Use of Crop Chemicals for Integrated Pest Control [and Discussion]

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Use of crop protection chemicals for integrated pest control

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Examples of and methods for achieving the selective use of pesticides in control of pests while conserving important beneficial natural enemies are discussed relative to the development of integrated pest management systems for apples in the U.S.A. Included are examples of physiologically selective acaricides, ecological selectivity conferred by application techniques and selectivity due to the development of resistant beneficial insects. A definition and examples of *ideal selectivity* of pesticides for this crop production system are discussed. Lastly, an approach to resistance management in an entire apple arthropod pest – natural enemy complex is discussed in relation to a long-used chemical control system (organophosphate pesticides) compared with a new chemical control programme based on pyrethroid insecticides.

Introduction

Research planning for development of crop protection chemicals should be critically related to changing trends in pest control or integrated pest management (i.p.m.). Resistance to pesticides in pests and higher costs for pesticide development and production, make essential more diversified approaches where tactics other than pesticides are used more extensively. Most crop protection scientists believe that few i.p.m. programmes will develop without pesticides. On many high-value crops, pesticides will be the central component around which i.p.m. systems are built. Possibilities for reducing the amounts of pesticides applied will be few, despite research to find alternatives.

Apples and other deciduous tree fruits are high-value crops. They currently require and probably will always require appreciable inputs of pesticides for effective crop protection. Currently some 3–10 applications of insecticide, comparable applications of fungicides, but only 1–2 applications of herbicide or rodenticide, are applied seasonally to control the wide range of pests that attack the crop in the U.S.A. Less pesticide could be used if tolerance levels for damage were above 1% of the harvested fruit (i.e. the current economic damage level).

Notwithstanding the heavy use of insecticides, apple has had a long history of research and implementation of i.p.m. From the beginning, these programmes involved the seemingly incompatible integration of broad-spectrum crop protection insecticides and biological control agents through a variety of innovative means. In this paper, the methods and future requirements for crop protection insecticides for apple i.p.m. are discussed. It is believed that pesticide requirements for this crop production system are representative of other high-value agricultural crops. The emphasis is on selectivity to natural enemies and maximizing the effective use-life of chemicals by minimizing resistance to pesticides among pests. As will be discussed, exploitation of resistance in natural enemy species is a useful way to achieve selectivity of certain insecticides. These concepts are discussed relative to the long-used organophosphorus-based (O-P) insecticides and the introduction of new insecticides for apple i.p.m.

SELECTIVE USE OF ORCHARD INSECTICIDES

The use of insecticides selective to natural enemies for apple pest control in North America dates back to the late 1930s to early 1940s, when scientists in Nova Scotia, owing to limited markets and the prohibitive cost of pesticides, developed a programme of 'harmonized' control based on the stomach poison lead arsenate (Pickett *et al.* 1958). This insecticide was effective against foliage and fruit feeding lepidopterous pests, for example the codling moth, *Carpocapsa pomonella* L., but it had little effect on secondary pests such as mites, aphids, scales, leafhoppers and their natural enemies. This broad-spectrum effectiveness on the major pests and lack of impact on other species including beneficial insects is still considered the 'ideal model' of insecticide selectivity for apple i.p.m. This concept of *ideal selectivity* will be discussed in several sections of this paper. Unfortunately, lead arsenate had some undesirable features of environmental persistence and mammalian toxicity, which, with developed resistance in codling moth populations in the early 1940s (Madsen & Morgan 1970), led to its demise and replacement by the less selective compound, DDT.

More recently and in association with i.p.m. (which has gained momentum since the mid-1960s), efforts to develop selective pesticides for apple i.p.m. have been directed in several ways. First, due to the repeated development of resistance to almost all acaricidal compounds, selective miticides and insecticides that are toxic to plant-feeding mites, especially spider mites (Tetranychidae), and pest insects but non-toxic to predaceous mites and insects have been identified. Efforts have been made to develop selective insecticides, such as botanical insecticides, third-generation pesticides (e.g. growth inhibitors like diflubenzuron), disease preparations (e.g. *Bacillus thuringiensis*) and synthetic sex pheromones to be used for mass trapping or mating disruption. Novel compounds or uses have been sought that would be species specific or effective on a selected group of pests. These developments are described in greater detail hereafter.

SELECTIVE INSECTICIDES AND MITICIDES FOR INTEGRATED MITE CONTROL

I.p.m. systems for plant-feeding mites have been developed and implemented to various degrees in virtually every major fruit-growing region of North America (reviewed in Croft & Strickler 1981) (table 1). To summarize, all programmes are commonly based on the use of pesticides for key pest control that are not detrimental to the most important natural enemies of spider mites. Selectivity of insecticide use can be achieved by a physiological tolerance or developed resistance to the chemical in the natural enemy or by the selective placement of the chemical (see later discussion) in the crop environment.

The development of selective insecticides to control insect pests, but to allow for integrated mite control, involves extensive screening research. Virtually every insecticide (Croft 1975*a*), fungicide (Jones & Croft 1974), herbicide, and growth regulator (Hislop *et al.* 1978) used on deciduous tree fruit crops is evaluated for its toxicity to the predators of plant-feeding mites. If this does not occur before registration, the compound will be evaluated by applied researchers maintaining current i.p.m. programmes. The ecological selectivity of pesticide use is often achieved by placement of pesticides in orchards so that they do not upset the biological control system for plant-feeding mites. For example, in Washington (Hoyt 1969), the toxic thinning agent for apples, carbaryl, is only placed on the outer periphery of apple trees to conserve the predatory mite, *Typhlodromus occidentalis* Nesbitt, which typically colonizes the inner regions of the tree in early season. In Michigan, *Amblyseius fallacis* Garmen is conserved by applying toxic chemicals to trees only in early season, when this predatory mite is protected in the orchard ground cover (Croft & McGroarty 1977). Border spraying of orchards selectively kills invading pests such as the codling moth, apple maggot, etc., while conserving more uniformly distributed orchard-inhabiting natural enemies.

TABLE 1. MAJOR INTEGRATED MITE CONTROL PROGRAMMES ON APPLE IN NORTH AMERICA

state or province	principal pest controlled†	principal natural enemies‡	research reference§	implementation reference§
Washington	Tm, Pu, As	To, Spp, Zm	Hoyt (1969)	Hoyt *et al.* (1970)
New York	Pu, Tu	Af, Tp	Watve & Lienk (1977)	Tette (1977)
Michigan	Pu, Tu, As	Af, Sp, Ag, Sm	Croft & McGroarty (1977)	Croft (1975)
California	Tp, Tu, Pu	To, Ss	Croft & Barnes (1971)	—
Pennsylvania	Pu, Tu	Sp, Af	Asquith (1971)	Asquith (1972)
North Carolina	Pu, Tu, As	Af, Sp	Rock & Yeargan (1971)	Rock (1972)
Virginia – W Va.	Pu, Tu	Af	Clancy & McAllister (1968)	—
Illinois	Pu, Tu	Af	Meyer (1974)	—
Oregon	Pu	To, Tp	Zwick (1972)	—
Missouri	Pu, Tu	Af	Poe & Enn (1969)	—
Utah	Tu, Tm, Pu, As	To, Zm	Davis (1970)	—
Colorado	Tu, Pu	To	Quist (1974)	—
New Jersey	Pu, Tu, As	Af	Swift (1970)	Christ (1971)
Ohio	Pu, Tu, As	Af, Zm, Ag	Holdsworth (1968)	Holdsworth (1974)
British Columbia	Tm, Pu, As	To, Tp, Zm	Downing & Molliet (1971)	Downing & Aarand (1968)
Quebec	Pu, Tu	Af	Parent (1967)	—
Nova Scotia	Pu, As	several	Sanford & Herbert (1970)	Anon. (1970)

† Pest importance in each area listed sequentially. Abbreviations: Tm, *Tetranchus mcdanieli*; Pu, *Panonychus ulmi*; As, *Aculus schlechtendali*; Tu, *Tetranychus urticae*; Tp, *Tetranychus pacificus*.

‡ Natural enemy importance in each area listed sequentially. Abbreviations: To, *Typhlodromus occidentalis*; Sp, *Stethorus punctum*; Am, *Zetzellia mali*; Af, *Amblyseius fallacis*; Tp, *Typhlodromus pyri*; Ag, *Agistemus fleschneri*; Ss, *Scolothrips sexmaculata*; Spp, *Stethorus picipes*.

§ References in these columns will be found in Croft (1981).

The selective manipulation of predator and prey populations of orchard mites is accomplished with physiologically selective miticides. In figure 1, some common cases of predator–prey interactions involving the spider mite, *Panonychus ulmi* Koch (European red mite), the alternative prey mite, *Aculus schlechtendali* Nalepa (apple rust mite), and the predatory mite, *A. fallacis*, are shown during the growing season in relation to successful biological control. In figure 1*a*, an effective ratio of *A. fallacis* to spider mites (0.4:2.0 per leaf) is present in early season and the pest mite is controlled biologically by the predator before it exceeds 15 per leaf (the economic injury level). In figure 1*b*, a less favourable ratio of predators to prey (0.25:8.0 per leaf) is present initially, and pest mites reach a density of 20 per leaf before biological control is attained. In this case, significant damage to the tree occurs. Figure 1*c* illustrates how a reduced rate of a selective miticide (e.g. propargite or cyhexatin) is used to reduce but not eliminate pest mites and thus change a predator:prey ratio from ineffective to effective. Figure 1*d* shows the impact of completely eliminating the prey mites by using a higher dosage of the selective acaricide; a subsequent starvation of predators occurs and a second outbreak of spider mites takes place thereafter.

Figure 1*e*, *f* demonstrates how apple rust mites can serve as alternative prey for *A. fallacis* and be managed by selective acaricides. In figure 1*e*, apple rust mites enter the apple tree before spider mite populations develop; *A. fallacis* preys on rust mites and becomes well distributed throughout the apple tree; since rust mite populations greater than 150 per leaf can be damaging to the tree, a selective acaricide (e.g. endosulphan) to control rust mites, aphids and leafhoppers is applied as spider mites begin to increase; rust mites are chemically controlled, and predators, which are unaffected directly by the spray, switch over to the spider mite prey, which are quickly controlled biologically. In figure 1*f*, a similar interaction occurs; however, rust mites are present only at moderate levels; predators are able to enter trees before spider mites, but they provide complete biological control of both plant-feeding pest species without the application of miticides.

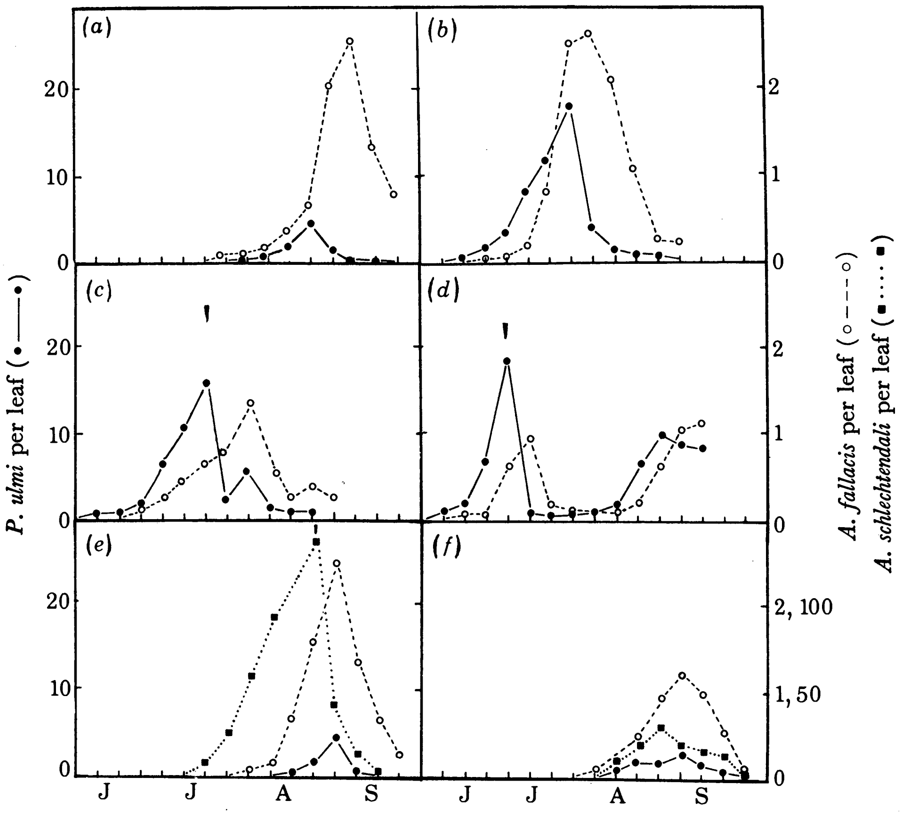
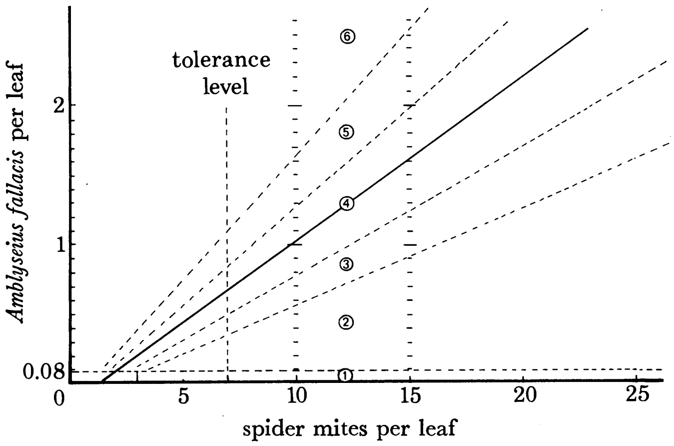


FIGURE 1. Population trends of *Amblyseius fallacis* and plant-feeding mites in Michigan apple orchards (adapted from Croft 1975*b*).

The basic selectivity components of the acaricide–predator–prey system have been integrated into a useful decision-making tool for growers and pest managers (see figure 2). This index was determined from field counts of predator and prey populations taken in orchards where both successful and unsuccessful biological control interaction occurred. A variety of similar indices with different prey thresholds can also be simulated from a dynamic population model developed by Dover *et al.* (1979). To use the predator:prey ratio index, one must plot counts of both predator and prey on the different axes of figure 2. It is unnecessary to make a mite control decision until the prey exceeds 7 per leaf. If there are more than 7 prey mites per leaf and fewer than 0.08 predators per leaf, a full-strength selective miticide is recommended (see region 1, figure 2). If the *A. fallacis*: *P. ulmi* ratio falls within regions 2 or 3, application of a reduced rate of selective miticide (e.g. cyhexatin, propargite) is needed to establish subsequent regulation by predators (e.g. see figure 1*c*). If a predator:prey ratio falls in region 4 or greater, possibilities for biological control are 50% or better and no selective acaricide is necessary unless later surveys show a less favourable condition.



region	suggested recommendation	probability for biological control
1	as bronzing appears, spray recommended miticide at full rate	very low
2	if bronzing appears, spray Plictran† 50 w.p. at 2 oz/100 gal or 8 oz per acre	equal to or less than 10%
3	if bronzing appears, spray Omite‡ 30 w.p. at $1\frac{1}{4}$ lb/100 gal or 5 lb per acre or Plictran 50 w.p. at $1\frac{1}{2}$ oz/100 gal or 6 oz per acre	greater than 10% but less than 50%
4	wait 1 week; biological control should occur soon; if not, spray Omite at $1\frac{1}{4}$ lb or Plictran $1\frac{1}{2}$ oz/100 gal	approximately 50%
5	same as 4	greater than 50% but less than 90%
6	wait 1 week; biological control is almost certain	greater than 90%

† Trade name for tricyclohexylhydroxytin.
‡ Trade name for 2-(*p-tert*-butylphenoxy)cyclohexyl 2-propynyl sulphite.

FIGURE 2. A decision-making index for estimating biological control of spider mites by *Amblyseius fallacis* (modified from Croft 1975*b*).

Table 2 lists registered and experimental miticides with different selective properties to phytophagous mites and predators. How the first three compounds suppress spider mites, while conserving phytoseiid mites, was demonstrated in figure 1*c*. These acaricides are toxic to predaceous stigmaeid mites, but not to predaceous insects (see table 2). Figure 1*e* showed how selective reduction of rust mites can be accomplished with compounds like endosulphan and ethion. Formetanate is a selective acaricide used in Pennsylvania to conserve the coccinellid mite predator *Stethorus punctum* LeConte; it provides chemical suppression of all plant-feeding mites and mite predators (see table 2). Two experimental compounds, Dupont 3796 and Fisons 21314, show better the 'ideal selectivity' as far as apple mite management is concerned (S. C.

Hoyt, unpublished). They suppress spider mites, they allow rust mites to survive at moderate levels and they are not toxic to most of the major predaceous mites or insects occurring in orchards (see table 2).

Development of selective insecticide control programmes

As noted earlier, selective insecticides that affect key pests but do not harm important natural enemies of all fruit pests have long been sought for control of deciduous tree fruit pests. There has, however, generally been little success in finding such compounds. Few such compounds are active only on pests and not natural enemies. Even if such chemicals could be found, few industrial companies could afford to develop them unless they were sufficiently broad-spectrum to be useful on many crops and different pest insects.

Table 2. Selective acaricides used in integrated mite control programmes in North America, and their toxicity to arthropod groups

compound	tetranychids	eriophyids	phytoseiids	stigmaeids	insect predators
cyhexatin	H	H	L	H	L
Vendex†	H	H	L	H	L
propargite	H	H	L	H	L
formetanate (hydrochloride)	H	H	H	H	L
endosulphan	L	H	L	H	M
ethion	M	H	M	—	—
Dupont 3796	H	L	L	—	—
Fison 21314	H	L	L	—	—

H, high toxicity; M, moderate toxicity; L, low toxicity; —, no information.

† Shell chemical: hexakis (β,β-dimethyl)phenethyl distannoxane.

Rather than with novel synthetic organic compounds, the greatest success in developing selective insecticides for apple insect control has come with plant-derived compounds, growth inhibitor chemicals, insect disease agents, or the more recently discovered synthetic pheromones. Of the plant-derived compounds, ryania has long been useful for i.p.m. in certain areas of North America (e.g. Nova Scotia) where insect pressure is low and biological control more effective than most other areas. Where insect pressure is greater (e.g. Wisconsin) (Oatman 1966), these chemicals do not have a sufficiently broad spectrum of activity and are not effective enough to be used commercially. Diflubenzuron, a chitin synthesis inhibitor, has shown some promise as a selective insecticide for apple and pear pests. It is highly active against codling moth and some leafrollers (see, for example, Gruys 1976), and is innocuous to most natural enemies of insects and mites.

Of the selective disease agents, *Bacillus thuringiensis* Berliner preparations show high activity against certain chewing lepidopterous pests (codling moth, red-banded leafroller, tufted apple budmoth) of apple (Oatman 1965; Thomas *et al.* 1978). Although pest populations and fruit injury are usually reduced appreciably with these agents, control is seldom commercially acceptable. It has been postulated that these pathogens may be useful for the control of pests that have partly effective natural enemies. Virus diseases have shown promise as control agents for the codling moth (Huber & Dickler 1977), red-banded leafroller (Glass 1958), and tufted apple budmoth (W. B. Bode, unpublished). Efficacy trials for control of these lepidopterous species by insect viruses have demonstrated effectiveness in the range giving 30–2 % damaged fruit at harvest.

There is some question of whether synthetic pheromones can be classified as pesticides, since insect control with them is achieved either by mass trapping or mating disruption, rather than by toxic effects. Again, they have been used most successfully against key lepidopterous pests. Proverbs *et al.* (1975) and Madsen *et al.* (1976) in British Columbia, Canada, demonstrated the potential for mass trapping the codling moth by using a sex pheromone lure. In an isolated but previously sprayed block, control was maintained below 0.5 % for 5 consecutive years by using mass trapping. In a less isolated situation, the percentage injury over a 3 year period increased from 0.000 75 to 0.0062 to 0.33 % infested fruit. In Nova Scotia, in contrast, researchers used mass trapping of an orchard that during the previous year had sustained 39.4 % fruit injury by the codling moth. In that year, damage was reduced to 9.8 % and in 3 succeeding years it declined to 6.7, 1.6 and 3.4 %. Similar success has been observed for the red-banded leafroller in New York (Trammel *et al.* 1974).

Mating disruption of apple pests with synthetic pheromones generally has been more successful than mass trapping methods. Cardé *et al.* (1975) used microencapsulated pheromone of the red-banded leafroller to disrupt male orientation to pheromone traps by 75 % with one application per season, and by over 99 % when applied every 5–7 days. Other studies demonstrated comparable success for this species (Wieres *et al.* 1978; Reissig *et al.* 1978) and the codling moth (Cardé *et al.* 1978; Moffitt 1978) in the U.S.A. Similar success in codling moth control by using pheromones has been achieved in Europe (see, for example, Charmillot 1980). The major problems with widespread use of pheromone control systems relates to their species specificity. Unless a single pheromone system works on several species, or a multiple blend system that works on a species complex, is developed (e.g. codling moth, apple maggot, plum curculio, red-banded leafroller), it is unlikely that these agents will replace conventional insecticides. The latter have a broader spectrum of activity and are easier to use, since they are active on almost all key pests occurring in orchards.

This latter point relative to species specificity of a pesticide raises a key question regarding ideal selectivity in insecticides. What should the ultimate goal of researchers and industry be in developing these compounds? Gruys (1976) has developed a relatively species-specific selective chemical control system for apple pests of Dutch orchards based on use of 4–8 individual compounds during the growing season. Although the system is effective, growers are reluctant to use these programmes because of the complexity in timing and application. As noted earlier, what would be more nearly ideal would be to have a single wide-spectrum compound or two that are toxic to most of the major key pests of apple, and yet non-toxic to most secondary pests and their natural enemies. Lead arsenate was close to this ideal in the past; in many ways azinphos-methyl, owing to a unique pattern of resistance, has become such a compound during the past decade (Croft 1979).

DEVELOPED RESISTANCE IN APPLE PESTS AND NATURAL ENEMIES RELATIVE TO PESTICIDE SELECTIVITY

Developed resistance by arthropods to insecticides used on apple has been a major cause of pest control failures on this crop, throughout the world. Especially in North America, it has also been the single most important factor leading to the selective use of broad-spectrum insecticides and i.p.m. The impact of resistance on apple has depended on whether the resistant arthropod was a key pest, secondary pest or a natural enemy. The patterns of resistance in apple arthropods have greatly influenced the long-term use and success of O-P insecticide programmes on this crop as well as attitudes towards the introduction of the more recently developed broad-spectrum insecticides (e.g. pyrethroids and carbamates) (Croft & Hoyt 1978; Croft 1979).

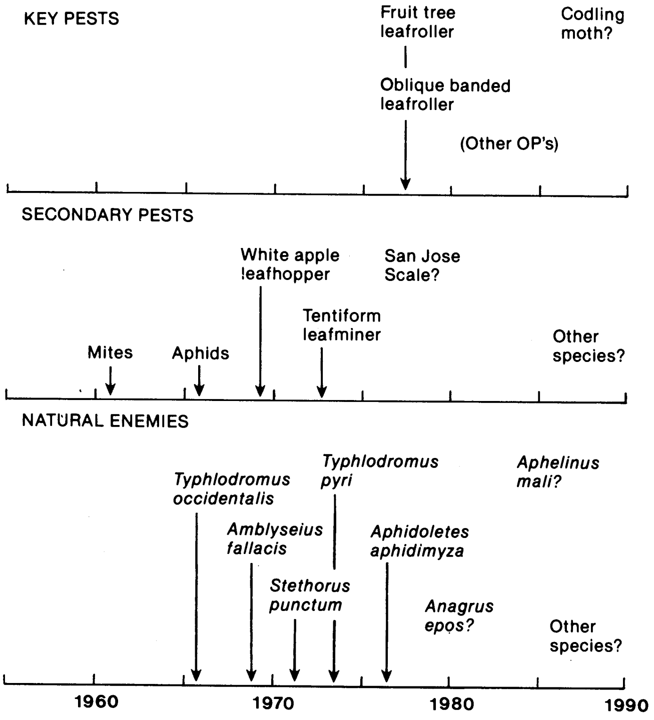


FIGURE 3. Patterns of O-P resistance developed in populations of arthropod key pests, secondary pests and natural enemies associated with apple in the United States, 1955–80.

THE PATTERN OF O-P RESISTANCE IN NORTH AMERICAN ORCHARDS

Insecticide resistance to O-P compounds, and in particular to azinphos-methyl, has not been reported for any major key pest of apple (i.e. codling moth, plum curculio, apple maggot, red banded leafroller) even though these compounds have been widely used for the past 20–30 years in most fruit-growing areas of North America (see figure 3). These species generally have few generations per season, few life stages exposed to treatment and tend to disperse from outside environments and hosts into commercial apple orchards. In contrast, among secondary pests of apple (see figure 3), including mites, aphids and leafhoppers, which have rapid rates of reproduction, all life stages exposed to insecticide treatments and relatively high host specificity, resistance strains developed quickly, within the first 5–15 years of O-P use. Fortunately, these species have predators and parasites that provide significant biological control when not affected by chemical use for key pest control. While there was a difficult transition period in the late 1950s and early 1960s with the emergence of resistant secondary pests and greatly suppressed beneficial natural enemies, with continued O-P use (due to its continued effectiveness on the key pests), there developed a number of pesticide-resistant natural enemies from the mid-1960s to the present (see figure 3).

The first evidence of widespread resistance beyond the pest trophic level was among predatory mites including the phytoseiid species *T. occidentalis* (Hoyt 1969; Croft & Jeppson 1970) in western North America, and *A. fallacis* (Motoyama *et al.* 1970) and the cocinnellid beetle, *S. punctum* (D. Asquith, personal communication), in the midwestern and eastern regions (see figure 3). Thereafter, evidence that similar resistance was developing in natural enemy species associated with aphids (e.g. *Aphidoletis aphidimyza*) (Adams & Prokopy 1977) and leafhoppers (Croft, unpublished) was observed. Possibly many other natural enemies associated with these crops have developed, or are in the process of developing, resistant strains, but as yet they have gone unmonitored (e.g. *Aphelinus mali*, *Anagrus epos*; figure 3). Evidence for this is the general stability observed in other pest – natural enemy systems associated with O-P usage on apples.

TABLE 3. CASES OF DEVELOPED RESISTANCE IN DECIDUOUS TREE FRUIT-INHABITING PHYTOSEIID MITES IN NORTH AMERICA

species	pesticide	resistance level (x-fold)	crop	conditions of selection†	location	selected references§
Amblyseins fallacis	azinphos-methyl	100–1000	apple	F	North Carolina	Motoyama *et at.* (1970)
	carbaryl	25–77		F	Indiana	Croft *et al.* (1976*b*)
	diazinon	119		F	Michigan	Croft & Meyer (1973)
	parathion	102–152		F	North Carolina	Rock *et al.* (1976)
	DDT	‡		F	Michigan	Croft *et al.* (1981)
	permethrin	14–100		F, L	Michigan	Strickler & Croft (1980, 1981)
Typhlodromus occidentalis	azinphos-methyl	101–104	apple	F	Washington, Utah	Croft & Jeppson (1970)
					California	Ahlstrom & Rock (1973)
	carbaryl	< 10	apple	F, L	Washington	Roush & Hoy (1980)
	permethrin	< 10	apple	L	Washington	Roush & Hoy (1978)
Typhlodromus pyri	azinphos-methyl	10–42	apple	F	U.S.A.	Watve & Lienk (1976)
					New Zealand	Penman *et al.* (1976)

† F, field; L, laboratory.
‡ Not calculated.
§ References given in Croft & Strickler (1981).

CASES AND USE OF INSECTICIDE-RESISTANT NATURAL ENEMIES

The most extensive use of insecticide-resistant natural enemies of apple has been with phytoseiid mites. A review of their resistance and the selectivity achieved when resistant forms are present follows. Only cases involving North American species that have been used locally in areas where resistance has not developed or that have been introduced to areas where these strains do not occur naturally are discussed (for a more extensive discussion of these topics, see Croft & Strickler (1981)).

Resistant species (*table* 3)

T. occidentalis was reported resistant or tolerant to O-P compounds as early as 1952 by Huffaker & Kennett (1953). Thereafter, populations highly resistant or tolerant to several

O-P compounds, including azinphos-methyl, diazinon, phosmet, parathion, tepp and phosalone, were reported from the semi-arid fruit-growing regions of western North America (see review and map in Croft & Brown 1975). Resistance to carbaryl has been present in this species for some time (S. C. Hoyt, unpublished); however, only recently has it been documented by Roush & Hoy (1980), who also selected carbaryl-resistant mites in laboratory studies. Moderately high resistance to permethrin also has been selected by these same methods in *T. occidentalis* (Roush & Hoy 1978).

In contrast to *T. occidentalis*, *T. pyri*, which is probably native in Europe, has not developed high levels (more than 100-fold; see table 3) of resistance to O-Ps, even though these compounds are commonly applied in northwestern and northeastern North America, western and eastern Europe, and New Zealand. In New Zealand, Hoyt (1972) first reported a tenfold resistance to azinphos-methyl. In New York, Watve & Lienk (1976) reported an l.c._{50} level indicating nearly a 20-fold resistance to azinphos-methyl when compared with the data of Hoyt (1972) for a susceptible strain. At this level predators tolerated field applications and provided appreciable biological control of *P. ulmi* in apple orchards. Most recently, Penman *et al.* (1976) documented *ca.* 40-fold resistance in New Zealand, but only after long-term exposure. *T. pyri* also is tolerant or has developed high levels of resistance to carbaryl (see, for example, Watve & Lienk 1976).

A. fallacis strains resistant to DDT, carbaryl and several O-P compounds (e.g. azinphos-methyl, parathion, phosmet, diazinon and stirofos) have been detected (see table 1), and O-P cross-resistance extends to at least 11 other insecticides (Croft *et al.* 1976). Whereas DDT and carbaryl resistances occur locally, O-P resistance is present throughout midwestern and eastern North America (see map in Croft & Brown 1975). Some success in developing a bi-resistant O-P × carbaryl strain was reported by Croft & Meyer (1973), but attempts to establish, maintain and manage it in the field have been unsuccessful (Croft & Hoying 1975). Recently, Croft *et al.* (1981) have found strains simultaneously resistant to O-Ps, DDT and permethrin. Furthermore, permethrin resistance has been elevated to levels above field dosages in laboratory selection experiments (Strickler & Croft 1980, 1981).

Use of resistant species

Endemic insecticide-resistant phytoseiid mites have been widely exploited in apple orchards in North America. In the U.S.A. and Canada, O-P resistant strains of the species *T. occidentalis* (western), *A. fallacis* (midwestern and eastern) and *T. pyri* (northeastern and eastern) occur on a widespread regional basis in apple orchards. In fact, they are so widely resistant and distributed that it is difficult to find susceptible strains for experimental studies (Croft, unpublished). As noted earlier, these resistances are the basis for selective insecticide use and i.p.m. programmes for mites that have been implemented in most major fruit-growing states (see table 1 and earlier discussion).

The tactic of transferring an insecticide-resistant strain within its native range, but taking advantage of unique-resistant features that may have developed elsewhere, is well established. The first demonstration was by Croft & Barnes (1972), who released and established resistant strains of *T. occidentalis* from Washington state and Utah, in a California orchard area where this species also occurred but was not resistant. Persistence of the mite was greatly improved in sprayed orchards, and i.p.m. of mites was possible after the establishment of the resistant forms (Croft & Barnes 1972). In addition to this study, there have been other cases of inter-orchard transfers of resistant phytoseiids within the distributional range of the species; however, published reports are rare. One exception is by Croft & Meyer (1973) and Croft & Hoying (1975), who attempted the transfer of a multiple-resistant (O-Ps and carbamate) strain of *A. fallacis* in orchards of the midwestern U.S.A. They observed that resistance to both chemicals could be maintained in one strain in the laboratory; however, when released in the field and selected equally by both chemical groups, resistance to O-P's remained very stable while carbamate resistance declined precipitously to a lower level within a few generations. Recently, tests to establish pyrethroid-resistant strains of both *T. occidentalis* and *A. fallacis* have been undertaken; however, successful establishment is yet to be proved (M. Hoy & K. Strickler, unpublished).

Probably the most successful and best documented case of establishment of an exotic insecticide-resistant phytoseiid mite has been with *T. occidentalis* in the major fruit-growing regions of Australia (J. L. Readshaw, unpublished). These mites were originally collected from orchards of central Washington state. In 1972, they were released in a commercial orchard near Canberra, where results were spectacular. Despite six commercial sprayings of azinphos-methyl for codling moth control, predators successfully overwintered and maintained *T. urticae* well below damaging levels throughout the 1972/73 season and thereafter. Later, large numbers of *T. occidentalis* were released in blocks throughout southeastern and southwestern Australia. Since the initial release, these predators have been recovered from most release sites. Projected economic assessments of this scheme suggest annual savings of $3M due to reduced pesticide costs. Only in the more humid areas of Australia, including Tasmania, has establishment of this mite not been successful. In these areas, work to establish resistant strains of *T. pyri* from New Zealand and *A. fallacis* from North America for control of the European red mite, *P. ulmi*, is currently underway.

Another interesting case history involves *T. pyri*, which is native to western Europe and probably was secondarily introduced into North America, Australia and New Zealand. It is the phytoseiid species most closely associated with the European red mite, *P. ulmi*, in its native home. In British orchards and most other areas of western Europe, *T. pyri* is the principal species associated with *P. ulmi*. However, in these regions there are fewer, major insect pests of apple compared with other apple areas of the world. Because of the low levels of O-Ps used and also the relatively low rate at which *T. pyri* acquires O-P resistance (see earlier discussion and Penman *et al.* (1976)), resistance among *T. pyri* populations has remained relatively low in these regions.

Recently, scientists in the U.K. have successfully reintroduced highly resistant strains of *T. pyri* from New Zealand back into Britain (Cranham & Solomon 1978, and unpublished). These mites established, overwintered and tolerated normal field rates of insecticides that previously eliminated the native strain each year. The interesting question arises as to whether these established resistant mites will revert appreciably with respect to resistance, given that the selection pressure in British orchards is much less than that which they were previously exposed to in New Zealand. While reversion may occur, it is unlikely that resistance will decrease below levels necessary for the mites to persist in the U.K. Based on these early trials, it appears likely that O-P resistant strains of *T. pyri* from New Zealand will be introduced throughout Europe and North America where less resistant strains of these species occur.

Future uses

Areas of new research with regard to insecticide-resistant phytoseiid mites include the preselection of strains resistant to pyrethroid insecticides, to provide selective use of these broad-spectrum agents. Using field collected strains, both Roush & Hoy (1978) and Strickler & Croft (1981) have successfully selected strains resistant to permethrin and have demonstrated release and survival after treatment in the field. As noted, tests to measure establishment and eventual impact are in progress (M. Hoy & K. Strickler, unpublished).

MANAGEMENT OF PESTS AND NATURAL ENEMIES RELATIVE TO DEVELOPED RESISTANCE

Another concept related to pesticide selectivity and resistance in apple species is resistance management. Only in the past few years have the factors influencing this phenomenon in pests (Georghiou & Taylor 1976, 1977*a*, *b*; Comins 1977*a*, *b*) and natural enemies (Croft & Brown 1975; Croft & Morse 1979; Morse & Croft 1981), been understood sufficiently to develop a theoretical basis for such an approach. Concepts underpinning the approach are as follows. Studies with pests have shown that a sequence of steps or phases are usually involved in resistance development. Initially, since a gene or the genes for resistance are usually associated with lower fitness in an insect population, there is a stage of stable or increasing susceptibility, a period of gene rearrangement, recombination and association of the resistance feature(s) with fitness factors in a population, followed by a low rate of resistance development. Later, resistance may increase to high levels. Reversion from high resistance levels is rare, however; it is more common if selection is discontinued in the initial stages of resistance development or before multiple resistances are involved. To retard the development of resistance one should monitor for it before an insect enters the state of rapidly increasing resistance and then change to a new insecticide with no cross-resistance to chemicals used earlier.

A second concept emerging from resistance models incorporating the major factors affecting resistance development (see table 1 in Georghiou & Taylor (1976), and Comins (1977*a*, *b*)), is the resistance threshold. This is a condition in which the *operational* factors affecting resistance management (e.g. application and selection thresholds, pest stage selected, mode of application, space-limited selection, alternating selection; see definition in Georghiou & Taylor (1977*b*)) are manipulated so that populations may initially increase in resistance to an insecticide but they revert back sufficiently fast or often enough after selections that resistance never enters the rapid increase phase. An intermediate possibility is to greatly retard the development of resistance by manipulating these factors.

At present, the boundary conditions or set of factors that can be manipulated to keep an arthropod pest system within the equilibrium or limited resistance state are poorly understood. However, models of resistance show that such conditions can exist. These models may be used to indicate how much refugia effect, selection level, etc., can be maintained before a high level of resistance occurs. The question becomes, What are the practical dimensions of management for such a system; are such manipulations feasible for practical pest control (e.g. economic injury levels)?

A major factor influencing resistance relates to leaving untreated refugia of arthropods. Georghiou & Taylor (1977*a*) and Comins (1977*a*), working with models of resistance, have found that this factor significantly influences predicted rates of resistance development in pests.

Morse & Croft (1981) showed that reducing the level of selection of susceptible strains of the two-spotted spider mite with the O-P azinphos-methyl permitted resistance development comparable with that of the pest in the predatory mite *Amblyseius fallacis* (Garman). Their data suggest that by modifying the level of pesticide selection and leaving some food for natural enemies to exploit after treatment, resistance development may be reduced in pests and resistance development among natural enemies enhanced (compared with that in the pest) in crops (e.g. apple) where effective biological control systems are operating concurrently with pesticides.

Concerning the patterns of O-P use and resistance for apple pest control in North America, it is puzzling why resistance to O-Ps in populations of the codling moth, plum curculio, apple maggot and red-banded leafroller has not developed. It is improbable that all four species lack the genetic potential or mechanisms for resistance. It took only some 6–20 years for DDT and lead arsenate resistance to develop in the codling moth (Morgan & Madsen 1970). If selection by O-Ps were similar to lead arsenate and DDT, then key pest species with multiple generations per season (i.e. codling moth, red-banded leafroller) should have developed resistance. In some parts of the United States (e.g. Washington state), growers have used O-P's extensively and continuously for the past 31 years without resistance developing in the codling moth (S. C. Hoyt, personal communication). A possible explanation for the lack of O-P resistance in these species is that by accident we have achieved the condition of resistance management as expressed earlier.

There are several reasons to suspect that such resistance management may have occurred accidentally. First, the population dynamics of the susceptible key pests of apple are explained more by what happens in wild alternate hosts or neglected apple trees beyond the confines of the treated orchard systems than by what happens within the commercial orchard. These migrating insects must have a considerable effect in diluting the limited resistant insects that overwinter within commercial orchards. Secondly, the pattern of O-P use over the past 20 years would seemingly reduce possibilities for resistance development. For example, during the first few years of O-P use, compounds like azinphos-methyl were applied at relatively high rates (3.0–4.5 lb 50% w.p. per acre; *ca.* 3.4–5.1 kg/ha). In the mid-1960s, application rates were lowered by 20–50% because of high effectiveness and to minimize impact on phytoseiid mite predators, which were beginning to develop resistant strains (Hoyt 1969). More importantly, the number of broad-spectrum O-P applications has been reduced by some 25–40% on a seasonal basis in most major fruit-growing states during the past 10 years. At some point after so many years of resistance not developing, it may be asked if resistance will ever develop provided we maintain present use patterns.

If we look closely at O-P use for apple pest control over the past 20 or more years, we seem to have followed several tactics recommended by specialists (Keiding 1967; Comins 1977*b*) for delaying or avoiding resistance: (1) many of these chemicals have a short chemical residue life (e.g. parathion, diazinon); (2) selection is mainly directed at a single life stage; (3) application is localized rather than over a wide area (see earlier discussion); (4) certain generations are left untreated (e.g. red-banded leafroller, codling moth); (5) selection has been lowered over time (see earlier discussion); (6) some rotation of O-P and non-O-P materials with different modes of action has been followed (e.g. diazinon, phosalone, carbaryl, endosulphan); (7) O-P chemical systems may be unstable and susceptible to resistance reversion among key apple pests (see, for example, the review in Keiding (1967)).

When the patterns of developed resistance in beneficial species to O-P compounds in apple orchards are considered, a strategy of resistance management among both arthropod groups is suggested. Based on the more selective nature of O-P compounds, there is an emphasis on the continued use of these chemicals. It is expected that more beneficial species will adapt to these compounds in the future, while it may be hoped that resistance among the key pests will not occur because of limited use. While these resistance conditions among pests and natural enemies have evolved by good fortune, it is hoped that they will continue. Considerable research on the dynamics of resistant and operational tactics available for manipulation must be completed if management relating to resistance in apple arthropods is to develop further (Croft 1979).

Because of the above developments, some researchers in North America are cautious about the use of any new chemical group for apple pest control that does not have selective features comparable with those provided by O-Ps (e.g. synthetic pyrethroids (SPs) and carbamates) (Croft & Hoyt 1978; Croft 1979). Even though O-Ps are ineffective on a few pest species (e.g. leafrollers, leafminers, leafhoppers), their selective benefits to certain natural enemies are sufficient to recommend their continued general use until resistance develops in a key pest or they become unsuitable owing to other factors such as economic, human safety and environmental effects). In contrast, the new SPs (e.g. permethrin, fenvalerate) have more favourable mammalian toxicity and higher effectiveness on key pests than azinphos-methyl, even though they are toxic to many natural enemies. Unfortunately, the propensity for key pests to develop resistance to them may be high (Croft & Hoyt 1978; Croft 1979). Through selection studies, the problem of toxicity to photoseiid mite predators appears to have been overcome (Rousch & Hoy, Strickler & Croft, unpublished). Resistance to these compounds in key pests could be minimized in the future by a careful 'phasing in' of SPs into current O-P systems and thereby using these newer compounds only when necessary. In anticipation of implementing more diversified chemical control tactics in an i.p.m. system that would include SPs, the following research activities are recommended to maintain a condition of resistance management among apple arthropod pests and natural enemies in the future.

1. Monitor O-P resistance in (1) key pests, e.g. codling moth and red-banded leafroller, (2) secondary indirect pests, e.g. white apple leafhopper and spotted tentiform leafminer, and (3) key natural enemy species, e.g. white apple leafhopper parasites and *Aphelinus mali*, over time.
2. Test and monitor for the resistance potential to SPs in (1) key pests, (2) secondary indirect pests and (3) key natural enemies (see above).
3. Conduct studies of cross-resistance, resistance mechanisms, and stability of resistance to O-Ps and SPs.
4. Develop by selection, insecticide resistant strains of natural enemies to SPs for field release in orchards regionally, nationally and internationally.
5. Study the manipulation of operational factors as they influence resistance by (1) modelling studies, (2) greenhouse experiments and (3) field evaluation by using orchard pests and natural enemies.

SUMMARY

In the early days of i.p.m. research, it was often considered that industry (possibly with governmental assistance) should develop selective insecticides that were species-specific and maximally effective for each target pest. In the light of the evolution of pesticide resistance in apple pests and with some experience with implementation of these types of systems in practice, it appears that such compounds would not be optimally effective in present apple i.p.m.

systems. It would be preferable to have a chemical (or a few chemicals) with good broad-spectrum activity on the major key pests of apple, but without highly toxic effects on most secondary pests of apple or their natural enemies. To minimize possibilities for resistance in key pests, insecticides should have a short persistence, be active on only one or a few life stages and only be used when other cost-competitive, non-chemical measures of control were not effective (Croft 1979). In the light of the difficulty in finding such compounds via screening alone, careful monitoring for developed resistance or intentional preselection for resistance in certain natural enemies may be a useful alternative way to achieve this selectivity.

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Discussion

M. G. Solomon (*East Malling Research Station, Maidstone, Kent, U.K.*). At the time that broad-spectrum organophosphates, such as azinphos-methyl, were introduced, it is likely that we would have avoided their use in orchards if selective alternatives, such as pirimicarb and diflubenzuron, had been available. However, as a result of its use over many years, azinphos-methyl has become a relatively selective material, as Professor Croft has explained. This is also true in orchards in England where some strains of the predator *Typhlodromus pyri* have developed resistance to this material.

The question now with pyrethroids, or any other new broad-spectrum material, is how to hasten their development as selective chemicals: how to encourage the development of resistance by predators and parasites. Professor Croft has mentioned the work that he is carrying out to artificially enhance pyrethroid resistance in the predator *Amblyseius fallacis* in the laboratory, but he started with field-collected strains that had already begun to develop resistance in the orchard as a result of pyrethroid usage.

A possible stratagem for arriving at this stage as quickly as possible would be deliberately to subject an orchard or group of orchards to maximum exposure to pyrethroids. The development of resistance by pests would also be hastened, of course, though the undesirable results of this might be minimized if the procedure were carried out at an ecologically isolated site.

Would Professor Croft comment on the desirability of this procedure?

B. A. Croft. Yes, such selection would also develop resistant pests and experience shows that far more resistant pests are produced than resistant natural enemies. I would recommend glasshouse or laboratory selection experiments where wild types of beneficial species are periodically introduced, rather than field selection trials. Even isolated field sites allow dissemination of the resistant pest biotype: I feel that this is just too dangerous, especially in view of the successful use of the glasshouse method in several instances (e.g. predatory mites, cecidomyiid predators).