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From planning to execution to the future: An overview of a concerted effort to enhance biological control in apple, pear, and walnut orchards in the western U.S.

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Running head: Enhancing biocontrol in western orchard systems

From planning to execution to the future: An overview of a concerted effort to enhance biological control in apple, pear, and walnut orchards in the western U.S.

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Abstract. We embarked on a large project designed to help enhance biological control in apple, pear and walnut orchards in the western U.S., where management programs were in the midst of a transition from older organo-phosphate insecticides to mating disruption and newer reduced-risk insecticides. A "pesticide replacement therapy" approach resulted in unstable management programs with unpredictable outbreaks of spider mites and aphids. Our project was designed to provide growers and pest managers with information on the effects of newer pesticide chemistries on a suite of representative natural enemies in both the laboratory and field, potential of new monitoring tools using herbivore-induced plant volatiles and floral volatiles, phenology of the key natural enemy species, economic consequences of using an enhanced biological control program, and value of an outreach program to get project outcomes into the hands of decision-makers. We present an overview of both the successes and failures of the project and of new projects that have spun off from this project to further enhance biological control in our systems in the near future.

Keywords: *conservation biological control; plant volatiles; pesticide effects on natural enemies; IPM decision-making; economic analysis; outreach*

1. Introduction

Integrated pest management (IPM) programs in tree crops in the western U.S. have been in a state of flux for the past 25 years, starting with the development and implementation of mating disruption (MD) for the management of codling moth (*Cydia pomonella* [L.]) in the early 1990s. Mating disruption greatly reduced the need for broad-spectrum "cover" sprays (typically azinphosmethyl or AZM) for codling moth and at least opened the door for increased use of conservation biological control (Brunner *et al.*, 2005). Growers have rapidly adopted codling moth MD in the state of Washington and the latest figures suggest that >90% of the apple and pear acreage now uses this approach. The second major factor that has contributed to the flux in IPM programs was the Federal Food Quality Protection Act (FQPA) of 1996 that mandated the U.S. Environmental Protection Agency to re-review registered pesticides with the goal of increasing the safety margin of residues found in food crops, particularly those likely to be included in the diets of infants and children (Anonymous, 2006). As part of this re-review process, particular emphasis was placed on the evaluation of organo-phosphate (OP) insecticides, which had been a mainstay in tree fruit production since the mid-1950's (Jones *et al.*, 2010b). While the loss of some OP's was a non-issue to tree fruit IPM programs, the loss of AZM for control of codling moth presented an extreme challenge to the status quo. Inevitably, this required the identification and use of alternate insecticides, because even IPM programs using MD typically requires at least one insecticide application early in the season (Brunner *et al.*, 2005) when MD is less effective for control of codling moth (Jones and Wiman, 2012).

While the FQPA initially restricted and later eliminated many of the OP's used in western tree fruit production, it indirectly stimulated the registration of a large number of "reduced-risk" insecticides that were slated to be OP replacements. This bounty of new insecticides provided a set of powerful tools that would allow better management of pesticide resistance in our key pests. Unfortunately, there was little information on the effects of these new materials on the natural enemy communities that had been shaped over a 50+ year period by OP use (Jones *et al.*, 2009). Although the reduced-risk insecticides tended to perform well in small-scale experimental tests, in large-scale commercial use many of the new materials resulted in increased aphid and mite populations to the point that the western orchard systems became relatively unstable with respect to secondary pests.

The genesis of this effort to enhance conservation biological control in western orchards was in 2006, when four of us published a white paper to introduce the idea that we were at a crossroad in the transition from pre-FQPA to post-FQPA IPM programs for apples in Washington state and that the future stability of these programs would require the enhancement of biological control (Jones *et al.*, 2006). Our contention was that biological control was more important than most people realized and that we needed to focus on which natural enemy species were the most effective (especially among the predators whose roles were less clear), when they were most active during the growing season, and how selective the newer classes of insecticides were for effective integration of natural enemies into our management programs.

We began to address these questions with support from the Washington Tree Fruit Research Commission in 2007-2009, focusing our efforts on evaluating field spray programs in apples, predation intensity on codling moth and leafrollers, tachinid parasitism of leafrollers, and phenology models for some of the natural enemies. An ideal opportunity to intensify this work presented itself when the United States Department of Agriculture (USDA) announced its Specialty Crop Research Initiative (SCRI) program in summer 2008. This grant program allowed large multiple-commodity, multi-institution, multi-state projects to pursue “trans-disciplinary” approaches with the proviso that they address practical industry-based solutions to improve the competitiveness of American agriculture. Our successful proposal to the USDA-SCRI program allowed us to expand our previous efforts in Washington to include the states of California and Oregon, and to broaden our initial focus on apples to include walnuts (California) and pears (Oregon and Washington), two additional tree crops that shared codling moth as the key pest in their IPM programs. This larger project focused on several issues that we felt could be addressed during the five-year period of the grant, and that we considered to be the most important roadblocks for enhancing biological control in western orchard systems (Table 1). Although at its heart the team for the USDA-SCRI project had a strong entomological focus, we knew that there were valuable reasons to include other disciplines that were better suited to answering questions about the costs and barriers to adoption of different IPM management strategies. In addition, the members of the team were united in the desire to make sure that the outreach effort provided growers and IPM consultants with the information generated from the project and that this information would not simply disappear when the five-year grant period ended.

2. Overview of project and results

In this special issue there are thirteen additional papers that detail the results of our research and outreach efforts from the USDA-SCRI project. While these papers do not report on every aspect of the project, they have been selected to provide a broad overview of the objectives of the complete project (Table 1). Here we provide a summary of the highlights of each contribution by grouping them into one of five categories: (1) pesticide effects on natural enemies; (2) use of plant volatiles to monitor natural enemies; (3) evaluating the importance of codling moth predation; (4) economics and barriers to adoption of conservation biological control; and (5) the outreach program.

2.1. Pesticide effects on natural enemies

The main premise for the project was that for those tree crops in the western U.S. that share codling moth as a primary pest, IPM programs could be made more effective and stable through greater recognition of the value of the pest control services provided by resident natural enemies. For conservation biological control to be fully integrated with a combined mating disruption - insecticide program for management of codling moth and a pesticide program for management of plant diseases, the selectivity of OP replacements and other pesticides commonly used in western orchards was of primary concern. Consequently, there are five papers in this issue that address different aspects of pesticide effects on natural enemy populations in both laboratory and field settings (Amarasekare *et al.*, 2016; Beers *et al.*, 2016a; Beers *et al.*, 2016b; Mills *et al.*, 2016a; Shearer *et al.*, 2016). These papers show that, in general, laboratory bioassays based on life table response experiments and the use of a demographic approach to evaluation of the combined lethal and sub-lethal effects of pesticides on natural enemies provided an effective way to estimate the potential for disruption of natural enemy populations (Amarasekare *et al.*, 2016). This detailed approach to laboratory bioassays had the added benefit of providing a common currency for comparison of effects across different pesticides and natural enemy taxa (Mills *et al.*, 2016a). The results clearly showed that reduced-risk insecticides are not necessarily selective and have the potential to be disruptive for natural enemy populations. However, although the most disruptive insecticides had a more consistent effect across natural enemy species, the relative response of individual natural enemy species to pesticide exposure varied widely among materials, making broader generalizations about pesticide effects on natural enemies more difficult (Banks *et al.*, 2011).

Field studies to verify the potential disruptive effects of pesticides identified from laboratory bioassays on natural enemy populations under commercial orchard conditions were easily the largest, most expensive, and most frustrating aspect of the USDA-SCRI project. In these comparative studies, we monitored the effects of disruptive and selective insecticide treatments for management of codling moth on the natural enemies on the secondary pests in apple, pear and walnut orchards. Large plots and sufficient replication were required to minimize the inter-plot movement of natural enemies and to adequately demonstrate the disruptive effects on natural enemy populations (Beers *et al.*, 2016a; Shearer *et al.*, 2016). Unfortunately, the use of large-plots with suitable controls proved to be logistically difficult, expensive, and required a degree of serendipity with respect to whether there was a sufficient abundance of both secondary pests and their natural enemies at the selected field sites to differentiate treatment effects. Despite the challenges and difficulties associated with the field trials, our project represents one of the largest field and laboratory studies to test the effects of some of the reduced-risk insecticides and fungicides on a range of predators and parasitoids found in tree crops in the western U.S. (Beers *et al.*, 2016a; Beers *et al.*, 2016b; Shearer *et al.*, 2016).

2.2. Use of plant volatiles to monitor natural enemies

Another major area we targeted through the USDA-SCRI project was the development of quick and reliable sampling tools for natural enemies. We focused on traps baited with herbivore-induced plant volatiles (HIPVs) and floral volatiles (FV) as lures (collectively referred to as "plant volatiles"), based on a range of studies showing the broad response by natural enemies across taxonomic groups (Chauhan *et al.*, 2007; James, 2003a; James, 2003b; James, 2005a; James, 2005b; Kahn *et al.*, 2008; Toth *et al.*, 2009; Yu *et al.*, 2008). Our earlier studies (Jones *et al.*, 2011) had suggested that lures combining different plant volatiles were more effective than single component lures, thus we focused our attention in this project on combination lures. Using several different approaches, in all three tree crop systems, we were able to identify lures that could be used for specific natural enemy groups (Jones *et al.*, 2016a). The number and diversity of natural enemies caught in the traps were substantial, which caused us to narrow our focus to various indicator species that were large and relatively easy to identify by non-taxonomists and pest managers. In our crop systems, green lacewings were especially attracted to multicomponent lures, with multiple "optimal" lure combinations. A second indicator group was syrphid flies, which showed both strong positive and negative responses to various lure combinations. The attraction of a broad range of Hymenoptera to phenylacetaldehyde also opens up many avenues for studies of ecosystem function. Using a combination of trap color, shape, and lure composition we were able to fine-tune traps for specific natural enemy groups.

As part of our evaluation of natural enemy phenology, we sampled orchards with various lure combinations throughout the season for a number of natural enemy taxa. Surprisingly, we found that phenology was largely independent of the crop system and potential prey items, but directly predictable by degree-day accumulations. Although the paper presented in this issue (Jones *et al.*, 2016b) focuses on a single green lacewing species (*Chrysopa nigricornis* Burmeister), ongoing research has revealed similar potential for degree-day prediction of the phenology of other lacewing species (*Chrysoperla* spp.), and for several species of syrphids (*Eupeodes volucris* Osten Sacken and *E. fummipennis* [Thomson]) (Jones, Mills, Horton, Shearer, Unruh, unpublished observations). This research has shown that several generalist predators emerged from overwintering much sooner than expected, which will require a re-evaluation of the idea that sprays during the delayed dormant period have little effect on natural enemy populations.

In addition to the phenology information generated by our season-long trapping with plant volatile lures, we were also able to estimate the generic richness and diversity of generalist predators in these crop systems in the western U.S. (Mills *et al.*, 2016b). The season-long samples also provided estimates of the seasonal variation in diversity indices for generalist predators in apple, pear and walnut orchards and for morphospecies of all predator and parasitoid taxa in walnut orchards in California. The diversity of different natural enemy groups was much greater than expected; we collected 31 different genera of foliage active generalist predators from all orchards combined, as well as up to 23 species of generalist foliage predators and 124 morphospecies of parasitoids from walnut orchards alone (Mills *et al.*, 2016b). This research showed a consistent pattern of increasing natural enemy diversity through the season in all three tree crops and highlighted the fact that natural enemy communities in agricultural systems are not "simple", patterns and insights that have been more effectively revealed through use of traps with plant volatile lures than through use of other sampling techniques.

2.3. Evaluating the importance of codling moth predation

The third goal of the project was to examine which predator species were affecting codling moth in our western orchard systems. While codling moth is the key pest common to apple, pear, and walnut systems in the western U.S., our investigations focused on predation in apple orchards in Washington State as a representative system. Molecular gut content analysis showed that earwigs, spiders and carabid beetles were responsible for most of the predation events recorded (Unruh *et al.*, 2016). Based on the information generated in this component of the project we can now prioritize conservation efforts for the natural enemies of codling moth, in addition to those of secondary pests, as our IPM programs evolve.

2.4. Economics and barriers to adoption of conservation biological control

One of the factors that drives adoption of different IPM practices is economic cost. Unfortunately, most studies comparing spray programs focus only on the cost of saved sprays (e.g., one fewer spray was needed where conservation biological control strategies were used) and rarely factor in the cost of applying materials (including tractor/operator costs), cost to the environment, and cost to human and animal health. While our study did not include the latter two costs, it did evaluate the cost of pesticides required for management of secondary pests following the use of pesticides identified to be potentially disruptive to their natural enemies from our pesticide evaluations (Gallardo *et al.*, 2016). Using spray records, the analysis showed that for every dollar spent on pesticides classified as potentially disruptive to natural enemies resulted in the need to spend another $0.47 - 0.51 for pesticides to control secondary pests in apple and pear, respectively. These cost estimates provide an important basis for making the case that conservation biological control is both a practical and cost-effective component of IPM systems.

From the standpoint of effective outreach, we needed to know more about our stakeholder community in order to provide them with suitable information about the value of conservation biological control. The sociologists on our team concentrated on the decision-making process and surveyed walnut and pear growers using both traditional mail and electronic means (Goldberger and Lehrer, 2016). They found that the majority of responders associated with both crops recognized that they use some form of conservation biological control (54 and 76% for walnuts and pears, respectively). However, when asked specifically if they chose pesticides for control of codling moth that minimized disruptive effects on natural enemies, 90 and 98% (walnuts/pears) answered “sometimes” or “always”. From this it is clear that some of the responders did not consider the full spectrum of management activities that could influence the success of conservation biological control. The survey data also highlighted a number of other factors that were associated with the responders’ use of conservation biological control practices: (1) organic management of at least part of their acreage; (2) use of degree-day calculations, mating disruption, or OP-alternatives for codling moth management; (3) desire to reduce environmental effects; and (4) perceived importance of university-based sources of IPM information. Overall, the survey data suggest that educational programs will continue to be a key factor in the adoption of conservation biological control.

2.5. Outreach program

The outreach program during the five-year period of the USDA-SCRI project consumed about 25% of the total resources available. During this time, members of the project team gave 92 presentations at industry and scientific meetings and 40 symposia presentations, wrote 21 popular articles in industry magazines, sponsored a two day comprehensive short course on conservation biological control that was attended by 80 stakeholders and video conferenced to three different locations, and gave 12 two to four hour training sessions on natural enemy identification and biology (Gadino *et al.*, 2016). In addition, we developed a state-of-the-art web site (enhancedbiocontrol.org) that was the repository for all the information developed for our project including photo galleries of the different natural enemies, video interviews with industry collaborators, videos of how laboratory bioassays and field experiments were performed, identification guides, handouts from the short courses, and all progress reports (Jones *et al.*, 2016c).

In addition to the project web site, information arising from the project has been or is in the process of being integrated into the Washington State University Decision Aid System (WSU-DAS) web site (Jones *et al.*, 2010a). While this web site is specific for growers and consultants in the state of Washington, it is used on >80% of the tree fruit acreage in the state to help in the IPM decision-making process. A key tool developed through our project was the Orchard Pesticide Effects on Natural Enemy Database (OPENED) which is available on our project web site as well as through the WSU-DAS website to help guide decisions on which pesticides would be least disruptive for natural enemies.

The USDA-SCRI project was also supported by an advisory committee consisting of extension personnel from each state, outside scientists, and industry members from each state. Their function was to help guide the research and outreach activities of the project. Although we maintained contact with committee members throughout the year, the most informative interactions occurred at our annual one-day committee meetings at which we provided presentations to the committee on the progress made and received input from the committee on opportunities to fine tune and improve various aspects of our research and extension program.

3. Leveraged projects

Although the direct and matching support for these large multi-institution grants is considerable, we found that leveraged funding increased the overall effort by nearly an equal margin in a range of different areas. For example, in the area of outreach, team members are currently developing web-based training courses and expanding the project web site to leave a lasting legacy that will be a key repository of information for conservation biological control. In addition, there are multiple lines of research spawned by the overall larger program that are using technology and results of our work to further the cause of increasing conservation biological control in western orchard systems.

Research from the use of plant volatile traps for the monitoring of natural enemy populations has spun off several new projects, including one to compare the natural enemy and pest communities associated with organic and conventional apple production in Washington. In addition, this same project has evaluated the use of low dose (10% label rates) applications of potentially disruptive pesticides and their effects on natural enemies and pest damage. Results of the recently completed work have shown that low dose pesticides applied at a frequency comparable to organic treatment timings (which is roughly twice as often as conventional applications) resulted in higher natural enemy densities with no differences in damage rates from a wide range of pests and a reduction of 80% pesticide use (Jones, unpublished).

A project on biological control of pear psylla has also been leveraged from the results of our USDA-SCRI project. Information obtained from our studies of pesticide effects, natural enemy monitoring and phenology, are currently being used in Oregon to mitigate the relatively harsh pesticide programs normally used in pears for pear psylla control. Several members of our USDA-SCRI project team also form a core group developing of a more biorational approach to pear psylla management in Washington and Oregon emphasizing conservation biological control.

In California, the USDA-SCRI project has leveraged additional funding for a project on enhancing the biological control of spider mites in walnut production. An earlier study of spider mite predators in walnuts (McMurtry and Flaherty, 1977) had suggested that western predatory mite *Galendromus occidentalis* (Nesbitt) and six-spotted thrips *Scolothrips sexmaculatus* (Perg.) were the dominant species on unsprayed trees. From surveys throughout the walnut-growing region over the past two years, it is clear that neither of these two specialist predators remain well represented in walnut orchards. Instead, the surveys showed that generalist phytoseiid predators dominate the natural enemy communities during the growing season. This highlights the need for greater emphasis on conservation of effective biological controls for mite management in IPM programs for walnuts in California (Mills, unpublished).

The final leveraged project is the development of models to assess pesticide impacts on pests and natural enemies. This project has developed demographic models that mimic the phenology and the reproductive performance of codling moth, obliquebanded leafroller (*Choristoneura rosaceana* [Harris]), and the lacewings *C. nigricornis* and *C. carnea* (Jones, unpublished). Using these demographic models, we can simulate the effects of pesticide applications at any time (or multiple times) during the season, using different levels of mortality based on specific residue degradation curves. These models allow us to quickly identify stages in the lifecycle that show the greatest sensitivity/insensitivity to pesticide mortality and to evaluate the likely outcome of different treatment programs. Once validated, these models can be combined with field residue degradation data to provide a much more realistic way of designing optimal management programs.

4. Conclusions

Large multi-institutional research and extension projects supported by the USDA-SCRI program are often viewed as successes or failures based on the traditional criteria of publications, presentations, web-pages, and impacts on the stakeholder groups for whom the work was done. In this context we are confident that our project has been a success, but beyond the traditional criteria, we have developed a number of new technologies and approaches that will likely find application across a broader range of agricultural systems than the western specialty tree crops for which they were intended. For example, the identification of suitable plant volatiles for monitoring a broad range of different natural enemy taxa, the discovery that the phenology of generalist predators is apparently independent of cropping systems and associated prey species, and the contributions made to improving methodologies for evaluating pesticide effects on natural enemies can be applied to other cropping systems with at least the same benefits as found in our western orchard systems. While the outreach component of our project was not necessarily unique or ground breaking, it made use of the best ideas from previous agricultural extension activities, and benefitted from working with our advisory committee and survey results from our stakeholders, to synthesize much of the information into an efficient and well-rounded package. In addition, our team put together an innovative web site as an integral part of the outreach effort, with a strong emphasis on creating a low-maintenance repository that will serve as a lasting legacy of the achievements of the project regardless of the opportunities for continued leveraged funding.

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Table 1. Specific objectives pursued under the USDA-SCRI project to enhance biological control in orchards in the western U.S.

1. Evaluate the sub-lethal effects of selected newer pesticides on key natural enemies in laboratory and field assays in apple, pear, and walnut orchards.

2. Characterize natural enemy phenology, including timing of emergence from overwintering areas, entry into orchard, and development within the orchard.

3. Evaluate attractants as natural enemy monitoring tools and compare them to traditional methods.

4. Develop molecular and video methods to monitor predation of codling moth.

5. Conduct economic analyses to determine long-term costs associated with IPM programs with and without various levels of biological control.

6. Survey clientele to identify optimal ways to present information that will lead to quicker adoption of new technologies; synthesize existing and new information to provide real-time support for pest control decisions by stakeholders; design an outreach program that will speed adoption of conservation bi

Graphical Abstract