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Pesticide Resistance Management of Pest and Beneficial Arthropods and More Biologically-Based IPM on Apple

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ABSTRACT Resistance evolution to organophosphate-based pesticides in apple and pear inhabiting arthropods of western North America extends to many classes of pest and some beneficial species. Resistance management programs to minimize resistance in pests while exploiting it in natural enemies have met with mixed success. Among beneficials, resistances have been exploited mostly among predators of pest mites. Evolution of resistant mites, leafminers, leafhopper, aphids, leafrollers and some internal fruit feeders have led to development of new monitoring methods and means to delay or avoid resistance. But it is resistance to azinphosmethyl in codling moth (*Cydia pomonella*) that is changing the pest control system and moving it from chemical to biologically-based means. Newly emerging IPM systems will depend more on use of biological, cultural, behavior and genetic controls. But more selective pesticides also will be needed to augment pheromones, resistant host plants and genetically altered organisms. These more biologically-based tactics will be prone to resistance evolution in pests as well, if used too unilaterally and/or too extensively.

KEY WORDS Pesticide resistance management, biologically-based IPM. apple, pear

More biologically-based integrated pest management (IPM) systems for apples and pears have evolved steadily since the 1960's. Their design has been influenced by the status of pests, by development of pesticide resistance, by the cost and lack of registration of new pesticides and by the availability of new biological, genetic and behavior methods of pest control (Croft & Hoyt 1983, Wearing 1988, Croft & Penman 1990, Croft & Giliomee 1993, Prokopy & Croft 1994). The challenge has been to hasten development of more biologically-based pest controls. Much effort has focused on overcoming resistance to pesticides and sustaining use of the newer control technologies that are coming on-line resistance management programs that avoid resistance in pests and exploit it in beneficial arthropods have been implemented with mixed success (Croft 1990). Many new resistance monitoring tools have been developed (Riedl et al. 1992), but only modest success has been had in using them in the field. Use of resistant natural enemies has had some success, but the need to select them regularly may be a problem in less chemical-dependent programs (Croft 1994).

Here, I address the current status and some trends predicted for pesticide resistance management and more biologically-based IPM in apple and pear production.

PESTICIDE RESISTANCE, MONITORING AND MANAGEMENT

Historically, resistance problems on apple and pear in western North America have been most severe for spider mites (*Tetranychus urticae, Tetranychus mcdanieli, Panonychus ulmi*), pear psylla (*Psylla pyricola*) and codling moth (*Cydia pomonella*). The field life of compounds for control of mites and psylla has often been only a few years, although recent IPM programs have extended this somewhat (Croft *et al.* 1989, Flexner *et al.* 1994). For spider mites, IPM based on biological control by organophosphate-resistant predator mites are widely used (Croft 1990). Organophosphates, like azinphosmethyl, have been used for codling moth control for 3 decades now. But their effectiveness is waning because of resistance problems. Monitoring and management systems of pesticide resistance for these groups are described below.

Spider mites: Since the introduction of IPM on apple in the 1960's needs for chemical mite control and resistance management have lessened. Evidence for possibilities for resistance management first came with the miticide, dicofol. Resistance to dicofol was reported for *Tetranychus mcdanieli* from apple in Washington state, and then later for *P. ulmi* and *T. urticae.* Today, resistance to dicofol is known to vary in spider mite populations from orchard to orchard in many areas of the USA (Croft & van de Baan 1988). The continued effectiveness of control with dicofol after many years of use suggests that reversion to susceptibility occurs. Reversion of resistance is a useful trait that may enable growers to reuse the product (see discussion below). Another group, the organotin (OT) acaricides were used for almost 30 years for spider mite control on tree fruits. Resistance to OTs is widespread and spider mites on apple and pear are affected by it. OT-resistant *P. ulmi* on apples in Washington state are primarily limited to orchards where growers have neglected biological mite control and relied only on acaricides to deal with spider mite problems. High levels of OT resistance are present in *T. urticae* in pear in the western USA (Hoyt et al. 1985, Knight et al. 1990). Formetanate hydrochloride resistance in *T. urticae* on pear has been reported from southern Oregon after only 1 to 3 years of use (Croft et al. 1984). The resistance potential to some new ovicides such as hexythiozox and chlofentezine appears to be high based on experimental field trials of resistance management alternatives (Flexner et al. 1994).

Spider mite predators and other natural enemies: As early as the late 1950's, the first cases of organophosphate-resistance in predaceous mites on apple were suspected in the field and then confirmed by laboratory bioassays (Croft 1990). Two phytoseiids were involved: *Typhlodromus pyri* and *Metaseiulus occidentalis.* These resistances soon led to development of integrated mite control programs in many areas which have continue in one form or another for the past 30 years. Most IPM programs were based on use of organophosphates to control insect pests to which the natural enemies of mites were resistant. Selective acaricides such as propargite, cyhexatin and fenbutatin oxide were useful in these programs. Over the years, resistances to other groups of insecticides and fungicides have been reported for natural enemies associated with apple and there is an increasing number of new resistant species including some chrysopids and even a few parasitoids (Croft 1990). Trends in research with pesticide resistant natural enemies and IPM have focused on development of multi-resistant strains of predators, especially ones highly resistant to pyrethroids, genetic improvement by selection in the laboratory and field and genetic engineering. For example, strains of *M. occidentalis* are now resistant to OPs, some carbamates, pyrethroids and sulfur (Croft 1990). Highly pyrethroid resistant *T. pyri* and *M. occidentalis* have been identified and marker genes for *M. occidentalis* have been transformed through microinjection (Presnail & Hoy 1992). Use of genetic engineering for incorporating resistance genes and other factors into populations is anticipated. One problem that may arise with greater use of biologically-based IPM is the level of selection that is necessary to maintain resistant natural enemies (Croft 1994). It may be counterproductive to keep selecting resistant beneficial when control of other pests is not needed. As more non-chemical methods are developed, use of pesticide-resistant natural enemies will likely lessen.

Fortunately, similar resistance monitoring techniques can be used for pest and predatory mites. In spite of early attempts to standardize test procedures using a slide-dip method (Anonymous 1974), resistance bioassays for spider mites and predatory mites still vary somewhat. This makes it difficult to compare test results and resistance levels from different areas. One international resistance group (IRAC) has adopted whole leaf residual assay for contact acaricides (Welty et al. 1987, Lemon 1988). A leaf disk residue assay (bean for *Tetranychus* sp., peach for *P. ulmi*) with 10 or 20 adult female mites per disk was used in recent studies of acaricide susceptibility in Oregon and Washington (Knight et al. 1990). Discriminating rates for detecting abamectin and fenbutatin oxide resistance in *T. mcdanieli* and *T. urticae* been established. Another potentially useful method is a rapid bioassay described by Dennehy et al. (1987). Better standardization of methods has been achieved for testing hexythiazox and clofentezine. The method adopted by IRAC is similar to one recommended by FAO (Anon. 1974, Lemon 1988). Baseline susceptibility of *P. ulmi*, *T. mcdanieli* and *T. urticae* to hexythiazox and clofentezine as well as diagnostic concentrations have been established (Knight et al. 1990. Rathman et al. 1990).

Resistance management for mites: Scientists have proposed guidelines for acaricide use on tree fruits to minimize resistance problems. 1) Rely on biological control if possible; 2) use a miticide only when necessary; 3) use the lowest effective rate, and 4) alternate applications with different modes of action. The multi-resistant mite predators on tree fruits, *M. occidentalis* and *T. pyri*, are very effective and can, if properly managed and protected, provide long-term, resistance-proof and inexpensive mite control. Compared to apples, biological mite control is not so successful on pears. Miticides are currently the only control option and should only be applied if thresholds of 1-2 feeding stages per leaf are exceeded. Thresholds are much higher on apples (10 feeding stages per leaf in early season and 30 in mid-season). Miticides and insecticides applied for other pest problems should be used at selective rates which allow mite predators to survive. Foliar sprays of non-selective pesticides (e. g. pyrethroids, certain carbamates) should be avoided. Only selective miticides which fit into IPM programs should be used in rotations. It is important to conduct a resistance monitoring program at regular intervals so that changes in susceptibility or resistance reversion can be detected at an early stage.

Resistance management with dicofol has been possible so long as it is not used more often than once every 2-3 years. Because of unstable OT resistance, fenbutatin oxide can be used once each season to get effective control of *T. urticae* and not increase resistance (Flexner et al. 1988, 1994). An example from a long-term trial of rotation, alternations and mixtures of an OT and hexythiozox is given in Figure 1. Either rotations (applied within season or from season to season) or mixtures of a fenbutatin oxide and the ovicide limited resistance to both compounds. Unilateral use of either the OT or ovicide resulted in rapid resistance long before it occurred with alternative or mixed acaricide uses.

Pear psylla: This homopteran has a similar history of resistance as spider mites in that it has usually developed to every compound to which this pest has been exposed since pesticides were first used for control (Riedl *et al.* 1981). Since 1978, fenvalerate, permethrin and cyfluthrin (plus oil) have been used to control this pest, but the amount of use has varied across pear growing regions.

Pyrethroid resistance developed first in Washington state and later in southern pear-growing areas in Oregon and California in spite of similar use histories (Follett et al. 1988, Croft et al. 1989). When psylla developed resistance to azinphosmethyl and ethylane, it also happened first in the northern areas. The reasons for this trend are not known. Bioassay tests conducted since 1982 in central Washington indicated a gradual decrease in susceptibility to pyrethroids (Burts et al., 1989). Switching to cyfluthrin, improved control temporarily. However, even cyfluthrin is failing in Washington where resistance levels are highest. Resistance appears to affect all pyrethroids. According to a survey, pyrethroid resistance is already present in most pear areas of northwest USA (Croft et al. 1989). However, only in Wenatchee and Yakima valleys of central Washington, are resistances high enough to cause field failures.

Resistance monitoring for pear psylla has been extensively evaluated since pyrethroid resistance was first discovered. The slide-dip assay described by Follet et al. (1985) has become the standard for monitoring resistance in overwintering adults. An intensive multi-year monitoring program for pyrethroid resistance is presently being carried out in northern states. Amitraz susceptibility of 1st and 2nd instar nymphs is being monitored at several locations in Washington and Oregon with tests recommended by the Fruit Crops Working Group of

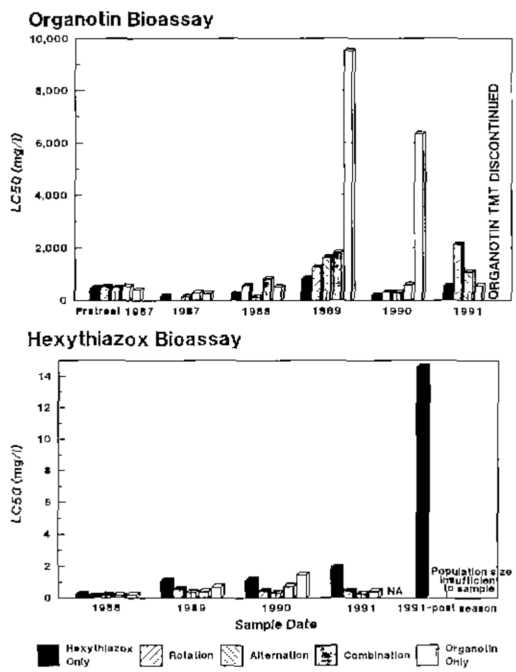

Fig. 1. Effects of three resistance management strategies versus unilateral use on organotin and hexythiozox LC_{50}s for *Tetranychus urticae* over a five year period of selection in Oregon pear orchards (after Flexner et al. 1994).

the Insecticide Resistance Action Committee (IRAC) (Lemon 1988).

Some degree of resistance management of pear psylla has been achieved by limiting pyrethroid use to prebloom applications, by moderating summer use and by combining use with oil applications. It has been estimated that such moderation has resulted in pyrethroids lasting twice as long as previous insecticide groups (*e. g.*, organophosphates; E. C. Burt, unpubl.). New resistance monitoring methods and resistance management procedures are now being developed for the avermectin insecticides. But due to resistance problems to the pyrethroids, there is great danger that the avermectins will be overused and rapid resistances will develop unless softer, more selective pesticide programs for control of this pest are developed (Westigard et al. 1986). Such programs have been experimentally tested, but registration of some products is delaying implementation of the resistance mangement programs.

Codling moth: Organophosphate insecticides, primarily azinphosmethyl, have been the mainstay for codling moth control in most apple growing areas of the world for more than 30 years. The long field life of azinphosmethyl against the codling moth is surprising particularly since it took only 6 years for DDT resistance to develop. There is evidece from several areas that azinphosmethly may be losing its effectiveness against codling moth. Feral male moths from a pear orchard in California's Sacramento Delta had an LC_{50} up to 7-fold higher than susceptible ones. In addition, laboratory tests indicated that azinphosmethyl resistance may be tied to lower fitness because this resistant strain produced fewer eggs than a susceptible strain (S. Welter & J. Dunley, unpubl.). Elevated LC_{50} values for feral male moths were also found in some apple orchards of Washington's Yakima Valley. A case of low-level resistance to the insect growth regulator (IGR) diflubenzuron was recently found in a codling moth population on pear in southern Oregon (Moffitt et al. 1988). This case is unique, since this population had never before been exposed to diflubenzuron or the benzoylphenylurea compounds. Topical assays of feral male moths as well as larval assays indicated cross-resistance to azinphosmethyl (H. R. Moffitt, pers. comm). A similar cross-resistance to difulbenzuron was found in the azinphosmethyl-resistant strain from California (S. Welter, per. comm). This is a troubling since cross-resistance may eliminate the IGR's as substitutes for azinphosmethyl if OP resistance should indeed become widespread in the near future.

Resistance monitoring for codling moth: A convenient and direct resistance monitoring method for lepidopterous species is the pheromone trap assay developed by Riedl et al. (1985) and Haynes et al. (1986). This bioassay permits testing of large numbers of feral males and provides immediate information on the insecticide susceptibility of orchard populations. Insects are collected with pheromone traps and treated topically with a small drop of insecticide dissolved in acetone (Riedl et al. 1985). A modified method involves exposure to different concentrations of insecticide by mixing it with the polybutane adhesive on the trap (Haynes et al. 1986). Both assays have been applied successfully in recent surveys of OP resistance in codling moth, Oriental fruit moth, Pandemis leafroller, and western tentiform leafminer in the western USA. Other trapping methods such as visual or olfactory traps could be employed for monitoring insecticide susceptibility in other pest species such as the various fruit flies for which pheromone traps are not available.

It is evident that new collection and testing methods such as the pheromone trap assay are needed to detect resistance when the frequency is still low. Biochemical tests which measure increased enzyme activity associated with detoxification of a pesticide in single insects offer considerable promise for detecting low-level resistance. So far such biochemical methods are unavailable for most resistant tree fruit insects. However, biochemical tests for resistance detection is well developed for some disease vectoring pests(Brown and Brogdon 1987).

Resistance management for codling moth: In light of the increasing incidences of field failures due to organophosphate resistance and the cross resistance that extends to almost all alternate insecticides, it is critical that more diversified systems of IPM be develop for control of this pest on a worldwide scale. Efforts to integrate methods as mating disruption of male moths, microbials and selective insecticides (*e. g.*, insect growth regulators), cultural controls such as destruction of unharvested fruit and biological control by egg parasitoids, are being tested as components of IPM for codling moth on a worldwide scale (Croft & Giliomee 1993). Use of much more diversified systems for control of this pest, which will include a number of resistance management components such as monitoring methods are a must for the future.

MORE BIOLOGICALLY-BASED IPM

Integrated mite control has been the corner stone of IPM on tree fruits in the western United States for almost three decades now. Integrating biological control of mites with chemicals was feasible when selective miticides became available and phytoseiid mite predators developed resistance to OP insecticides. This occurred only after many years of large annual oscillations in pest populations, severe resistance problems, and long periods of unstable pest control. The development of selective pesticides such as diflubenzuron, fenoxycarb, pirimicarb, clofentezine and hexythiazox for control of major pests represents a significant advance for IPM on tree fruits. This has made it possible to eliminate OP insecticides and other broad-spectrum pesticides from spray programs. Already widely used in some tree fruit regions of Europe, lack of registrations has so far prevented the use of such selective programs on tree fruits in the United States.

OP resistance in the codling moth with possible cross resistance to other chemical groups (e. g. IGRs) may force growers in the western USA to consider pyrethroids as replacements for azinphosmethyl. The negative consequences of such actions should be avoided (Croft & Hoyt 1978). Replacing azinphosmethyl with pyrethroids for codling moth control would do serious harm to biological mite control and increase the need for acaricide treatments. As a result severe acaricide resistance problems could develop similar to those before integrated mite control was introduced in the 1960's

Resistance problems are likely to become less severe as we shift from conventional chemical control to more biologically intensive IPM programs. However, more biologically intensive IPM program will not be immune to evolution of resistance--resistance to such measures as pheromone control and even host plant resistance and biological control can and has occurred (Croft 1992).

Selective pesticides will still be used as key elements of control of such pests as codling moth, leafrollers and pear psylla. Certain compounds are heavily used in these programs since the number of selective pesticides is quite limited and other control options are not yet available. For instance, the IGR diflubenzuron has replaced azinphosmethyl for codling moth control on apple in northern Italy and other European fruit-growing areas and is now the only recommended insecticide for that purpose. Similarly, fenoxycarb is the only recommended insecticide for leafroller control. Experience has shown that reliance on a single pesticide can very quickly result in resistance development. Therefore, efforts to develop and register additional non-disruptive alternatives for control of codling moth and other pest species on tree fruits need to be increased to reduce the risk of resistance, make present IPM programs more stable and thus assure their continuity.

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