Perspective

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Tree fruit IPM programs in the western United States: the challenge of enhancing biological control through intensive management

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Abstract

The seminal work of Stern and his coauthors on integrated control has had a profound and long-lasting effect on the development of IPM programs in western orchard systems. Management systems based solely on pesticides have proven to be unstable, and the success of IPM systems in western orchards has been driven by conservation of natural enemies to control secondary pests, combined with pesticides and mating disruption to suppress the key lepidopteran pests. However, the legislatively mandated changes in pesticide use patterns prompted by the Food Quality Protection Act of 1996 have resulted in an increased instability of pest populations in orchards because of natural enemy destruction. The management system changes have made it necessary to focus efforts on enhancing biological control not only of secondary pests but also of primary lepidopteran pests to help augment new pesticides and mating disruption tactics. The new management programs envisioned will be information extensive as well as time sensitive and will require redesign of educational and outreach programs to be successful. The developing programs will continue to use the core principles of Stern and his co-authors, but go beyond them to incorporate changes in society, technology and information transfer, as needed.
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1 INTRODUCTION

The basic theory of integrated pest management (IPM) has been available for 50 years.[1] More than any other concept in entomology and plant pathology, IPM has captured the attention of at least two generations of workers who have expanded the original ideas, perfected new techniques and generated innovative solutions. Tree fruit production in the western USA has historically been one of the best examples of how the ideas of Stern *et al.*[1] on the integration of chemical and biological control can be implemented. However, changes in regulations and technologies make it even more important today to provide simple, clear and easy-to-follow guidelines to enhance the integration of biological control into orchard IPM systems.

A review of the work of Stern *et al.*[1] shows that they considered several components to be crucial for the integration of pesticides and biological control. These components are: (1) the recognition of ecosystem-level interactions between pests and their natural enemies, (2) methods of sampling and predicting pest occurrence, (3) enhancing benefits of natural enemies through importation, augmentation or conservation and (4) understanding the effects of pesticides on natural enemies and how to mitigate those effects through ecological (i.e. dose, timing or location of pesticide application) and physiological (i.e. choice of toxicant) selectivity.

The development of IPM in western tree crops has been shaped by two factors. First, most of the systems have at least one lepidopteran pest that feeds directly on the marketed product and that would be classified by Stern *et al.*[1] as a severe pest whose general equilibrium level is above the economic threshold and that requires frequent interventions to prevent economic damage. The low economic threshold is a direct result of consumer preference for cosmetically perfect produce destined for fresh market. Examples of these pests include codling moth [*Cydia pomonella* (L.)] on apples, pears and walnuts, oriental fruit moth [*Grapholita molesta* (Busck)] and peach twig borer (*Anarsia lineatella* Zeller) on peaches and navel orangeworm [*Amyelois transitella* (Walker)] and peach twig borer on almonds and pistachios. Depending on the crop and the export market, these pests may also be of quarantine importance. Historically, these key pests were controlled using broad-spectrum organochlorine or organophosphate (OP) insecticides, although, as will be discussed later, new tactics and pesticides are currently being used. The second major factor driving tree crop IPM has been secondary pest problems, particularly spider mites and aphids. These two

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pest groups can be characterized as having short generation times, high reproductive rates and a genetic composition that might predispose them to the development of resistance.

The focus of this paper is on western tree crops, where regional low humidity reduces the disease pressure and where the complex of pest insects is reduced compared with those in eastern North America. These conditions simplify management programs, and natural enemies are not subjected to the heavy fungicide pressure common in other areas. While the focus here is on western USA production, it should be noted that, worldwide, entomologists working on tree crops have faced similar (or worse) situations to those described below in trying to develop IPM programs that have long-term stability and are accepted by producers. Unsurprisingly, solutions worldwide typically follow the same general patterns as described below, with departures typically caused by local pest and disease complexes and legislative differences between countries.

2 DEVELOPMENT OF IPM PROGRAMS

Tree fruit IPM in the western USA can arguably be said to have formally begun with the work of Hoyt.[2] Hoyt demonstrated how chemical control of codling moth using high rates of OPs, in combination with certain fungicides, post-bloom thinners and miticides, greatly reduced the ability of the predatory mite, *Galendromus* [= *Typhlodromus*] *occidentalis* (Nesbitt) to regulate populations of spider mites. During this era, Washington growers were making four or more applications of miticides per season, which resulted in rapid evolution of miticide resistance, poor efficacy and high cost to the growers.[3,4] Hoyt found that changing the pesticides used (i.e. physiological selectivity) and reducing dosages and improving both location and timing of applications (i.e. ecological selectivity) resulted in a dramatic decrease in spider mite problems while generalist natural enemies became more abundant.[2] Thus, Hoyt's integrated mite management program addressed directly three (numbers 1, 3 and 4) of the four aspects that Stern *et al*.[1] considered crucial for the successful integration of chemical and biological control.

Perhaps one of the more interesting unreported aspects of the integrated mite management story was the difficulty in getting the program accepted by growers, consultants and fieldmen. In part, this resistance probably came from their lack of familiarity with the idea of biological control, but also from cultural inertia and the associated difficulty of introducing new concepts to a relatively conservative group. A primary reason for integrated mite management finally being accepted was that, because of the high cost and poor control achieved with miticides, growers felt they had little to lose by trying something new. Serendipity also played a role in the form of a spring freeze that destroyed much of the apple crop in the Yakima Valley in 1966. Growers wanted to cut costs on the suddenly low-value crop, and these factors allowed Hoyt and coworkers to test their management program on large acreages with relatively low resistance from growers.[3] The most noticeable results were that orchards not under IPM and orchards using the new program could be distinguished easily from a distance; non-IPM orchards showed substantial browning of foliage from mite feeding, whereas the foliage in IPM orchards remained a healthy green color. This obvious visual expression of success in the IPM program had a large impact on the industry, and the program spread rapidly in Washington after that point. There have been minor glitches in stability of the IPM program throughout the years, especially during the early 1980s when cyhexatin resistance caused some growers to increase cyhexatin rates, which led to destruction of the predator populations. However, the balance was quickly re-established, and, in 1989, only 10% of the acreage was treated for mites.[5]

Further progress in tree fruit IPM was bolstered by block grants from NSF, EPA and USDA, which allowed collaboration among scientists in eastern and western USA production areas, but also enhanced collaboration with scientists in other cropping systems. These collaborations and the state of the art of tree fruit IPM in the late 1970s and early 1980s have been detailed in several books[6,7] documenting the advances made in the successful integration of chemical and biological control. In particular, the greatest improvements came in the areas of monitoring technology (i.e. discovery of the chemical structure of insect pheromones and their formulation into lures), monitoring programs (e.g. ecological studies leading to presence/absence or sequential sampling programs), defining economic thresholds and the development of physiological time (degree-day) models and the optimized timing and efficacy of pesticide applications based on those models. These improvements provided a strong framework upon which to base management strategies for key pests in these cropping systems.

Most of the western orchard IPM programs have historically relied heavily on OP insecticides, from their introduction in the late 1950s until the mid-1990s when the chemicals became a key regulatory target under the Food Quality Protection Act (FQPA) of 1996. Azinphos-methyl in particular has been used from roughly 1958 until now (2009) for control of codling moth, and, in spite of little effort towards resistance management during this period, it has remained an effective control for codling moth in most geographic regions. The stability of these products in IPM programs is likely due, in part, to the fact that the relatively high field rate used would overwhelm the relatively low resistance ratios observed in most field populations.[8,9] Long-term use of azinphos-methyl and other OPs also resulted in selection for resistance in some populations of natural enemies. The development of resistance in natural enemies allowed them to continue to be effective biological control agents for secondary pests in orchards where OPs were used to control direct pests. Examples include the eulophid *Pnigalio flavipes* (Ashmead) for control of western tentiform leafminer in the Pacific Northwest,[10] *G. occidentalis* for control of spider mites on almond and walnut in California[11,12] and *Trioxys pallidus* (Haliday) on walnut aphid in California.[13,14] While most of the selection occurred in commercial orchards, there were also efforts to select for resistance in laboratory strains of the natural enemies and release them in the field.

3 RAPID CHANGE IN TREE FRUIT IPM

Two factors arising since the mid-1990s have resulted in huge changes in the management programs that are used in western tree crops. The first factor was the development and implementation of mating disruption for controlling many of the key lepidopteran pests (e.g. oriental fruit moth, codling moth, peach twig borer). The second factor was the legislatively mandated reduction in the use of many OP insecticides. Mating disruption continues to evolve, with recent noticeable improvements occurring in formulations and application methods. In addition, improved understanding of how mating disruption affects individual behavior[15,16] and population biology[17,18] is also helping guide the use and development of new mating disruption technologies. Even with the current technologies,

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mating disruption allows greatly reduced pesticide inputs for control of key pests, thus facilitating conservation of natural enemies. Mating disruption has become a major part of modern IPM programs for codling moth (≈75% of Washington apple and pear acreage)[19] and oriental fruit moth [≈70% of the fresh and 40% of the processed peach acreage in California (Bentley WJ, private communication, 2009)].

The reduction in OP use brought on by FQPA has indirectly resulted in the registration of a large number of new pesticides for major primary and secondary pests. In general, these compounds have low mammalian toxicity and a shorter residual activity period and require ingestion (rather than just contact with the pesticide residue) to be effective; these characteristics combine to reduce their efficacy compared with the OPs that they are replacing. The new products can provide excellent control, but precise timing and coverage of the target site are critical, and the products must be applied as part of an overall IPM program (typically with mating disruption) to achieve efficacy similar to that associated with the use of OPs alone. In addition, these newer materials include several new chemical classes that do not necessarily have low toxicity to natural enemies and are being employed in rotations to limit resistance development in the target pests. Unfortunately, the greater diversity of these pesticides and their different modes of action and detoxification result in unknown consequences for natural enemies in western orchards, and the resistance management tactics targeted at the key pests reduce the likelihood that natural enemy populations will develop resistance naturally in the field. It would be fair to characterize current management programs based on non-OP insecticides as being comparatively unstable, particularly with respect to mite and aphid problems. For example, miticide use in the year 2000 was estimated as ≈1 spray per year on 32% of the acreage,[20] which was up from only 10% in 1989;[5] this trend is making it necessary to focus greater efforts on better incorporating biological control into these systems.

4 INTEGRATING CONSERVATION BIOLOGICAL CONTROL BACK INTO THE SYSTEM

Efforts at integrating biological control back into IPM programs have been hampered in part by the perception that biological control is ineffective. This is because IPM practitioners tend to think in terms of the extraordinarily high efficacy (>90% mortality) of azinphos-methyl and other OPs against key pests. On the other hand, the outbreaks of secondary pests that can follow OP sprays also serve as a reminder of how important biological control can be.[1] It is known from both empirical and theoretical studies that even moderate amounts of natural-enemy-induced mortality can significantly reduce the pest pressure that growers face. For example, Jones *et al.*[19] used a simple stage-structured population model to show that a 25% increase in the mortality rate of codling moth larvae would result in a 44 and 68% reduction in population densities of the moth after one and two generations respectively (Fig. 1). This type of information, along with field data showing that parasitism of both codling moth and leafroller may reach or exceed 25–30%, has helped convince many growers and consultants that biological control should be a part of any comprehensive IPM program in western orchards.[19]

In an effort to enhance the role of biological control in western orchards in a time of rapidly changing pesticide chemistry and adoption of mating disruption, the authors believe that there is a need to revisit the basics of IPM as outlined by Stern *et al.*,[1] and to expand beyond those boundaries. In particular, there is a critical need (1) to identify effectively which natural enemy species contribute most to the suppression of the primary lepidopteran pests in western tree fruit crops, (2) to evaluate the physiological selectivity of newer classes of pesticide on a suite of common natural enemies in western tree fruit orchards and (3) to develop and evaluate monitoring tools for natural enemies that could be used to track the ecological and physiological selectivity of pesticides used in IPM programs.

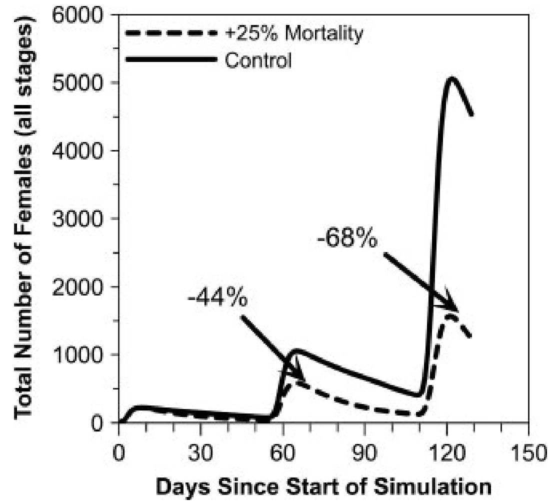

Figure 1. The result of stage-specific Leslie matrix simulations comparing population growth rates of codling moth with the normal mortality schedule (control, solid line) and where larval mortality is increased 25% (dotted line).

4.1 Identifying key natural enemies

There has been considerable effort in the last two decades on the potential to develop tactics that lead to increases in diversity of natural enemies in crop systems. However, it has become clear that the encouragement of natural enemy diversity per se contributes less to the stability of IPM than the enhancement of key natural enemies, which are known to be important for the suppression of specific pests that affect the crop. In western tree crops, the key natural enemies of secondary pests are in many cases already known. However, those that could contribute most to the suppression of primary pests in general have yet to be identified.

Identifying key natural enemies has historically relied on direct observation of feeding or parasitism events. Unfortunately, this approach is both labor and time intensive and is made logistically difficult by diurnal activity patterns of the natural enemies.[21] Recent technological advances provide new opportunities to record both predation and parasitism events in the field using small sensitive video cameras coupled with high-density data storage.[22] This approach is amenable to monitoring predation events at night, can be used in microhabitats that are difficult to monitor by direct visual observation and is currently being employed to study predation and parasitism of codling moth larvae in Pacific Northwest orchards (Unruh TR, unpublished data).

Predator gut content analysis (GCA) provides a valuable complementary approach to video recording of predation events for the identification of key predator species. Recent advances in the use of monoclonal antibodies and PCR to detect prey-specific regions of DNA allow for more practical application of this technology.[23] Monoclonal antibodies have been developed and

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used to identify key predators of pear psylla, *Cacopsylla pyricola* (Foerster), in western pear orchards,[24] and marker sequences are currently being used to identify key predators of codling moth (Unruh TR, unpublished data).

4.2 Physiological selectivity of newer classes of pesticides

The inimical effects of insecticides on natural enemies were well known at the time of the publication by Stern *et al.*,[1] but these effects have proven to be even more complex than envisioned 50 years ago. Traditionally, the effect of pesticides on natural enemies was evaluated by measuring mortality rates (using LC_{50} statistics) 24–48 h following topical application or exposure to residues. However, for the newer pesticides, natural enemies may experience more subtle sublethal effects, such as reduced fecundity or male-biased sex ratios, the impacts of which are more difficult to predict. For example, it is difficult intuitively to estimate whether a 60% reduction in fecundity has a greater effect than a 50% acute mortality. Thus, the need to incorporate sublethal effects requires a different approach, based on demography, that uses life table response assays coupled with stage-structured population models.[25]

A demographic approach makes it possible to combine both acute and sublethal (survivorship, development rate, fecundity, sex ratio) effects associated with exposure to pesticides into a single index, which in turn makes it possible to compare the consequences of pesticide application on population growth in both pest and natural enemy populations.[26] Moreover, stage-structured models allow the overall impact of a pesticide on a natural enemy to be used as a population recovery index,[25] which facilitates comparison of the effect of different pesticide materials on different natural enemy species. For example, this approach has been used to estimate the effects of different insecticides on *Mastrus ridibundus* (Grav.), a parasitoid of codling moth (Mills NJ, unpublished data). A graph comparing the population recovery of *M. ridibundus* populations in the absence (control) and presence of various insecticides is shown in Fig. 2. The influence of acute toxicity of spinosad to *M. ridibundus* is virtually matched in its effects by the sublethal action of acetamiprid (a modest reduction in adult survivorship combined with a significant loss of fecundity), when expressed in terms of the parasitoid's population growth rate. Pyriproxyfen causes a male bias in offspring sex ratio and also substantially prolongs the population recovery time compared with that in control of *M. ridibundus*. These demographic tools allow better estimation of the true effect of pesticides on natural enemy populations and help to improve the ability to use physiological selectivity in guiding the choice of pesticides.

4.3 Monitoring tools for natural enemies

The most effective approach to elevating the role of natural enemies in western tree fruit IPM is to protect them from the disruptive effects of non-selective pesticides. However, to convince growers and consultants that more selective materials applied at less disruptive times in the season will indeed improve biological control requires the development of simple monitoring tools for the rapid assessment of natural enemy activity. Standard monitoring techniques for natural enemies include beating trays, leaf samples, pitfall traps, visual counts, rearing of samples of immature hosts and deployment of sentinel hosts.[21] Many of these techniques are both time and labor intensive, and may be impractical for IPM decision-making. Recent research, however, has shown that many natural enemies respond to herbivore-induced

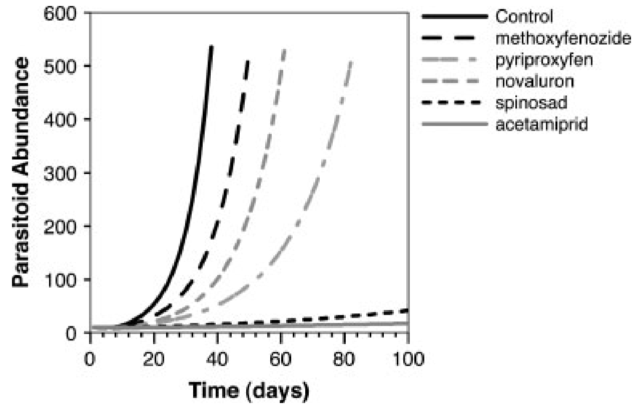

Figure 2. The pesticide-induced changes in population growth rates for the codling moth parasitoid, *Mastrus ridibundus*, using laboratory bioassays and demographic projection.

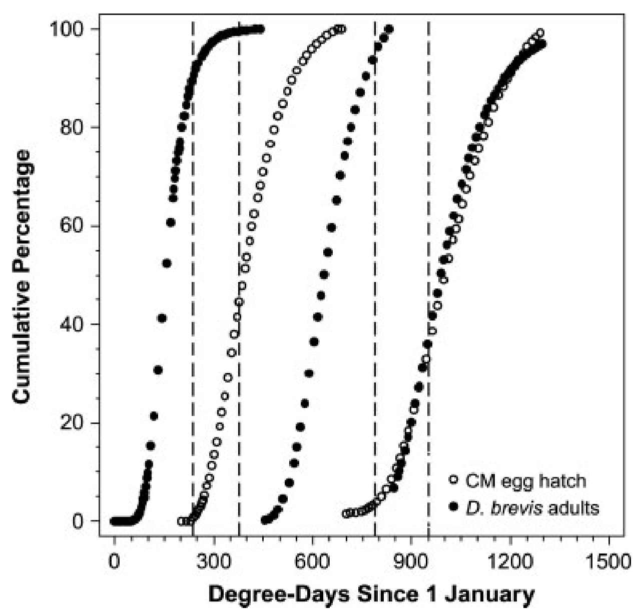

Figure 3. Overlap between the phenology of codling moth egg hatch (open circles) and *Deraeocoris brevis* adult emergence (closed circles). Vertical dotted lines indicate the timing of normal codling moth insecticide applications in the overwintering and summer generations in Washington 2008.

plant volatiles (HIPVs), and that these simple and inexpensive chemicals can be used effectively as lures in traps to monitor the activity of specific natural enemy species in the field.[27,28]

Monitoring tools are needed not only to assess the seasonal phenology of key natural enemy species and identify periods of high vulnerability to disruption but also to track the response of natural enemies in orchards to gain a better understanding of the ecological selectivity of different IPM programs. The importance of understanding natural enemy phenology can be illustrated for the true bug, *Deraeocoris brevis* Knight, a key predator of pear psylla and aphids in western orchards.[29] The foraging and oviposition periods for overwintered and first summer-generation adults of *D. brevis* are almost completed when insecticide sprays (vertical dashed lines in Fig. 3) are applied for control of the overwintering generation codling moth. In contrast, the second summer generation of *D. brevis* adults virtually overlaps the

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hatch of summer-generation codling moth eggs (Fig. 3) (Jones VP and Horton DR, unpublished data). Thus, the conservation and continued activity of *D. brevis* at this point in the season would require either the deletion of a summer codling moth spray or the choice of a pesticide that is compatible with *D. brevis* adults.

5 IMPLEMENTING ENHANCED BIOLOGICAL CONTROL PROGRAMS

As detailed above, the information required to implement programs that lead to enhanced biological control in western orchards is extensive and time sensitive and must integrate a wide range of considerations. Western orchard systems have several key diseases, multiple arthropod pests, several key natural enemies (depending on the crop) and >20 pesticides that are commonly used. The complexity of the system, demands on grower/consultant time not related to IPM and the lack of appropriate educational background make it highly doubtful that the traditional information transfer system (research–extension specialist–county agent–stakeholder) can provide the support needed to implement enhanced biological control.

The traditional information transfer system is in peril because ongoing budget cuts will have two important effects on the current system. First, reduced funding and allocation of resources to University Cooperative Extension programs will weaken continuing education programs needed to expand the training of current IPM practitioners. Secondly, the continuing loss of undergraduate programs in entomology/plant pathology/IPM or graduate-level programs in pest management will reduce the broad IPM background needed by the next generation of IPM practitioners; the reduced background training further increases the need for continuing education to create a feedback loop. Both of these educational issues are a consequence of the reduced willingness in state legislatures to fund higher education, and are unlikely to be reversed any time soon. To deal with these problems, it is clear that it is necessary to embrace new partnerships with the affected industries and pursue and implement new technologies to improve the efficiency of the existing educational system and to gain a better understanding of how to improve and speed up the flow of technology transfer from research to implementation. It is no longer feasible to have a lag period of up to 7 years for adoption of new agricultural technologies.[30]

One of the most obvious ways to deal with the complexity of management programs and the reduced role of university extension programs is to redirect resources into web-based programs that provide the education, training and decision support information needed by industry. In Washington State, a web-based decision support system called WSU-Decision Aid System (DAS, das.wsu.edu) has been developed for pest management in apple, cherry, pear, peach and nectarine orchards. DAS currently has ten insect models, three disease models and a model for storage scald of apple; in the next few years, incorporation of other relevant models is anticipated. DAS integrates weather data, model predictions and pesticide recommendations (including known natural enemy and non-target pest effects) and provides straightforward management recommendations triggered by model inputs. The weather data that drive the system are provided by Washington State University AgWeatherNet, which is a near-real-time network with 140 weather stations distributed across the state. In addition, user-entered data can be used, and site-specific weather forecasts are obtained from the National Oceanic and Atmospheric Administration (NOAA) which make it possible to project model and management requirements for up to 10 days ahead. This system has the advantage of being available at all times, and a single change in the management program is immediately made available to all the users. By comparison, the typical 'winter meeting schedule' for scientists, growers and IPM practitioners in tree crops has a relatively narrow window of time during which educational updates are possible; if that window is missed, educational opportunities must often wait until the following winter.

While DAS and similar systems are key steps towards helping the industry implement optimal management programs, they can also provide researchers and educators with tools to visualize, improve and implement those management strategies. DAS provides a basic framework for current management programs, so that, as information on natural enemy phenology and susceptibility to pesticides is added, the system makes it possible to see areas where changes in management are required and where additional educational resources are needed.

For the agricultural industry to get the maximum benefit out of DAS-type decision support systems, the continuing educational experience has to be modified to reflect the reality that certain types of information (e.g. choice of pesticide and timing of applications) are more effectively transmitted through the decision support system than through more traditional methods. Continuing education programs will remain important, and will have to provide the general background information required to understand and implement the new management programs. The authors feel that continuing education must embrace the use of web-based curricula and certification programs. The advantages of such programs would be to reduce the time-inefficient multiple-meeting approach that is currently used and to leverage resources using web modules developed by teams from multiple regions/states. Such web-based courses could be served from a central location that would be maintained using fees from the certification program.

In summary, tree crops grown in the western USA are currently in a period of rapid change that requires the re-evaluation of current IPM programs. Historically, the vision of IPM put forth by Stern *et al*.[1] has been the basis of programs in the western region and will continue to be a guiding force in the future. However, IPM programs are evolutionary processes that regularly need to be re-evaluated and redesigned to improve their efficiency and to deal with changes in technology, environmental and worker safety concerns, cultural climate and economic realities. While historic patterns and experience can be used as a guide, it is also imperative to recognize the limitations of historical solutions and to broaden perspectives on approaches to optimize management programs from research to final adoption. For the IPM programs of the future to achieve the same stability as those of the past, it is clearly necessary to move in the direction of information-intensive IPM programs that enhance biological control as the basis for IPM.

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REFERENCES

1 Stern VM, Smith RF, van den Bosch R and Hagen KS, The integrated control concept. *Hilgardia* **29**:81–101 (1959).

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2 Hoyt SC, Integrated chemical control of insects and biological control of mites on apple in Washington. *J Econ Entomol* **62**:74–86 (1969).
3 Hoyt SC, Mite complex on apples, in *Biological Control in the Western United States: Accomplishments and Benefits of Regional Research Project W-84, 1964–1989*, ed. by Nechols JR, Anders LA, Beardsley JW, Goeden RD and Jackson CG. University of California Division of Agricultural and Natural Resources, Berkeley, CA, pp. 63–66 (1995).
4 Hoyt SC and Caltagirone LE, The developing programs of integrated control of pests of apples in Washington and peaches in California, in *Biological Control*, ed. by Huffaker CB. Plenum Press, New York, NY, pp. 395–421 (1971).
5 Beers EH and Brunner JF, Washington state apple and pear pesticide use survey, 1989–1990. Report to USDA-NAPIAP, Washington, DC (1991).
6 Boethel DJ and Eikenbary RD, *Pest Management Programs for Deciduous Tree Fruits and Nuts*. Plenum Press, New York, NY (1979).
7 Croft BA and Hoyt SC, *Integrated Management of Insect Pests of Pome and Stone Fruits*. John Wiley & Sons, New York, NY (1983).
8 Knight AL, Brunner JF and Alston D, Survey of azinphos-methyl resistance in codling moth (Lepidoptera: Tortricidae) in Washington and Utah. *J Econ Entomol* **87**:285–292 (1994).
9 Varela LG, Welter SC, Jones VP, Brunner JF and Riedl H, Monitoring and characterization of insecticide resistance in codling moth (Lepidoptera: Tortricidae) in four western states. *J Econ Entomol* **86**:1–10 (1993).
10 Beers EH, Control strategies for leafminers and leafhoppers revisited, in *New Directions in Tree Fruit Pest Management*, ed. by Williams K, Beers EH and Grove GG. Good Fruit Grower, Yakima, WA, pp. 157–167 (1991).
11 Hoy MA, Barnett WW, Hendricks LC, Castro D, Cahn D and Bentley WJ, Managing spider mites in almonds with pesticide resistant predators. *Cal Agric* **38**:18–20 (1984).
12 Hoy MA and Knop NF, Selection for and genetic analysis of permethrin resistance in *Metaseiulus occidentalis*: genetic improvement of a biological control agent. *Ent Exp Appl* **30**:10–18 (1981).
13 Hoy MA, Cave FE, Beede RH, Grant J, Krueger WH, Olson WH, *et al*, Release, dispersal, and recovery of a laboratory-selected strain of the walnut aphid parasite *Trioxys pallidus* (Hymenoptera: Aphidiidae) resistant to azinphosmethyl. *J Econ Entomol* **83**:89–96 (1990).
14 Hoy MA and Cave FE, Toxicity of pesticides used on walnuts to a wild and azinphosmethyl-resistant strain of *Trioxys pallidus (Hymenoptera: Aphidiidae)*. *J Econ Entomol* **82**:1585–1592 (1989).
15 Carde RT and Minks AK, Control of moth pests by mating disruption: successes and constraints. *Annu Rev Entomol* **40**:559–585 (1995).
16 Witzgall P, Stelinski LL, Gut LJ and Thomson D, Codling moth management and chemical ecology. *Ann Rev Entomol* **53**:25.21–25.20 (2008).
17 Jones VP, Wiman NG and Brunner JF, Comparison of delayed female mating on reproductive biology of codling moth and obliquebanded leafroller. *Environ Entomol* **37**:679–685 (2008).
18 Jones VP and Aihara-Sasaki M, Demographic analysis of delayed mating in mating disruption: a case study with *Cryptophlebia illepida* (Lepidoptera: Tortricidae). *J Econ Entomol* **94**:785–792 (2001).
19 Jones VP, Unruh TR, Horton DR and Brunner JF, Improving apple IPM by maximizing opportunities for biological control. [Online]. *Good Fruit Grower* (December 2006). Available: http://www.goodfruit.com/subscriber/archive/2006/Dec-2006/[2009].
20 Jones WE, Tangren J, Beers EH and Brunner JF, *IPM in Washington State Orchards: A Survey of Management Practices for the 2000 Season*. [Online]. Available: http://opus.tfrec.wsu.edu/~wjones/Survey2000/ [2009].
21 Mills NJ, Parsitoids and predators, in *Insect Sampling in Forest Ecosystems*, ed. by Leather SR. Blackwell, Oxford, UK, pp. 254–278 (2005).
22 Merfield CN, Wratten SD and Navntoft S, Video analysis of predation by polyphagous invertebrate predators in the laboratory and field. *Biol Cont* **29**:5–13 (2004).
23 Symondson WO, Molecular identification of prey in predator diets. *Mol Ecol* **11**:627–641 (2002).
24 Unruh TR, Yu T, Willett LS, Garczynski SF and Horton DR, Development of monoclonal antibodies to pear psylla (Hemiptera: Psyllidae) and evaluation of field predation by two key predators. *Ann Entomol Soc Amer* **101**:887–898 (2008).
25 Stark JD, Sugayama RL and Kovaleski A, Why demographic and modeling approaches should be adopted for estimating the effects of pesticides on biocontrol agents. *BioControl* **52**:365–374 (2007).
26 Stavrinides MC and Mills NJ, Demographic effects of pesticides on biological control of Pacific spider mite (*Tetranychus pacificus*) by the western predatory mite (*Galendromus occidentalis*). *Biol Cont* **48**:267–273 (2009).
27 Kahn ZR, James DG, Midega CAO and Pickett JA, Chemical ecology and conservation biological control. *Biol Cont* **45**:210–224 (2008).
28 James DG, Further field evaluation of synthetic herbivore-induced plant volatiles as attractants for beneficial insects. *J Chem Ecol* **31**:481–495 (2005).
29 Beers EH, Brunner JF, Willett MJ and Warner GM, *Orchard Pest Management: A Resource Book for the Pacific Northwest*. Good Fruit Grower, Yakima, WA (1993).
30 Alston JM, Norton GW and Pardey PG, *Science Under Scarcity: Principles and Practices for Agricultural Research Evaluation and Priority Setting*. Cornell University Press, Ithaca, NY (1995).

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