EFFECTS OF THE LOSS OF ORGANOPHOSPHATE PESTICIDES IN THE US: OPPORTUNITIES AND NEEDS TO IMPROVE IPM PROGRAMS

Vincent P. Jones[1], Shawn A. Steffan[1], Larry A. Hull[2], Jay F. Brunner[1] & David J. Biddinger[2] consider the future of insect control systems with special reference to IPM programs in tree fruit following the loss of OP insecticides
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Abstract

The passage of the US Food Quality Protection Act (FQPA) in 1996 mandated that all pesticides in the US undergo re-registration with a focus on reducing cumulative risk of exposure to pesticides sharing a common mode of action. Enforcement of FQPA has resulted in the modification of use patterns and removal (or pending removal) of many organophosphate (OP) insecticides that had previously seen wide use. The FQPA-mandated changes in pesticide use patterns and new pesticide registrations are providing challenges to integrated pest management (IPM) practitioners but, at the same time, are providing opportunities to develop more ecologically balanced IPM programs. We present the case of the US apple industry, where IPM programs are in the midst of the transition from OPs used for the last 50+ years to newer pesticide chemistries, use of mating disruption for key lepidopteran pests, and greater emphasis on biological control. The new IPM programs being developed are more information intensive and will require a renewed focus on research, deployment of new technologies, and enhanced educational programs for long-term success.

Introduction

Although researchers design IPM programs based on a broad range of ecological factors, societal concerns and pressures may force legislative action to engender rapid change in unplanned ways (Flint & van den Bosch, 1981). Such a change was initiated in 1996 for US agro-ecosystems dependent upon organophosphate (OP) insecticides when the US Congress passed the Food Quality Protection Act (FQPA) (Whalon *et al.*, 1999). FQPA tasked the US Environmental Protection Agency (EPA) to re-register all pesticides within ten years. In addition, EPA was required to increase safety margins for pesticides used on food crops typically found in the diets of infants and children (Anonymous, 2006). Fundamentally, FQPA shifted EPA's regulatory focus from a risk-benefit analysis to one driven by risk alone. As part of this process, EPA considered the cumulative risk of exposure to pesticides sharing a common mode of action, and initially, EPA focused its attention on the OP insecticides, which they considered to be the highest risk category. The result has been that many OPs were (or are being) removed from the marketplace and others have restricted uses. Subsequent to FQPA, the regulatory focus on OPs has shifted again to consider their effects on farm workers and the environment, especially water quality.

From a broad perspective, the loss of OP insecticides on larger cropping systems in the US has been relatively painless because many systems had already moved on to newer pesticide chemistries to deal with problems associated with worker safety, water quality, or insecticide resistance (Whalon *et al.*, 1999). However, this generalization is not universally true and minor crops with little support for research on efficacy, residue degradation, or particularly problematic pests might be left with few or no viable replacement pesticides after the FQPA review is complete. The apple industry in the US is well known for its IPM programs and is one of the larger cropping systems currently in the final transition to the newer pesticide chemistries, making it a timely case study for the rest of this article. The slow transition to OP alternatives by the apple industry has been a result of the continued high efficacy of OPs against various key pests that feed directly on the fruit (e.g., codling moth (*Cydia pomonella*), plum curculio (*Conotrachelus nenuphar*), apple maggot (*Rhagoletis pomonella*), the relatively high cost of most OP alternatives, and the precarious stability of its IPM programs based on OPs.

IPM in theory and practice

The IPM philosophy as articulated by Stern *et al.* (1959) has been the dominant ecologically based management paradigm for insects and diseases over the past 50+ years. Under this paradigm, management decisions are initiated only when sampling of pests and natural enemies indicates that pest population levels (or disease incidence) will increase to the point that economic loss will exceed management cost (known as the gain threshold or economic injury level). Inherent in IPM is the fundamental premise that biological control (BC) agents (predators, parasitoids and pathogens) can regulate pest populations below damaging levels, with insecticides and other direct interventions used only as a last resort (Stern *et al.*, 1959). The goal of IPM is to minimize the number and severity of perturbations in the agro-ecosystem while reducing the economic, environmental, and human health costs associated with the particular management option(s) used (Flint &

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van den Bosch, 1981). When perturbations are needed, the goal is to shift the balance to favor natural enemies using the most selective tactics that will have the greatest impact on the pest complex without inducing secondary pest upsets associated with natural enemy destruction (Jones, 2002; Ripper, 1956; van den Bosch & Stern, 1962). For pesticide use, ecological (minimizing natural enemy exposure in space or time) and physiological selectivity (choice of toxicant, dose, or formulation to minimize impact on natural enemies while enhancing pest mortality) are often requisites of a successful IPM program (Hull & Beers, 1985; Ripper, 1956; van den Bosch & Stern, 1962).

Unfortunately, BC alone is often unable to prevent economic losses in high value crops where even a small amount of pest feeding may result in the complete loss of the product (*e.g.*, a caterpillar in an apple). The inability of BC to prevent economic loss is magnified if an exotic pest is introduced without the natural enemy complex found in its home range, or if cultural practices in the system favor pest buildup while inhibiting natural enemies (Stern *et al.*, 1959). In these situations, the pests' normal (unmanaged) population levels would always be above the economic threshold and pesticides become the dominant management tactic. However, experience in many agro-ecosystems has shown that if pesticides are used without consideration of the natural enemy complex, the management system shifts to a "pesticide treadmill" syndrome where pesticides are used for dealing not only with the initial pest(s), but also with the secondary pests whose natural enemies are destroyed (van den Bosch & Stern, 1962). In the more IPM-friendly systems, selective use of pesticides along with the development of resistance to those materials by key natural enemies can produce a hybrid management program where the direct pests are controlled by pesticides and secondary pests are controlled by natural enemies (Van Driesche & Bellows, 1996). However, even these hybrid systems typically have a greatly reduced natural enemy complex (in terms of diversity and abundance) compared to situations where no pesticides are used. This limits the stability of hybrid IPM programs because the lack of redundancy (in terms of natural enemy roles) reduces the ability of one natural enemy to compensate for insecticide-induced inhibition of another.

The apple production system is an example of a hybrid IPM program. Overall, the management program is driven in most areas by the need to control the codling moth, which is considered the key pest of apple worldwide. In the US, this pest has been controlled by the use of broad-spectrum OPs (particularly azinphosmethyl or AZM) since the late 1950s. Initially, the introduction of AZM resulted in severe secondary pest outbreaks, particularly with spider mites whose natural enemies were suppressed by AZM (Hoyt, 1969). These spider mite population outbreaks typically required of 2–3 pesticide (miticides) applications to reduce population levels. This management program based solely on pesticides became increasingly unstable because of the ability of spider mites to develop resistance to the miticides and the high cost of control. The development of resistance to AZM in the western orchard predatory mite (*Galendromus occidentalis*) in the western US (Hoyt, 1969), and the ladybeetle (*Stethorus punctum*) or phytoseiid mites in the eastern US (*Typhlodromus pyri* and *Neoseiulus fallacis*) (Asquith *et al.*, 1980), along with reducing the rates of AZM, resulted in the establishment of the hybrid IPM program that still exists in US apple orchards. Collectively, these integrated mite management programs in apples save 1–2 applications per year of miticides for a cost savings of ≈$125–250/ha annually.

The lesson learned in the apple system in the 1960s was obvious – hybrid IPM systems are relatively fragile and can be easily disrupted by the indiscriminate use of pesticides, particularly broad-spectrum pesticides where natural enemies have not yet evolved resistance. Thus, the large-scale modifications of existing programs, such as those imposed by FQPA, may destabilize the management system yet also provide the opportunity to design more ecologically balanced IPM programs.

Apple IPM in transition

Within the apple industry, two factors have been driving management programs since the 1990s. First, while the passage of FQPA is ultimately leading to the reduction or elimination of older pesticide chemistries, indirectly it has stimulated the registration of 23 new pesticides active ingredients (Anonymous, 2010). Many of these products are considered "reduced-risk" materials, primarily because they have a reduced effect on human health, lower toxicity to wildlife, and a lower potential for groundwater contamination. Secondly, starting in the early 1990s, the registration and adoption of mating disruption (MD) for moth pests allowed for the development of more selective management programs (Brunner *et al.*, 2001). MD is the controlled release of synthetic sex pheromones from dispensers distributed throughout the orchard, in an attempt to either prevent or delay mating, both of which can reduce pest population growth (Jones & Aihara-Sasaki, 2001; Jones *et al.*, 2008). For codling moth, MD adoption occurred first in the western US, with ≈ 80% of Washington apple acreage now using MD as part of an IPM program (Fig. 1). Research and demonstration projects have consistently shown that use of MD over a 2–3 year period can dramatically reduce the need for insecticide applications specifically targeted towards codling moth or secondary pests (Brunner *et al.*, 2005; Brunner *et al.*, 2001). Use of MD in the eastern US has lagged behind the western US because the pest complex is more diverse. However, MD is now used on at

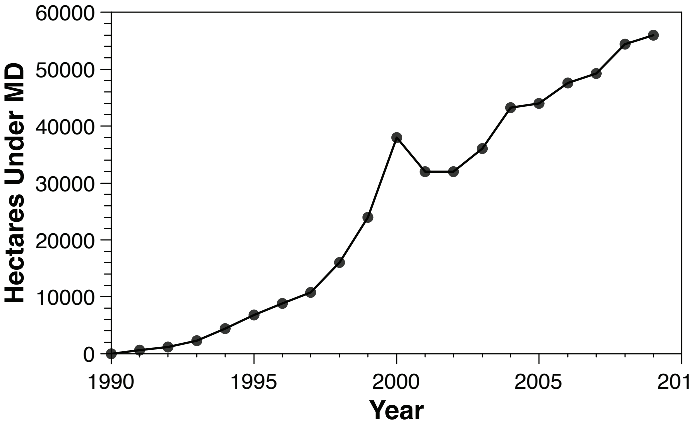

Figure 1. Estimated hectares of apples treated with mating disruption in Washington 1990–2009

least 15% of the acreage in Pennsylvania and 25% in Michigan for codling moth and oriental fruit moth control.

Perhaps the most troubling feature of insecticide use in both eastern and western regions is that the number of applications for direct pests remains relatively constant despite the increased adoption of MD (Fig. 2A,B) (Anonymous, 2008). In part, this may be the result of the shorter residual activity, lower efficacy, or the greater selectivity of the materials replacing the OP insecticides. In Washington, these issues have lead to the recommendation that MD must be the basis of all IPM programs so that pesticide use for both direct and indirect pests can be reduced to allow natural enemy survival.

Effect of OP loss on system stability

IPM researchers are finding that although many of the new pesticides can be considered "reduced-risk" from a mammalian toxicity viewpoint, this classification does not reflect their effect on natural enemies. OP insecticides are typically active enough that acute mortality is the most notable effect on natural enemies. However, some of the newer insecticides are being shown to have more subtle effects including increased mortality, complete or partial sterility, behavioral changes, or skewing of the sex ratio (Biddinger & Hull, 1995; Jones *et al.*, 2009). To examine these effects between different pesticides more closely, studies are now adopting longer-term bioassays that incorporate multiple methods of exposure and use of population growth rates as the common methodology to compare effects of a given pesticide among different species of natural enemies (Stark *et al.*, 2007a; Stark *et al.*, 2007b). Alternatives to bioassays include field studies that document changes in community composition and population dynamics (Atanassov *et al.*, 2003; Biddinger *et al.*, 1994; Leslie *et al.*, 2009). Requiring these sorts of natural enemy studies as part of the US EPA registration process would go a long way towards reducing instability in our management systems when we change from one pesticide to another.

Perhaps one of the most challenging issues facing the apple industry following the loss of OP insecticides is the loss of the simplicity and predictability in the IPM programs. Pest managers used to be well acquainted with OP-based systems and knew that misuse of pesticides could result in severe consequences (e.g. increased spider mite or aphid population levels). However, the current management programs are no longer simple, and use of the 23 new active ingredients available to pest managers is actively reshaping the natural enemy complex. An example of this reshaping can be seen in Pennsylvania apple orchards where BC of spider mites by *S. punctum* was possible because it had developed OP resistance in the 1960s (Asquith *et al.*, 1980). However, changes in the pesticide use patterns starting in the mid 1990s resulted in the virtual elimination of *S. punctum* and its replacement by a resistant strain of *T. pyri* that is better at suppressing mite populations resulting in further reductions in miticide use (Fig. 2B) (Biddinger *et al.*, 2009). Fundamentally, the development of pesticide resistance (or cross-resistance between new and older materials) drives the natural enemy complex in a particular area under insecticide-intensive management (Croft, 1982; Tabashnik & Croft, 1985). Of both theoretical and practical importance, the broad range of new pesticide active ingredients currently available makes pesticide resistance management for the key pests easier, but also decreases the likelihood that natural enemies will concurrently develop resistance in the field.

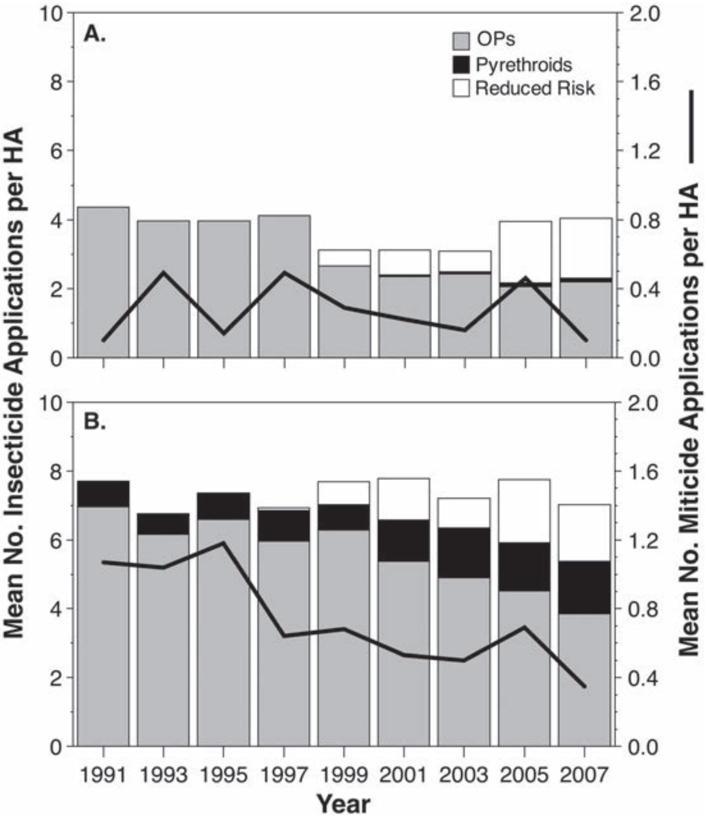

Figure 2. Mean number of insecticide and miticide applications per hectare in the western (A.) and eastern (B.) apple orchards based on NASS pesticide survey data

Directions for the future

As we move out of the OP era in tree fruits, it is clear that we are at a proverbial fork in the road where we can either pursue "pesticide replacement therapy" and continue to rely heavily on pesticide-dominated hybrid IPM systems, or move towards a more ecologically balanced approach characterized by greater reliance on natural enemies. Achieving the ecologically balanced IPM program we envision will require fundamental changes in research approaches, introspection regarding our research and educational priorities, and refinement and implementation of new management technologies.

First and foremost, research will again need to focus on ecological processes and how management tactics influence the entire community assemblage occurring in the system as advocated by van den Bosch and Stern (1962). In designing new IPM programs, it is crucial to recognize that there are multiple factors affecting pest population growth and even relatively small amounts of mortality can be important. For example, Jones *et al.* (2009) used a simple simulation of codling moth population growth to demonstrate that 25% added mortality resulted in population reductions of 44 and 68% after one and two generations, respectively. This example has been used to show IPM practitioners that BC is not strictly for secondary pests, but is also vital for reducing problems with key pests. This rationale should also guide pesticide use back towards being more of a correction to the balance of pest/natural enemy populations as was pioneered in the mid-1980s for maintaining balance between spider mites and their predators (Tanigoshi *et al.*, 1983).

Another research priority is the importance of different natural enemies in BC (Jones *et al.*, 2009). Our knowledge of the role of predators is particularly rudimentary (except for certain notable exceptions such as the spider mite predators discussed previously), because predators are rarely specifically associated with a particular pest stage; instead they are free-living and many are generalist feeders. Moreover, direct visual observation or biochemical gut content analysis is often needed to detect their activity because in the act of feeding they often leave little or no evidence of their presence. The role of parasitoids is also important, but at least for the major pests, detecting their activity is much easier because parasitoids have at least one life stage (typically the larval) intimately associated with the host; collect that stage of the host and you have a way to associate the host with the parasitoid. However, parasitoids have great taxonomic diversity, they are difficult to identify, and as a group they have broad ecological roles, which makes understanding their effect on management programs difficult. Regardless of whether we are considering predators or parasitoids, current ecological thought suggests that increased natural enemy diversity alone is not synonymous with improved BC of our pests (Snyder *et al.*, 2005), although diversity may be a useful indicator of pesticide effects on community structure. Teasing apart the roles of the various natural enemies in BC will require a much greater understanding of their spatial and temporal overlap with the prey or hosts of interest. In addition, we also need to focus more explicitly on the functional roles of species and how diversity can be manipulated to sustain redundancy and reliability of BC.

The third area of research is driven by the need to develop tools that simplify natural enemy sampling. Current sampling techniques (e.g. beating trays or sweep nets) often give highly inaccurate estimates of when certain natural enemies occur, their population trends, and their importance. Work over the past 20 years has shown that natural enemies respond to plant volatiles that are released when herbivores feed (Herbivore Induced Plant Volatiles or HIPVs), and that these HIPVs can be used to monitor a broad range of natural enemy populations (James, 2003a; b; Kahn *et al.*, 2008). Recent work in Washington apple orchards with HIPVs is allowing scientists to develop phenology models to minimize natural enemy exposure to pesticides and to evaluate the effects of different management programs on natural enemy populations (Jones *et al.*, 2009).

The increasing complexity of our management system also taxes our outdated and inadequate education system for IPM practitioners (Jones *et al.*, 2010; Jones *et al.*, 2009). We need to focus efforts on the development and implementation of decision support systems to help IPM practitioners understand the complexity of the agro-ecosystem and guide their choices in timing and understanding the effects of different management strategies. The Washington State University–Decision Aid System (das.wsu.edu) is one such system that integrates environmental data, model predictions (10 insects, three diseases, and one horticultural model), management recommendations, and an associated pesticide database (Jones *et al.*, 2010). However, even this system will need constant updates as natural enemy phenology models are developed and pesticide effects are better understood.

Further into the future, technological advances in robotics and computer vision-based sensors are being pioneered that will make "robotic scouting" possible (Singh *et al.*, 2009). Robotic scouting, when combined with a robotic sprayer, should allow spot treatments on a much smaller scale than is currently feasible. Even the development of simple automated pheromone traps that only need periodic servicing and that can wirelessly transmit their data would reduce monitoring costs and make the use of spot treatments more feasible. This area should not be overlooked because data in Washington's apple orchards (Jones, unpublished) shows that codling moth populations are highly clumped around the edges of the orchards, which would allow the area treated to be dramatically reduced while enhancing BC.

It is clear that the IPM programs of the future must address the needs expressed in the past to integrate a wider range of management options, including a better understanding as to their effects on the agro-ecosystem as a whole (Stern *et al.*, 1959; van den Bosch & Stern, 1962). In general, we will need to continue to reduce the rates and frequency of pesticide usage, and increase our focus on enhancing BC (Jones *et al.*, 2009). There is also growing apprehension about the effects of pesticide residues to humans, the environment, and key beneficial species (including honeybees and native pollinators) and IPM must adapt to deal with these societal concerns. We envision that a more information-intensive and spatially focused management program geared towards enhanced BC can likely meet the future needs of IPM. Ironically, the legislatively mandated loss of OP insecticides is providing the opportunity to improve IPM.

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David Biddinger is a Research Associate Professor, Department of Entomology, based at the Penn State University Fruit Research and Extension Center in Biglerville, PA. He obtained his BS & MS degrees in entomology from Michigan State University and his PhD is in entomology from Penn State University. He has been working in tree fruit IPM for 25 years and at various times has been an IPM scout, crop consultant, research & development rep for a pesticide company, as well as a university IPM research and extension specialist. In the last 9 years with Penn State, he has been helping the fruit industry to transition through the pesticide changes dictated by FQPA to more ecologically-based IPM systems that are more reliant on conservation biological control. As a trained taxonomist, he is currently examining the effects on arthropod community structure in orchards transitioning away from broad spectrum pesticides, through biodiversity measures of predatory mites, parasitic Hymenoptera and Diptera, generalist predators and native pollinators. He has taught courses in insect taxonomy/systematic and insect ecology.

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