators *Amblyseius andersoni* and *T. phialatus* in vineyards: Dimethoate inhibited the development of the predator populations for over 2 months, parathion-methyl EC altered the balance in favor of the prey when used frequently, and microencapsulated parathion-methyl did not affect the ratio of *P. ulmi* to its phytoseiid predators, owing to tolerance acquired by the predators (Grande and Ingrassia, 1988).

2) Role of alternative prey. Settle *et al* (1996) indicated that population increases of detritivores and plankton-feeders in rice fields resulted in the abundance of generalist predators in the 1st third of the season, by which alternative prey gives the predator populations a 'head start' on later-developing pest populations, decoupling predator populations from a strict dependence on herbivore populations. This process should strongly suppress pest populations and generally lend stability to rice ecosystems. Ethiofencarb at rates as low as 208.4 g a.i./100 litres provided equally as effective aphid control and conserved predator numbers. Prothiofos and chlorpyrifos-methyl as low as 166.7 g a.i./100 litres kept aphid numbers below those in untreated plots and caused a smaller reduction

in the combined population of insect predators (El-Sayed and El-Ghar, 1992).

3) Predation on resistant variety and fecundity inhibition with JHA. Predation on *A. fabae* by larvae of *C. septempunctata* and *C. carnea* in the laboratory was higher on the resistant variety of *V. faba* than on the susceptible. After treatment of aphids, *A. fabae* and host plants with the insect growth regulator DSC 24300 I (JHA), only very low initial aphid mortality but a slow-acting inhibition of aphid fecundity could be detected if the young stages were contaminated. The effects of plant resistance and predator activity could be increased strongly by a combination of both factors with this selective insecticide (Yakti and Poehling, 1988).

g. Negative impacts by neglecting selectivity to predators

1) Resurgence of pest. The application of methomyl decreased the incidence of the lycosid *P. astrigera* and caused a resurgence of *P. xylostella* population through differential mortality levels between the pest and its predator, which is a major biotic mortality agent of immature pest based on an immunological test. The LC₅₀ for the lycosid was around 10 ppm as against about 7500 ppm for 4th-instar larvae of *P. xylostella* using the dipping method and about 20 000 ppm for 3rd-instar larvae by feeding methomyl-contaminated cabbage leaves. Applications of sublethal concentration of methomyl to 4th-instar larvae and pupae of *P. xylostella* stimulated the fecundity and egg fertilization of the derived adults (Nemoto, 1993).

2) Loosing selectivity of resistant predator. In apple orchards in England, foliar sprays of cypermethrin or pirimiphos-methyl at commercially recommended rates were harmful to OP-resistant strains of *T. pyri*, leading to increases in numbers of its prey, *P. ulmi* (Cross and Berrie, 1994).

h. Control of pests by insecticides compatible with predator

Predation on *A. fabae* by larvae of *C. septempunctata* and *C. carnea* could be increased strongly by a combination of both factors of the varietal resistance with Bolero of *V. faba* and selective insecticide, DSC 24300

I (JHA) which caused a very low initial aphid mortality but a slow-acting inhibition of aphid fecundity (Yakti and Poehling, 1988). Residential area treated with 3 ground-level applications per week of ULV-applied malathion (48 ml a.i./ha) in combination with weekly releases of *T. amboinensis* (100 females per block) reduced *A. aegypti* by about 96%, however, malathion alone reduced pest densities during the 14-week study by about 29% (Focks *et al.*, 1986). Thiodicarb offers growers an effective management tool for >90% control of larvae of *A. gemmatilis* 7 days after treatment in soybeans field in Georgia, USA while not adversely affecting populations of the lygaeid predator *G. punctipes* (Chandler and Sumner, 1993). In an apple orchard in Canada, biological control was effective in plots (most insecticide replaced by alternatives such as insecticide soap, insect pathogens, and insect growth regulators) and all captan (harmless to phytophagous mites and *T. pyri*) plots: maximum counts of *P. ulmi* and *Aculus schlechtendali* were <1.5/leaf and 6/leaf, respectively (Hardman *et al.*, 1995). In an apple orchard in Indiana, clofentezine-treated trees, with the help of *A. fallacis*, kept *P. ulmi* populations at subeconomic levels throughout the entire season, only if insecticide sprays did not disrupt predatory mite populations (Stanyard *et al.*, 1998). An integrated control programme was conducted to control *P. citri* by releases of the *Leptomastix dactylopii* and the *C. montrouzieri*, to keep ants from disturbing the beneficial activity by applying gum or chlorpyrifos to the trees trunks, and to prevent damage caused by the other pests with selective insecticides. Compared with traditional methods, the number of insecticide treatments was reduced, the use of non-selective insecticides was reduced by 70%, and the percentage of fruits damaged by *P. citri* was below 10%. However, the mean cost of integrated management was not reduced because of the high costs of rearing beneficial insects (Racit *et al.*, 1997). Pirimicarb as a selective insecticide in plum orchard trials was effective against spring populations of *Brachycaudus helichrysi* and showed no damaging effects on polyphagous predators, by which the mid- to late-season *Phorodon humuli* were heavily preyed on and remained below economic thresholds. Otherwise, broad-spectrum insecticide

sprays are damaging to natural enemy populations, which led populations of pesticide-resistant *P. humuli* to increase unchecked (Hartfield and Caampbell, 1996). The application of lambda-cyhalothrin in Bt cotton brought a 12% increase in yield and was shown to cause no significant disruption of season-long predator to pest ratios, by total numbers of natural enemy (*Geocoris* spp., *Orius* sp., Coccinellidae, lacewings, spiders, parasitoid wasps and Carabidae) and pest populations (*Pseudatomoscelis seriatus*, stink bugs and *Lygus* spp.) (Cole *et al.*, 1997).

5.2.2. Exploitation of insecticide resistant predator

a. Selection of insecticide resistant predator

A predator of the citrus pest *A. aurantii* in southern Africa, *Chilocorus nigrita* was selected for 5 generations with triazophos. Tendency to develop resistance against triazophos was indicated (Schoeman, 1987). Populations of *T. pyri* in apple orchards were subjected to selection of various concentration of deltamethrin. The 24 h LC₅₀ for the strain that had received 3.1 g a.i./ha was 3.75 times larger than that for the strain from the untreated plots (Fitzgerald and Solomon, 1992).

The mite *A. nicholsi*, a predator of the *P. citri* in citrus orchards in China, is susceptible to OP insecticides used against *Diaphorina citri*, a vector of citrus yellow shoot disease. After selection for 33 generations with phosmet, a resistant strain of *A. nicholsi* was obtained 18.9 times higher than the initial LD₅₀ of 52.5 ppm (Huang *et al.*, 1987).

b. Selective toxicity of insecticide resistant predator

In commercial apple orchards in England, foliar sprays of cypermethrin or pirimiphos-methyl at commercially recommended rates were harmful to OP-resistant predatory mite *T. pyri*, leading to increases in numbers of its prey, *P. ulmi* (Cross and Berrie, 1994). During 1988-89, a population of the predatory mite *N. longispinosus* from tea fields in eastern Shizuoka Prefecture was shown to exhibit multiple resistances to methidathion, methomyl, cypermethrin, fenvalerate and fluvalinate. However, fenpropathrin and permethrin emulsifiable concentrates at field rates were highly toxic to the predator, although a wettable powder formulation

of permethrin was not toxic (Mochizuki, 1992). A filter paper bioassay was used to determine the sensitivity of laboratory strains of *X. flavipes* and one of its prey, larvae of *T. castaneum* to malathion. LD₅₀s for adult *X. flavipes* were estimated to be 51.4 ng a.i./filter for males and 45.9 ng a.i./filter for females. *X. flavipes* was 4.3- and 10.2-fold more tolerant of malathion than laboratory strains of the parasitoids *A. calandrar*e and *B. hebetor*, respectively (Baker and Arbogast, 1995).

c. Field application of insecticide resistant predator

The pesticides resistant predator *Metaseiulus occidentalis* introduced into orchards in the Crimea, USSR in 1976 kept populations of the fruit tree red spider mite, *P. ulmi* below an economic level in 1986-88 (Petrushov *et al.*, 1988). A pyr-resistant strain of the predatory mite *A. womersleyi* was released onto tea bushes under permethrin application, to prevent the resurgence of *T. kanzawai* on tea plants caused by the application of Pyr. The released predators successfully survived. In the plot where *A. womersleyi* was released, the damage to new leaves was less severe than in the control plot and the predators remained resistant to the permethrin in the bushes. The selective use of pesticides that are harmless against natural enemies is necessary to achieve a program of integrated tea pest management (Mochizuki, 2003). The New Zealand strain of *T. pyri* with lower mortality and less repellency to cypermethrin or azinphos-methyl than native *T. pyri* was imported into Nova Scotia, Canada in 1988, reared on potted apple trees treated with dilute cypermethrin throughout 1988-94, colonized trees, and exerted effective control of *P. ulmi* and *A. schlechtendali*, from 1988 to 1993 in an apple orchard. Maximum densities of motile *P. ulmi* decreased from 32 per leaf in 1988 to 10 in 1989 and to <1 per leaf in 1990 and 1991. In a second orchard trial, cypermethrin was applied in mid-May 1992 to eliminate native *T. pyri*, and then New Zealand *T. pyri* released, colonized, dispersed, and suppressed *P. ulmi* and *A. schlechtendali* despite pyrethroid residues on all trees (Hardman *et al.*, 1997). The imported phytoseiid *P. persimilis* gave effective control of *T. urticae* in 1982 and 1983 when it was released into strawberry plantings with low levels of *T. urticae*

infestation. Growers who released *P. persimilis* in Queensland were able to reduce the number of insecticide and acaricide sprays by about 70%, resulting in a marked improvement in fruit quality due to the elimination of spray-associated damage (Waite, 1988). Chemical applications against insect pests and diseases were successfully integrated with the predator.

6. Conclusion

We attempted to integrate the factors affecting development of insecticide resistance in insect pests, focused on taking advantage of the nature of chemicals to delay the resistance development by mixture, rotation, or mosaics, and emphasized on the compatibility of insecticide(s) with the biological agents in the frame of IPM.

Insecticide(s) with negatively correlated cross-resistance, due to the different target sites or mode of actions, is recommended to implement the management strategy of insecticide resistant population. Chemical nature affected to feeding, locomotion, flight activity, mating competition, and predator avoidance. However, strategies to prevent the development of resistance should comply with the interests of growers for whom frequency of pesticide applications and income are important. Application frequency was reduced by the potentiation process and longer residual activity, and was increased by losing insecticide activity to target pest due to frequent spray to control secondary pest, by intrinsic short residual activity, and by the vulnerability to resistance development of a chemical.

Delaying resistance development by using mixture strategy depends on each component killing high percentage of the exposed insects on the assumption that resistance is due to the inheritance of a single semi-dominant allele and there is no cross-resistance, particularly if coupled with immigration of susceptible insects into treated areas or with relative fitness disadvantage associated with the resistance alleles. Mixture for delaying resistance development was listed in Table 1. The development of resistance was delayed by selecting *N. cincticeps* with the structurally different mixture. However, potential

disadvantages associated with mixtures include disruption of biological control, promotion of resistance in secondary pests, selection of very resistant population, decrease of susceptibility, and extension of cross-resistance range. Further researches are needed in the use of mixture on 1) synergistic mechanism, 2) the impact to agricultural insect populations and 3) substantial benefits to the growers - spray frequency, yield increase, and ranges of insecticide activity and cross-resistance.

Rotational strategy may delay the development of resistance at least the same as, or better than, successive or mixture treatments, when the frequency of R exceeds about 0.02, or 0.01. Other methods considered were 1) rotation with high and low doses, 2) rotation of Pyr and other insecticides, and 3) rotation of azinphos-methyl and others with different metabolism. Cases of rotation for delaying resistance were listed in Table 2. Rotational applications had sound background in the insecticide efficacy, yield, and net profit.

Resistance is delayed by a process analogous to insecticide rotations if movement between treated sectors occurs between generations. The use of a mosaic in which insecticides are applied in different sectors of a grid pattern delayed resistance in highly mobile insects with relatively specific requirements for host or habitat. For sedentary aphids, unrelated insecticides sprayed at first and then exchanged or rotated in different areas at next application was found to delay the resistance development. Plots of mixtures of imidacloprid-treated and untreated rows had significantly reduced feeding injury and first-generation population of *L. decemlineata* and decreased densities of life stages and percentage defoliation.

A High fecundity and low immigration of susceptible individuals into populations selected by insecticides contributed greatly to the rapid development of resistance. On the evolution of insecticide resistance, the dynamics of host-parasitoid interactions conceived and parasitoids decreased the number of generations in which pesticide treatment is required and they could be complementary to refuges from pesticides. Insecticide selectivity and resistance of parasitoid or predator contribute for the improvement of refuge role.

Insecticides compatible with parasitoids were listed in

Table 3. Selectivity of insecticides was checked on terms of adult emergence, fertility and longevity of female, mortality by direct application and by dried residues, searching host, and range of beneficial organisms. The insecticide selectivity are considered to be affected by several conditions in fields, (1) traits of insecticides such as persistence in toxicity and specificity in development stage and species, (2) target site arrival route and time of an active ingredients such as application method, residual uptake and penetration, (3) factors of host environment such as position of parasitized egg masses, and direct or indirect exposure of mummies, (4) parasitoid biology at the time of insecticide application which influenced the adult mortality of egg parasitoid, pupation from cadavers, parasitism and parasitoid emergence, (5) host originated protection mechanism such as eggshell, parasitized or not, and resistance to insecticide, and (6) insecticide pressure on host and parasitoid.

For establishment of the insecticide resistant parasitoid, migration of the parasitoid, survivorship, refuge from insecticide, availability of resistant parasitoids, frequency of use of alternative pesticides were considered. To use parasitoids under the pressure of pesticides, parasitoids with insecticide resistant or tolerant were tested, collected from field, and/or selected. For field application, parasitism success to host and resistance stability are important.

Selective insecticides to predators were listed in Table 4. The insecticides safe to predator were examined at various points, by supplying insecticide-treated cabbage to aphid, by treating it at the recommended dose to field, by applying dosages causing 90% mortality of prey larvae, or by repeatedly spraying with several fungicides or insecticides in the apple orchard. Selectivity was expressed in 99% mortality to pest, in differential indexes by LC_{50} of predator over that of pest, and in viability of immature stage of predator. Each insecticide to specific development stage had different activity of larval mortality, pupation, eggs hatching, female fertility, and reproductive performance of aphid predator. Factors affecting to selective toxicity are 1) mixing mineral oil, 2) application method of insecticides-ingestion or residual contact, 3) feeding on insecticide contaminated prey, 4) trait of individual insecticide, 5) sub-lethal doses, and

6) sensitivity differences by the developmental stage of predators. The effects of plant resistance and predator activity could be increased strongly by a combination of both factors with selective insect growth regulator. To improve the predator/prey ratio in field, application time, method, and formulation of pesticide, reducing dose rate, using mulches and weeds, multicropping and managing of surroundings are suggested. Alternative prey enriched generalist predators decoupling dependence of predators on herbivorous pest populations, and consequently stabilized rice ecosystems. Resurgence in prey numbers was caused by insecticides harmful to OP-resistant predator, stimulatory to the fecundity and egg fertilization of insect pest. Using selective insecticides caused no significant disruption of season- long predator to pest ratios, kept *P. humuli* in plum orchard below economic thresholds, reduced the number of insecticide treatments and the percentage of damaged fruits, and increased yield.

Insecticide resistant predator *T. pyri* could effectively take its functional roles with augmented viability in apple orchards through resistance to the insecticide used against its prey or through cross-resistance to wide range of insecticides. Wettable powder was better than emulsifiable concentrate of permethrin for a multiple resistant predatory mite. Predator *X. flavipes* was more tolerant of malathion than the parasitoids. Insecticide resistant populations of predators were effectively controlled its phytophagous preys, reduced spray number, and improved fruit quality.

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