Building a multi-tactic pheromone-based pest management system in western

IFAFS / RAMP Report - 2001

Introduction

Two grants supported by the USDA-CSREES were funded through the Initiative for Future Agriculture and Food Systems (IFAFS) and FQPA Risk Mitigation for Major Food Crop Systems (RAMP) programs. The grant titles were "Building a multi-tactic pheromone-based pest management system in western" for the IFAFS grant and "Enhancing pheromone mating disruption programs for lepidopterous pests in western orchards" for the RAMP grant. These grants were funded through Washington State University (IFAFS) and University of California, Berkeley (RAMP) with subcontracts to participating institutions and agencies. The granting agency and programs asked the PIs in each grant to coordinate activities in order to carry out the stated objectives. The PIs agreed to act in this manner and have worked diligently to integrate activities of the two programs. The proposals that were funded our outlined below.

Project Description

INTRODUCTION – Codling moth (CM), *Cydia pomonella* L., is the key pest of pome fruit production in the western region of the United States (US) and is an important economic pest of walnut (Beers et al. 1993). Apple and pear are grown on 300,000 acres in five states (WA, OR, ID, UT, CA) and account for over $1.5 billion in farm gate value annually. The western region ranks first in apple and pear production and accounts for 70% of the fresh market apples sold in the US and 90% of the pear production. In addition, walnuts are produced on nearly 200,000 acres in CA.

Organophosphate (OP) insecticides are the most widely used class of insecticides in pome fruit orchards in the western US (Beers and Brunner 1991, NASS 1992, 1994, 1996, 1998). Resistance to OP insecticides occurs in the key pests, codling moth and leafrollers, and has been documented in pome fruit orchards throughout the western US (Varela et al. 1993, Knight et al. 1994, Dunley et al. 2000). Many secondary pests, such as aphids, leafhoppers, and leafminers, have also developed high levels of resistance to OP and carbamate insecticides. In contrast, most biological control agents are highly susceptible to broad-spectrum insecticides (Croft and Brown 1975, Croft 1990). Continued use of broad-spectrum insecticides represents a major barrier to the implementation of biological control for many secondary pests.

Implementation of the Food Quality Protection Act of 1996 (FQPA) will limit the availability and use of OP, carbamate and other insecticides that have been used for over 30 years (Whalon et al. 1999). Because apple and pear are important foods in the diets of infants and children (NAS 1993), the FQPA will restrict pesticides used on these crops more than on others. A new strategy that reduces reliance on broad-spectrum insecticides and integrates newer selective pesticides with other tactics is necessary to maintain or enhance the long-term economic viability of the western orchard industry.

Use of mating disruption for control of the CM has been shown to be an effective strategy in western orchards (Knight 1995, Gut and Brunner 1998). The widespread adoption of CM mating disruption (CMMD) in western apple and pear orchards resulted from efforts of the highly successful Codling Moth Areawide Management Project (CAMP) – 1995-1999 (Calkins 1998, Alway 1998, also see http://www.pwa.ars.usda.gov/yarl/areawide/areawide.html and http://www.tfrec.wsu.edu/IPMnews/IPM010198.html for additional information). CAMP was successful in achieving its goals of implementing mating disruption as the primary control for CM, reducing broad-spectrum insecticide use by about 75%, and enhancing opportunities for biological control in pome fruit orchards. Table 1 summarizes data from the five CAMP sites showing the changes in CM populations, damage, and reductions in insecticides and pheromone treatment rates.

The impact of CAMP ultimately ranged far beyond the initial five sites as new one-year "seed grants" were used to establish more areawide efforts. The area of the original CAMP sites was 3,110 acres and involved 66 growers. However, by 1999 the original CAMP sites had expanded and encompassed 4,815 acres and involved 109 growers. In the third through fifth years of CAMP, funding for one year only was provided to initiate new "areawide" projects. In these three years, 17 additional areawide projects were initiated in five states involving 16,150 acres and 352 growers. The CAMP project, as illustrated by its continued growth, allowed small- and medium-sized growers to take advantage of a technology that worked best on large contiguous acreage by forming cooperative groups to treat large regions.

The use of CMMD in Washington provides a good example of adoption rates of the technology that has taken place in western apple and pear orchards. In 1994, prior to CAMP, only about 11,000 acres of apple and pear were treated with CMMD. In the last year of CAMP, 1999, that acreage had expanded to 60,000 acres or approximately 30% of pome fruit acreage in Washington. That acreage is expected to increase to nearly 85,000 acres (45%) in 2000. CAMP has been recognized regionally and nationally for its accomplishments in promoting the implementation of IPM technology, receiving three USDA Technology Transfer awards. However, the success story of CMMD in western pome fruit orchards is only partially complete. The successful growth in implementation of mating disruption, made possible by CAMP, is only the first step in an ongoing process to implement a dramatic new approach to pest management in western orchards. Although 40% of all pome fruit acres are treated with CMMD in the west, most required one or two OP insecticide applications to supplement CMMD (Table 1). Implementation of FQPA will most likely eliminate the use of most of the insecticides used currently for supplemental control (Whalon et al. 1999). In addition, their continued use is a barrier to a greater expression of biological control in orchards (Croft 1990). While there is great potential to expand the acreage using CMMD, several factors represent barriers not only to expanding the use of this technology, but may also threaten the advances that have been achieved. Additionally, almost 200,000 acres of walnuts remained largely unaffected by CAMP projects, because new techniques

Table 1. Data from CAMP sites 1995-1999.

Location (crop) and Year	Average CM per trap per year	Percent fruit injury by CM	Avg. no. insecticide applications for CM per acre	Avg. no. pheromone dispensers per acre	Percent fruit injury by LR (damage by other insects)
Randall Island, CA (Pear)					
1995	59.7	0.71	1.0	800	0.21
1996	36.0	0.16	0.8	400	0.31
1997	78.2	0.24	1.0	400	0.53
1998	12.9	0.01	1.3	400	0.01
1999	13.6	0.05	0.9	<400	0.14
Medford, OR (Pear/Apple)					
1995	3.1	0.26	0.7	400	0.45 (0.82)
1996	1.4	0.04	0.9	400	0.32 (1.23)
1997	3.5	0.09	1.0	400	0.23 (1.84)
1998	7.7	0.16	1.5	375	0.58 (2.44)
1999	4.2	0.08	1.1	365	0.06 (0.70)
Lake Osoyoos, WA (Apple)					

1995	4.3	0.22	2.2	400	1.00
1996	0.8	0.04	1.8	400	0.36
1997	0.3	0.06	0.2	400	0.37 (0.4)
1998	0.2	0.07	0.0	295	0.44 (0.8)
1999	0.3	0.03	0.02	259	0.75 (1.0)
Howard Flat, WA (Apple)					
1995	8.8	0.55	1.7	400	0.00
1996	1.5	0.20	1.1	390	0.21 (0.00)
1997	0.8	0.01	0.7	275	0.14 (0.19)
1998	0.8	0.02	0.5	250	0.09 (0.51)
1999	0.5	0.03	0.3*	225	0.71 (0.08)
Parker Heights, WA (Apple/Pear)					
1995	5.8	0.20	3.1	400	0.23 (0.8)
1996	2.8	0.08	1.0	400	0.15 (1.6)
1997	2.0	0.05	1.0	400	0.03 (0.6)
1998	4.2	0.18	1.0	200	0.12 (0.9)
1999	3.2	0.67	0.2	200	0.37 (0.6)

* estimated data; records not complete.

need to be developed for the large-canopied walnut trees, and more extensive work is required for technology transfer to a new cropping system. Therefore, 60% of the apples and pears (165,000 acres) and virtually all of the walnut acres (ca. 200,000 acres) need to be included in this revolution in tree fruit IPM practices. The successful inclusion of these acres will require developing new pheromone delivery approaches, improving efficacy of mating disruption in marginal situations, reducing the risk and costs of the programs, and harvesting the potential benefits of enhanced biological control of secondary pests.

Secondary pests have the potential to cause crop loss in orchards using CMMD and thus undermine further adoption. For example, leafrollers were the most consistent secondary pest causing fruit injury in apple orchards using CMMD (Knight 1995, Gut and Brunner 1998, Table 1). Alternatives to broad-spectrum insecticides for managing leafrollers are limited. *Bacillus thuringiensis* (Bt) insecticides, generally considered compatible with biological control, have been used to control leafrollers (Brunner 1994, Brunner 1995a, b, Brunner et al. 1995, Knight 1997, Knight et al. 1998). Suppression of leafrollers with pheromones has been evaluated (Knight et al. 1998, Knight and Turner 1999, Gut and Brunner 1993) and the potential for enhancing biological control of leafrollers has been examined (Pfannenstiel et al. 2000, Brunner 1996).

Stink bugs have long been established as pests of a variety of economically important crops, including cotton (Toscano and Stern 1976), soybeans (Daugherty et al. 1964), and a variety of tree fruits (Madsen 1950, Borden et al. 1952). The stink bugs, *Euschistus conspersus* and *Chlorochroa ligata* (McGhee et al. 1996), the mullein plant bug, *Campylomma verbasci*, and the boxelder bug, *Leptocoris rubrolineatus*, have caused serious crop loss in pome fruit orchards over the last five years (McGhee and 1998, Brunner et al. 1998). While damage from true bugs and leafrollers is not always associated with reduced use of broad-spectrum insecticides in orchards implementing CMMD, the need to apply additional controls for these pests reduces economic and biological advantages of this technology.

The appearance of a new pest can threaten the stability of pest management systems built on use of multiple selective tactics. In Washington, the emergence of the lacanobia fruitworm, *Lacanobia subjuncta*, as a major new pest represents the vulnerability of CMMD to sudden changes in the pest complex (Landolt 1998). Preliminary data suggest that the lacanobia fruitworm has developed resistance to certain organophosphate and carbamate insecticides (Brunner unpublished). Control of the lacanobia fruitworm relies upon use of broad-spectrum insecticides in summer (Doerr 1999).

The potential for increased biological control of certain apple and pear pests was documented in CAMP. By comparing levels of biological control agents in CAMP sites with similar conventional sites enhanced levels of natural enemies were documented along with reduced densities of pests (Beers et al. 1999). The greatest potential for biological control in orchard systems is with indirect pests (aphids, leafhoppers, leafminer). However, there is untapped potential for enhancing biological control for leafrollers, noctuids, pear psylla, and other pests. Biological control agents for most orchard pests have been identified (Beers et al. 1993), but their activity in orchards, even CMMD orchards, is limited by the continued use of broad-spectrum insecticides

Monitoring and thresholds are key components of any IPM system, but monitoring of CM in mating disrupted orchards has proved a challenge. Use of high-load pheromone lures has provided a means of assessing risk of CM damage in these orchards (Gut and Brunner 1998), but there are too many situations in which this monitoring system does not adequately predict damage. Pheromone-based monitoring systems are limited because they only assess male activity. Improvements in monitoring programs hold great promise with the discovery of powerful food-based attractants for CM and other Lepidoptera (Light et al. unpublished, Landolt 2000). It is highly likely that these non-pheromone attractants will not be compromised by a pheromone-permeated environment and may accurately monitor the activity of males and females.

GOALS and OBJECTIVES:

This proposal builds upon the successful integrated pest management program established in CAMP, primarily by providing a second phase of research and education. Opportunities such as this to radically transform agricultural systems are rare. Significant transformations in management practices usually result from crises or new technologies; both of these are now present in pome fruit production. FQPA represents a crisis in that it brings changes in pest control programs during a time of economic stress. Pheromone-mediated pest control and newly developed groups of selective insecticides represent new technologies. Thus, the time is ripe to harvest the benefits of CAMP and develop the knowledge that will increase and sustain the transition to pheromone-based IPM in orchards throughout the western US.

This proposal establishes four goals, with supporting objectives, as outlined below. Research, demonstration, and education programs proposed here will extend the benefits of CAMP to new producers and to new cropping systems. IPM programs in western fruit orchards will be further transformed from OP-dominated systems to programs that rely on integrated combinations of more environmentally friendly tactics, with CMMD as the foundation. This will require large-scale demonstration plots throughout the western US, and careful study of these plots over several years.

The stability of CMMD can also be increased by further reducing the risk of sustaining crop damage, along with reducing costs of pest management. Monitoring and better timing of pest control interventions are ways to reduce risk and cost. The objectives of this proposal address these issues in three specific ways. Implementation of non-pheromone monitoring methods may provide better predictions of pest densities in mating disrupted orchards reducing the unnecessary use of supplemental controls. Increased efficacy of selective insecticides by modifying feeding or host finding behaviors of pests will help reduce the effects of pesticides on non-target insects. Finally, the development of new pheromone delivery systems may further increase efficacy and reduce the cost of mating disruption. Research on these topics will be conducted in a variety of pest and orchard conditions in three states increasing the opportunities to develop regional as well as local IPM programs.

As the CAMP program was implemented over several years, management of secondary pests became more problematic. Biological control was recognized as an untapped resource for many secondary pests. With diminishing use of broad-spectrum insecticides, biological control of secondary pests, through conservation and manipulation of biological control agents, is becoming a greater possibility. The objectives of this proposal will further enhance biological control in three specific ways. First, the effects of newly developed insecticides on natural enemies will be evaluated, both in the field and in bioassays that are more detailed. Second, orchard groundcover and border vegetation will be manipulated to enhance leafroller and possibly aphid biological control. Third, those elements of the natural ecosystem that support key biological control agents of pear psylla and leafrollers will be characterized, providing the knowledge to engineer agroecosystem diversity to enhance biological control. This research will be conducted in three western states, under a diversity of conditions, which will strengthen the findings and broaden their applicability.

Finally, and most importantly, this proposal will develop the knowledge base that will allow growers and crop consultants to implement the best practices for their particular situations, increasing their level and understanding of IPM. A program of information dissemination using all modern technology (electronic media, internet, etc.) will be developed to keep producers aware of progress in furthering the benefits of CMMD. Intensive workshops on key issues will be held, as well as formal courses for those needing continuing education. Durable products will include manuals on how to establish pheromone-based IPM, and guidelines on conserving and enhancing biological control in orchards Educational programs will be coordinated across the western region and will annually build on the new knowledge that becomes available.

GOAL 1: Stabilize and extend the codling moth mating disruption (CMMD) system to 75% of pome fruit and 25% of walnut acreage in WA, OR and CA.
Obj. 1.1: Evaluate CMMD programs that replace supplemental controls of organophosphates with selective insecticides (oils, IGRs, particle film, microbials, neo-neurotoxins).
Obj. 1.2: Evaluate alternative pheromone delivery technologies for mating disruption (sprayable formulations, aerosol emitters, paraffin emulsion, etc.).
Obj. 1.3: Evaluate new pheromone technology for multi-species mating disruption programs.
Obj. 1.4: Develop and evaluate alternative non-pheromone based monitoring systems.
Obj. 1.5: Evaluate feeding stimulants and baits as tools in a selective control program.

GOAL 2: Double the impact of biological control agents in orchards through the use of selective control tactics.
Obj. 2.1: Evaluate/compare biological control in orchards using mating disruption integrated with other selective tactics.
Obj. 2.2: Develop bioassay methods that predict impacts of selective insecticides on biological control agents.
Obj. 2.3: Develop a risk rating system for conservation of biological control agents in orchards.

GOAL 3: Stabilize the management of specific pest populations through manipulation of orchard ecosystems, including groundcovers and surrounding habitats.
Obj. 3.1: Manage groundcover and near-orchard habitats to promote leafroller natural enemies.
Obj. 3.2: Identify alternative hosts (extra-orchard) for key natural enemies of pear psylla that are suitable for habitat manipulations.
Obj. 3.3: Understand the role of extra-orchard elements as predictors of pest risk from true bugs, and use trap crops, attractants and other tactics to manage these pests.

GOAL 4: Create an integrated educational plan to support the implementation and sustainability of a pheromone-based IPM system for western orchards.
Obj. 4.1: Conduct workshops and intensive courses, establish electronic information dissemination systems, and publish guidelines to support decision makers implementing selective IPM programs.

GOAL 1: Stabilize and extend the codling moth mating disruption (CMMD) system to 75% of pome fruit and 25% of walnut acreage in WA, OR and CA.

Obj. 1.1: Evaluate CMMD programs that replace supplemental controls of organophosphates with selective insecticides (oils, IGRs, particle film, microbials, neo-neurotoxins).

Maintaining control of the key pest, codling moth, in western orchards is the critical component of pheromone-based IPM programs. In most orchards CMMD must be supplemented with insecticides to prevent unacceptable crop losses. Insecticides currently used are organophosphate or carbamate insecticides (Calkins 1998). However, these broad-spectrum insecticides may be replaced or unavailable in the near future (Whalon et al. 1999). Fortunately, more selective alternative controls such as horticultural-grade petroleum oils (Hilton and VanBuskirk 1999, VanBuskirk et al. 1998, Brunner et al. 1996, Fernandez 2000), biological insecticides (Brunner et al. 1995, Brunner 1994, Knight 1997, Dunley et al. 2000), insect growth regulators (Van Steenwyk and Fouche 1996a, b, Brunner 1998, Gut et al. 1996), and other novel chemistries (Brunner and Bisabri 1998, Glenn et al. 2000, Unruh et al. 2000, Knight et al. 2000, Dunley et al. 2000) already are or are being registered for use in pome fruit. However, grower experience in using these pest control tools has been limited either by perceptions that the approaches are too risky or because they are new (recently registered). This objective will compare a "novel" pest control program using only selective insecticides with a "conventional" program using organophosphate or carbamate insecticides. This will contrast the relative efficacy, economic value, and benefit for biological control (Obj. 2.1).

Obj. 1.2: Evaluate alternative pheromone delivery technologies for mating disruption (sprayable formulations, aerosol emitters, paraffin emulsion, etc.).

New technologies for dispensing pheromones in orchards are needed to reduce the cost of mating disruption, increase grower flexibility in integrating this approach with other tactics, improve efficacy, and allow implementation in different cropping systems with different canopy structures. New pheromone delivery systems are being developed that may operate different on the insect. These include: 1) aerosol emitters that emit high amount of pheromone from few point sources (Shorey and Gerber 1996, Baker et al. 1997, Fadamiro and Baker 1999, Issacs et al. 1999); 2) sprayable formulations; and 3) attract and kill approaches (Charmillot et al. 1996, Charmillot et al. 2000, Losel et al. 2000).

The aerosol emitters are placed at a low density (expected to be less than 1 per acre), but the final emitter density is determined largely by orchard geometry (perimeter and shape). Because emitter density is much lower than hand-applied dispensers (200-1000 per acre) placement into the canopy of mature walnut trees is logistically more feasible. Studies to date with aerosol emitters for control of codling moth have had mixed, but promising results. Using an areawide approach in 1999 in California, almost 700 acres of pear were treated with emitters and had less than 0.1% damage (Shorey and Elkins 1999). Knight (1999) demonstrated similar positive results using pheromone emitters and a reduced OP control program in Washington apple.

In tall (> 30 feet) tree canopies, such as mature walnut, optimal placement of pheromones is very difficult. Other techniques may be required, such as sprayable formulations. Sprayable formulations of the CM pheromone are now under development by 3M and Consep companies. Research in 1999 with the 3M product suggested that 2- 6 weeks of efficacy might be possible. The most promising aspects of the sprayable formulations may be their potential for aerial applications and flexibility to design control programs for multiple species using different tactics.

Point sources of sex pheromone and insecticides can be used to remove males from the population in an "attract and kill" technology. This approach has been evaluated in several European countries and recently a product (Last Call CM) has been registered in the US. Attract and kill technologies show promise for treating small orchards, hilly or windy sites, areas near bin piles, or orchard borders under mating disruption or in combination with selective insecticides.

Obj. 1.3 Evaluate new pheromone technology for multi-species mating disruption programs.

To further reduce the need for OP insecticides in tree fruit, non-insecticidal tactics such as MD should be developed for other target pests. While mating disruption for codling moth has proven successful in tree fruits, the management tactic has yet to be fully developed for other important tortricid pests, such as the oblique-banded leafroller (OBLR), *Choristoneura rosaceana*, and *Pandemis* leafrollers (Beers et al. 1993). Following the adoption of CMMD and major reductions in use of broad-spectrum insecticides, these pests became a greater problem and in some cases threatened the continuation of pheromone-based programs (Knight 1995, Gut and Brunner 1998). Growers initially responded to the presence of leafrollers with summer use of OP insecticides. However, because of the impact of OP use in summer on biocontrol (Knight 1994) and insecticide resistance in leafrollers (Dunley et al. 2000) growers have looked for alternatives. One effect has been an increased use of Bt insecticides over the past five years (NASS 1996, 1998). Bts are only moderately effective against leafrollers and sublethal effects on larval developmental have caused problems in monitoring summer populations and timing spray decisions (Brunner 1994, Brunner 1995a, b, Brunner et al. 1995, Knight 1997, Knight et al. 1998).

Mating disruption for leafrollers has been attempted with mixed results (Gut and Brunner 1993, Knight et al. 1997, Knight et al. 1998). An areawide OBLR and CM MD project was implemented on apple on more than 500 acres near Brewster, WA, in 1998. This project uses a dual-dispenser (combined CM and LR pheromone, Isomate-C SPECIAL) produced by Pacific Biocontrol similar to their CM-only dispenser. The program has met grower expectations, but the CM pheromone releases at a faster rate when combined with the OBLR pheromone and does not provide season-long control. While in need of improvements, this program demonstrates that leafroller MD has potential to become an important IPM tactic.

Development of other pheromone delivery techniques for CM may also be amenable for use against leafrollers and other pests. Use of aerosol emitters (Obj. 1.2) may simplify placement of dispensers with pheromones for multiple species (e.g., CM and leafrollers). Additionally, sprayable pheromone technologies may provide an easy means of implementing MD of multiple species.

Mating disruption may also be appropriate for other non-lepidopterous orchard pests. The sex pheromones of some true bug species have been identified and developed for use in monitoring programs. However, the natural histories of some true bugs may limit the utility of this tactic (McBrien and Millar 1999). Currently, sex pheromones are being identified for grape mealybug, *Pseudococcus maritimus* (J. Millar, pers. comm.). This pest and others with similar biology, such as San Jose scale, are potential targets of future MD programs.

Obj. 1.4: Develop and evaluate alternative non-pheromone based monitoring systems.

Presently, monitoring of codling moth and leafrollers in commercial apple and pear orchards is conducted using sex pheromone-baited traps that attract males. These traps have been useful for timing insecticide applications but have been problematic in relating trap catches to larval populations or damage levels. Similar problems exist with pheromone traps for lacanobia fruitworm. Additionally, when pheromone traps are used in mating disrupted orchards, catch and interpretation of catch becomes even more difficult.

There are new chemical attractants for moth pests of apple and pear that remain effective under mating disruption and may provide better indicators of populations or damage risk because they are attractive to females and males. These new attractants include a pear chemical (kairomone) that is attractive to both sexes of codling moth, and a set of feeding attractants that are attractive to noctuid pests (Landolt 2000, Hitchcox 2000) as well as leafrollers and codling moth (P. Landolt, unpublished data). These chemical attractants are currently being developed both as lures for monitoring moths and as baits for use as new pest control technologies. Much work has already been completed to develop suitable formulations, optimize attractant dose, select suitable traps, and, in the case of the noctuid attractant, to compare the new attractant to other monitoring methods (Hitchcox 2000).

Obj. 1.5: Evaluate feeding stimulants and baits as tools in a selective control program.

The selectivity of pesticide programs can be further enhanced by a variety of approaches such as selective placement, improved application techniques, or use of feeding stimulants (Hull and Beers 1985). Each of these approaches has the potential to reduce the level of pesticides required to achieve commercially acceptable control. Examples include baits used for control of corn rootworm (Metcalf et al. 1987), attract and kill systems for codling moth (Charmillot et al 2000) and bait sprays for tropical fruit flies (Steiner 1952). There are several non-pheromone attractants and stimulants that could be useful against apple and pear pests. A host kairomone has been discovered in pear (Light et al. unpublished) that is attractive to both sexes of the codling moth, raising the prospect of developing and attract and kill product. Additionally, several chemical blends isolated from fermented sweet baits are attractive to males and females of both noctuid and tortricid moths (Landolt 2000). Research is underway with all of these systems to develop pest control technologies for use in orchard IPM.

Recent developments with phagostimulants represent new opportunities for increased pesticide efficacy. This is especially true for most newly registered insecticides that require ingestion to be effective. Many chemicals have been found to stimulate feeding in larval Lepidoptera. These chemicals are mostly sugars (Meisner et al. 1972), amino acids (Ascher, et al. 1976), cyclic nucleotides (Ma and Kubo 1977), and numerous secondary plant chemicals (De Boer et al. 1992). Non-sugar feeding stimulants have been discovered for codling moth that might increase ingestion of pesticides and thus improve efficacy (J. J. Brown et al., unpublished). Under experimental conditions the potential phagostimulants are usually examined by evaluation of amount of food ingested in choice or non-choice tests. It has been reported that Bt insecticide efficacy increased when a feeding stimulant was added to a commercial formulation (Brownbridge 1993). Preliminary data also indicate that mortality can be increased by a factor of 6 from exposure to spinosad with feeding stimulants (J. J. Brown, unpublished).

There are other possibilities for managing insect populations by modifying feeding behavior. These include use of non-host plant volatiles that mask the host plant cues, and physical masking agents, such as particle film (kaolin), that effectively reduce pest populations and crop loss. Chemical repellants or irritants also have the potential to modify insect behavior, and their potential as pest management tactics should be examined.

GOAL 2: Double the impact of biological control agents in orchards through the use of selective control tactics.

Obj. 2.1: Evaluate/compare biological control in orchards using mating disruption integrated with other selective tactics.

Delaying application of pest controls until pest densities reach the action threshold is a fundamental tenet of IPM(Stern 1973). In "second level IPM" (Prokopy et al. 1996), treatment thresholds are raised (relaxed) by accounting for a lower pest population growth rate from the activity natural enemies and use of less disruptive, and possibly less efficacious, insecticides. A primary challenge in transitioning pome fruit production in the western US into "second level IPM" is the dearth of reliable economic injury levels for most secondary pests. This lack of information is due to a long history of broad-spectrum insecticide use dictated by codling moth control, highly diverse agronomic practices, incomplete information on the efficacy of new selective products, and the interaction of all these with indirect damage caused by most secondary pests (Beers 1991). The relationship between pest and natural enemy abundance on pest population growth trajectories is even more poorly known, with the notable exception of tetranychid mite management (Tanigoshi et al. 1983), which further hinders this transition. Fortunately, recent experiences gained in CAMP and smaller experimental and comparative studies show that pesticide control of secondary pests can either be reduced, or replaced with selective pesticides, in the absence of rigorous thresholds and a quantitative understanding of natural enemy activity. We propose methods below to evaluate the enhanced benefits of biological control in a “novel” management regime as described in Obj 1.1. Data will provide the basis to liberalize the conservative action thresholds presently in use and add to our understanding of the natural enemy/pest ratios on pest populations. These data will also provide information to validate bioassay results developed in Obj. 2.2, and form part of the database supporting development of a risk-rating system for biological control proposed in Obj. 2.3.

Obj. 2.2: Develop bioassay methods that predict impacts of selective insecticides on biological control agents.

One of the primary goals of modern integrated pest management is the intelligent and rational use of selective pesticides to minimize impacts on non-target species, particularly those that provide biological control of secondary pests. Acute toxicity tests have been the traditional bioassay method for assessing the impact of broad-spectrum neurotoxic insecticides on natural enemies (Croft 1990; Jepson 1993). However, the new generation of insecticides that will replace products at risk from FQPA implementation are more likely to cause significant sublethal effects than acute toxicity (Jepson 1993; Sibly 1996). Thus, an important challenge in this project is to develop novel bioassays that expose natural enemies to the multiple routes of insecticide exposure and link individual performance to population effects (Calow et al. 1997; Banken & Stark 1998). The data from these bioassays will be used to develop a risk rating system (Obj. 2.3).

Obj. 2.3: Develop a risk rating system for conservation of biological control agents in orchards.

A challenge in ecotoxicology is to make sure that measurement endpoints derived from bioassays of toxicants can be used effectively to protect ecological systems (Calow 1998). IPM decision-makers need simplified information that supports decisions about the use of selective chemical tactics in relation to both pest species and time of the season. Enhancement of biological control in western orchards is determined by the susceptibility of natural enemies to chemical tactics as well as their likelihood of exposure (Stark et al. 1995). Thus, data to be obtained from both the ecotoxicity tests (Obj. 2.2) and the larger-scale field evaluations (Obj. 2.1) will need to be integrated into an effective risk rating system for the selective chemical tactics.

GOAL 3: Stabilize the management of specific pest populations through manipulation of orchard ecosystems, including groundcovers and surrounding habitats.

Obj. 3.1: Manage groundcover and near-orchard habitats to promote leafroller natural enemies.

Several species of parasitoids have been identified from leafroller pests of tree fruits in the Pacific Northwest (Beers et al. 1993). However, generally low levels of leafroller biological control occur in fruit orchards, probably limited by the use of OP and other broad-spectrum insecticides (Brunner, unpublished). An opportunity exists to modify the orchard environment by replacing broad-spectrum insecticides with selective insecticides that do not impact biological control agents (Obj 1.1). After substituting selective insecticides for broad-spectrum insecticides, parasitoid impact can be further enhanced by managing elements of the orchard ecosystem, both flora and fauna, such as groundcover management.

Groundcover manipulation can result in enhanced biological control of specific pests in orchards and vineyards (Altieri and Schmidt 1985). Mixed plantings may attract different insect groups, both beneficial and detrimental. Groundcover must be specifically evaluated for different crops, environmental conditions, and pest/beneficial associations. For example, legumes have benefited orchard systems by increasing beneficial arthropod densities and by aiding in the supply of nitrogen to the soil (Smith et al. 1995).

Several parasitoid species attack *P. pyrusana* and *C. rosaceana* in Washington, including one exotic species (Brunner 1996), which can produce high parasitism rates in some situations (Pfannenstiel et al. 2000). Recent studies show that parasitism during the overwintering leafroller generation, both in western North America (Pfannenstiel et al. 2000) and in Europe (Evenhuis and Vlug 1983), is limited by the absence of an overwintering host for parasitoids in or near orchards. They stated that identification of overwintering hosts is likely to lead to a solution to inadequate leafroller biological control. Recent studies in Washington show that *Ancylis comptana*, *Xenotemna pallorana*, and two other leafrollers are overwintering hosts of the exotic parasitoid, *Colpoclypeus florus*. *Ancylis*, a strawberry leafroller from Europe, occurs sporadically on both garden strawberries and Wood's rose, a native to the Northwest, and is parasitized by *Colpoclypeus florus* in late fall as large larvae prepare to overwinter. Studies show a sharp drop in parasitism rates in orchards in spring with increasing distance from roses that harbored *Ancylis* and *Colpoclypeus* the previous fall (Pfannenstiel et al. 2000). *Xenotemna*, a native species, is a leafroller found sporadically in alfalfa in central Washington and has been shown experimentally to be a suitable host for *C. florus* in apple orchards (Nobbs 1997). Alfalfa is sometimes used as a green mulch and ground cover in organic apple and pears. As yet unidentified leafrollers feeding on red osier dogwood and on cottonwood have also been found to support *C. florus* in fall. The selective manipulation of flora and fauna in situations such as these may augment biological control of leafrollers in orchards using selective control programs.

Obj. 3.2: Identify alternative hosts (extra-orchard) for key natural enemies of pear psylla that are suitable for habitat manipulations.

In the absence of broad-spectrum insecticide use, pear and apple orchards in the Pacific Northwest are characterized by a diversity of predatory and parasitic arthropods (Westigard et al. 1968). For many predator species, it is known (Horton and Lewis 2000, Miliczky et al. 2000) or inferred (Gut et al. 1982) that adjacent, non-orchard habitats are a source of arthropods moving into orchards. However, with some exceptions (Horton and Lewis 2000), it remains to be determined what specific plant species outside of the orchard are the important sources of natural enemies in orchards. These basic ecological relationships must be examined before manipulation of plant habitats (e.g., by creating hedgerows, by adding ground covers or windbreaks, or by conserving plant species in neighboring habitats [Pickett and Bugg 1998; Barbosa 1998]) has an opportunity to be successful. For example, Horton and Lewis (2000) showed that a gall forming aphids on poplar windbreaks (*Populus nigra*) are important hosts for two heteropteran predators of pear psylla. Similar information is available for other tree species supporting these and related predatory bugs (Horton and Lewis 2000). However, much less is known about what alternative habitats support other beneficial taxa, including members of the Coccinellidae, Neuroptera, Nabidae, Syrphidae, Araneidae, and the parasitoid *Trechnites psyllae*, all of which are potentially important natural enemies in orchards.

Objectives of this research are to identify what plant species in habitats surrounding pear growing regions of the Pacific Northwest are sources of natural enemies moving into orchards and to describe seasonal use of orchard and non-orchard host plants by important natural enemies of pear psylla (Horton and Lewis 2000).

Obj. 3.3: Understand the role of extra-orchard elements as predictors of pest risk from true bugs, and use trap crops, attractants and other tactics to manage these pests.

In the apple and pear production areas of the western US, stink bugs have historically been regarded as sporadic or secondary pests (Beers et al. 1993). In recent years, however, crop losses attributed to stink bug and other true bugs have increased (McGhee et al. 1996, VanBuskirk et al. 1999, Brunner, unpublished). The primary stink bug species involved are *Euschistus conspersus*, *Chlorochroa ligata*, *Acrosternum hilare* and *Thyanta pallidovirens.* Stink bugs are not residents of orchards but spend most of their life cycle in native plant habitats, invading orchards to feed on fruit only during certain times of the year, usually near harvest. Therefore, management options must take into consideration how to mitigate stink bug populations in native plant habitats, or how to prevent movement into orchards.

Despite the importance of stink bugs as agricultural pests, few pheromones have been identified for phytophagous stink bugs (McBrien and Millar 1999), and only one has been commercialized (for *E. conspersus*). For the few species studied, pheromone components generally appear to be produced by mature males from patches of unicellular glands (Borges et al. 1987, Evans et al. 1990) rather than from discrete, macroscopic glands that can be readily dissected for analysis. Identification and synthesis of the sex pheromones of five major stink bug pests in the western US, including *Thyanta pallidovirens* (Millar 1997, McBrien et al. 1998), *Acrosternum hilare* (Millar et al. 1998, McBrien and Millar, manuscript in prep.), and 3 *Chlorochroa* spp. (Ho 2000) have recently been accomplished.

Use of aggregation or sex pheromones, attractive plants, new trap designs, or combinations thereof, along with selective insecticides, needs to be evaluated as management tactics. Bugs are often found near traps (Aldrich et al. 1991) but do not enter traps in large numbers, or may enter and leave (Zalom 1992). Certain plants, e.g. *Verbascum thapsus*, appear to enhance aggregation of *E. conspersus,* suggesting that plant volatiles might be important synergists with pheromones in influencing stink bug behavior (Brunner, unpublished).

GOAL 4: Create an integrated educational plan to support the implementation and sustainability of a pheromone-based IPM system for western orchards.

Obj. 4.1: Conduct workshops and intensive courses, establish electronic information dissemination systems, and publish guidelines to support decision makers implementing selective IPM programs.

The "Strategic Plan for Apple IPM in the Western United States" (Appendix A for the introduction and priority areas of research, education, and regulatory actions identified) identifies as high priority needs the research and educational objectives outlined in this proposal. In order to foster continued adoption of pheromone-based pest management, information on new monitoring methods and successful alternative tactics identified by researchers should be conveyed to growers in a timely fashion. Pheromone-based pest management represents a fundamental shift in the knowledge base and management inputs needed by growers and professional crop consultants. Research and extension personnel will have to take advantage of all new information exchange methods to meet this demand in order to ensure the successful implementation and continuation of evolving pheromone-based IPM programs.

RELEVANCE AND SIGNIFICANCE

This proposal specifically addresses issues outlined in the IFAFS section 14.5 Critical and Emerging Pest Management Challenges. This section addresses the critical importance of cropping systems at risk under FQPA implementation. Apple and pear are at the top of the list of foods in the diets of infants and children (NAS 1993).

This proposal is multi-state, multi-institutional and multi-disciplinary, all priority setting issues for IFAFS. It addresses the needs of small and medium-sized producers by continuing to develop areawide management concepts that allow these growers to take advantage of technology that works better when employed over large, multi-farm sites. The benefits of CAMP, which this proposal seeks to build upon, worked with growers whose average farm size was 45 acres, and many farms were in the range of 10 to 30 acres.

The research and educational programs in this proposal will significantly reduce use of broad-spectrum pesticides, providing a safer workplace for farm workers and reducing environmental impact. The economics of CAMP demonstrated that a pheromone-based IPM system could be economical compared to traditional practices. This proposal would enhance benefits of biological control in orchards, establishing a low-cost renewable resource based management system that will be cost effective for the producer and sustainable over time.

This project will provide the research and educational base for transforming western orchard management practices that have been in place for over 35 years. New practices will provide a sustainable, economical and safer pest management system that will help US agriculture compete in a global economy.

APPROACH

The four goals of our proposal will be met using a combination of jointly coordinated projects across all three states, as well as more focused experiments conducted in more limited areas. As new findings and techniques are developed within individual regions, these results will be incorporated into later, more expansive projects across the regions. This coordinated research will allow a better division of labor and use of individual expertise, as well as capitalizing on the diversity of conditions and environments occurring in the western US.

GOAL 1: Stabilize and extend the codling moth mating disruption (CMMD) system to 75% of pome fruit and 25% of walnut acreage in WA, OR and CA.

Obj. 1.1: Evaluate CMMD programs that replace supplemental controls of organophosphates with selective insecticides (oils, IGRs, particle film, microbials, neo-neurotoxins).

Study sites will be established in each major western pome fruit production region of the three states of Washington (8), Oregon (4) and California (4). Study sites will be contiguous 150-200 acres comprised of apple only, apple and pear, or pear only. CMMD will be applied to the entire area at each site as part of the growers' normal practice. Such sites are plentiful following the success of CAMP. Two supplemental treatment regimes will be standardized on each area, a "conventional" regime using broad-spectrum insecticides plus CMMD and a "novel" regime using selective insecticides plus CMMD. The "novel" treatment regime will eliminate use of OP, carbamate (including carbaryl traditionally used as a thinning agent for apples), chlorinated hydrocarbon and synthetic pyrethroid insecticides. Products used will include but not be limited to Bts (e.g. Dipel WDG, Javelin), tebufenozide (Confirm), spinosad (Success), horticultural mineral oil, imidacloprid (Provado), indoxacarb (Avaunt), pyriproxyfen (Esteem) and particle film (Surround). The "novel" treatment regime will be specified prior to the initiation of the project as newly registered products could be available within a year. Treatment regimes will be replicated (3 to 4 per site) within each site and across sites within a state. General pest monitoring will be conducted in each study site using protocols developed in the CAMP study. A smaller (7 to 10 acres) site within each replicate (replicates to be 20-30 acres) will be identified for intensive monitoring of selected pests and natural enemies. Pests to be monitored include codling moth, leafrollers, leafminer, spider mites, aphids and pear psylla (pear only). These pests represent key components or representatives of key pest groups that will reflect the efficacy of different treatment regimes and the impact of these regimes on natural enemy and secondary pest populations (Obj. 2.1).

A pest control advisor will be selected to work with growers in each study site to manage pest control programs, collect treatment records and assist a state coordinator in collecting pest and beneficial insect data. Pest densities will be monitored using traps, foliage samples and visual examinations following established protocols. Impact of pests will be evaluated by examining fruit at harvest for damage in each treatment regime. Different study sites can be compared for trends in data over time. Data on cost of programs and crop damage will be analyzed by an economist to determine the overall impact of the treatment regimes on grower profitability.

It is expected that there will be measurable differences in pest densities in the different treatment regimes within and between years. The goal will be to maintain key pest densities within acceptable limits in both treatment regimes. Secondary pest densities will be maintained below treatment thresholds but control measures for secondary pests are expected to be different between treatment regimes. Study sites will be used for demonstration field tours to discuss with growers options for replacing conventional insecticides (Obj. 4.1). Results from study sites will be used in workshops and popular publications to share experiences with growers not actively involved in the project.

Obj. 1.2: Evaluate alternative pheromone delivery technologies for mating disruption (sprayable formulations, aerosol emitters, paraffin emulsion, etc.).

A series of layered studies ranging from physiological to whole-orchard level studies will be used to determine orchard and program traits that key to program success. Behavioral assays will include research using portable electroantennograms (Milli et al. 1997, Witzgall et al. 2000), tethered virgin females, and release of sterile marked codling moths from the Sterile Insect Release program in Penticton, Canada. Small plot work will be conducted in the first years of this grant as successful program parameters are defined: 1) duration of application, 2) appropriate application techniques (e.g. number of units/droplets per ha), and 3) spatial pattern of the various delivery devices. In addition, environmental and orchard conditions will be correlated in early research efforts for subsequent study (e.g. wind conditions, orchard canopy structure and spacing and orchard topography). These studies will be replicated across states so as to maximize replication and the range of conditions found in the 3 western US states. Interactions between program performance and biological parameters such as moth pressure will be one significant variable compared across and within states given the dramatic inter-regional variability in moth densities. As programs further develop, larger research plots (20 acres) will be used to mimic more realistic grower situations and to enhance grower adoption as demonstration plots. This stepping stone model from small, carefully manipulated trials to larger, demonstration plots proved key to earlier success with CMMD program implementation.

Obj. 1.3: Evaluate new pheromone technology for multi-species mating disruption programs.

Leafroller MD programs will be established in combination with CMMD programs at five sites: three in WA, one in OR, and one in CA. Because of the longer research history with this product, Dual-dispensers will be used in 2001, based on the Isomate-C Special dispenser (Pacific Biocontrol). Comparison blocks will be established using CMMD only. Efficacy of CM and leafroller MD programs will be monitored throughout the season.

New technologies such as aerosol dispensers and sprayable pheromones will be evaluated for use in multiple-species MD. Test sites will be established in each of the three states, such that several levels of pest pressure from leafrollers and codling moth will be represented. Comparisons will be made with the Isomate-C Special dispensers, which currently appears closest to commercial application.

Preliminary studies will be made to determine the feasibility of using true bug pheromones for mating disruption. Specifically, examination will be made of pheromones developed in Obj. 3.3.

Obj. 1.4: Develop and evaluate alternative non-pheromone based monitoring systems.

Developmental work that needs to be completed includes experiments to relate captures of moths to moth phenology, larval density, and crop damage. This will include field experiments in which multiple monitoring methods are conducted to relate captures of moths in attractant traps with phenological events in the life history of the insect, such as mating, ovarian development, oviposition, and egg hatch. This information will be used to validate degree day models, as has been done for codling moth relative to the capture of males in pheromone traps. Some of this work has been conducted for the lacanobia fruitworm attracted to acetic acid and isoamyl alcohol, but needs to be done for *Pandemis* and oblique-banded leafrollers attracted to acetic acid, and for codling moth attracted to the pear kairomone and for codling moth attracted to a chemical feeding attractant. Experiments to relate trap captures to subsequent larval populations and to fruit damage will be conducted for each attractant and pest discussed here, with monitoring traps maintained in orchards providing a broad range of population pressures and during early and late season generations. Trap catch data for females and males will be analyzed for correlation with larval densities and fruit damage. Larval populations will be assessed visually for codling moth and leafroller larvae and by limb taps for lacanobia fruitworm larvae. The efficacy of the kairomonal lure for codling moth will be evaluated in Washington and California in pome fruits and walnuts. Sets of lures using the CM kairomone lure at various rates will be contrasted within orchards to the traditional 10 mg lure baited with codlemone for attraction to codling moth. Releases of sterilized codling moth will be made in various orchards in the 2 states so as to homogenize the pressure between sites.

Obj. 1.5: Evaluate feeding stimulants and baits as tools in a selective control program.

Three promising additives for enhancing the uptake of either spinosad or azinphosmethyl have been identified. These include inositol, monosodium glutamate (MSG) and saccharin. Laboratory assays suggest saccharin can improve the efficacy some products, such as spinosad, by 6-fold and double the mortality of neonates exposed to very low rates of azinphosmethyl. Following additional laboratory screenings of potential feeding stimulants, semi-field tests will be conducted. Pesticide formulations enhanced with feeding stimulants will be applied to apple foliage and fruit. Samples of foliage and fruit will be removed at intervals following application and larvae of CM, OBLR and lacanobia fruitworm exposed to residues in the laboratory. Based on semi-field tests large plot field trial will be established to asses seasonal control under grower conditions and to determine if enhanced formulations cause adverse effects, i.e. fruit russet.

Experiments are planned to test several prototype bait stations in apple orchards for assessments of effectiveness in killing attracted moths (leafrollers, CM and lacanobia fruitworm). Moth populations, eggs, larval densities and fruit damage will be assessed in orchard blocks with different densities of bait stations and compared to untreated controls. The best combination of bait station type and station density for each insect will be selected to incorporate into a pest management program where bait stations will be compared with conventional tactics for pest control. This work will be done independently for codling moth, leafrollers, lacanobia fruitworm and other noctuid pests.

GOAL 2: Double the impact of biological control agents in orchards through the use of selective control tactics.

Obj. 2.1: Evaluate/compare biological control in orchards using mating disruption integrated with other selective tactics.

Monitoring of biocontrol of flagship guilds: Pest population abundance data provided in Obj. 1.1 will be supplemented with additional sampling of 4 natural enemy guilds because their hosts/prey are abundant, they have 3 or more generations per season, and they can be monitored efficiently. The most important secondary pests, the leafroller complex, will be addressed in Obj. 3.1. Guilds include predators of tetranychid mites, the parasitoid complex of the western tentiform leafminer, predators of the apple aphid complex and parasitoids of rosy apple aphid, and predators and parasitoids of pear psylla. Specific methods include leaf collection and brushing for the mite complex, leaf collection and dissection for the leafminer parasitoids, beat tray sampling for predator abundance of aphids and pear psylla, leaf cluster analyses of parasitism rates of rosy apple aphid, and dissection of psylla nymphs for parasitism. These methods are in common use in one or more of the participating laboratories.

Sleeve cage evaluation of natural enemy effects on population growth: Experimental methods of evaluating natural enemy impact on pest populations include life table analyses (Bellows and VanDriesche 1999), various augmentation and exclusion methods, and assorted serological and molecular methods (Agusti et al. 1999, Luck et al. 1999). We have chosen the most traditional of these, sleeve cage exclusions, to demonstrate natural enemy impact on the 4 flagship guilds. Replicated open and closed sleeve cages will be deployed twice each season for each of the 4 guilds. The method reduces the effect of variation in pest abundance on evaluations of natural enemies, from which the correlative method of field monitoring of flagship guilds suffers.

Obj. 2.2: Develop bioassay methods that predict impacts of selective insecticides on biological control agents.

A three-tiered system will be used to develop effective bioassays of the impact of selective insecticides on natural enemies. Tier 1 will be simple acute toxicity assays with model natural enemies (NEs), Tier 2 will relate component factors to population growth rates in laboratory assays and microcosms of intermediate complexity also with model NEs, and Tier 3 will repeat the Tier 2 testing with key species found in western apple and pear orchards. Field verification will be obtained from Objective 2.1.

Five species will be used as model natural enemies to represent the taxonomic range of natural enemies found in western orchards: a mite predator (*Galandromus occidentalis*), a green lacewing (*Chrysoperla carnea*), a minute pirate bug (*Orius tristicolor*), and two parasitoids (*Trichogramma platneri* and *Colpoclypeus florus*). Four species have been extensively tested for insecticide tolerances by the IOBC/IOLB working group on Pesticides and Beneficial Insects (Hassan et al. 1991) and are readily available from commercial insectaries. The fifth species, *C. florus*, in readily reared in large numbers for bioassay testing. Insecticides to be tested will include products identified as potential alternatives to OP insecticides in the recently prepared FQPA transition document for apples (Brunner, unpublished). Acute toxicities are already known for many registered insecticides from the European work.

The acute toxicity assay will be a conventional test exposing natural enemies for fixed periods of time (from 7 to 14 days) to fresh, dry, residues of each test product under constant environmental conditions. The products will be applied to glass plates or leaves at the highest field rates and either prey (for predators) or honey (for parasitoids) provided as supplemental food. Separate tests will be conducted for both juvenile and adult stages of the predators. Life table response experiments (LTRE) are considered the most effective way to estimate demographic responses to toxicants (Sibly 1999). However, the disadvantage of such experiments is the time, labor and expense associated with continuous monitoring of the performance of a cohort of individuals. Following Walthall and Stark (1997), Tier 2 assays will be developed to examine how closely individual life table components for the natural enemies, that are simpler to estimate in laboratory microcosms, compare to population growth rates obtained from a full LTRE. Both sets of estimates will be obtained using laboratory microcosms that include the plant, insect host, and natural enemy, and allow topical, residual, and oral exposure of the natural enemies to each test product applied in a logarithmic series of concentrations. Tier 3 assays will be identical to Tier 2 but will be restricted to products identified as showing significant sublethal effects in Tier 2. Tier 3 tests will be applied to 6 key natural enemies found in apple and pear. These include *Pnigalio flavipes, Trechnites psyllae, Anagrus* sp., *Deraeocoris brevis, Harmonia axyridis,* and *Phidippus* sp. *Galandromus occidentalis*, *C. florus* and *C. carnea*, also important components of orchard systems, are covered in Tier 2.

Obj. 2.3: Develop a risk rating system for conservation of biological control agents in orchards.

There is no universal system that identifies risk to all natural enemies at all times; hence, a risk rating scheme will be developed that compares two different approaches, a risk quotient and a risk index. A risk quotient for each insecticide by species combination can be derived as a ratio of actual use field concentration to the predicted no effect concentration determined from the laboratory bioassays (Obj. 2.2). A risk index for each of the test insecticides, however, will take into account both the susceptibility of the natural enemies and their probability of exposure. The bioassays developed in Obj. 2.2 will show the effect of each insecticide on the survivorship, developmental rate and reproductive capacity of test natural enemies and how these life table components relate to overall population growth rates in microcosms. Based on similarity of life cycles among natural enemies, we will examine the potential to extrapolate susceptibilities determined in laboratory assays for model natural enemy species to a broader range of natural enemy species. Field validation of effects will be derived from Obj. 2.1 for flagship guilds and under Obj 3.1 for leafroller natural enemies. Phenological observations from these studies and Obj. 1.1 will be used to analyze the likelihood of exposure in the field. Field exposure is an important element of a risk index as natural enemies may be able to avoid exposure due to patterns of phenology or activity, despite being susceptible to a particular product.

GOAL 3: Stabilize the management of specific pest populations through manipulation of orchard ecosystems, including groundcovers and surrounding habitats.

Obj. 3.1: Manage groundcover and near-orchard habitats to promote leafroller natural enemies.

Ground cover modification: Ground cover treatments of grass (standard) and alfalfa have been established in large replicated plots (3) in an apple orchard, each plot consisting of approximately 0.5 acres. Baseline data have been collected on leafroller densities and parasite abundance (Brunner, unpublished). Larvae of *Xenotemna pallorana* were seeded in alfalfa in 1999 as an alternate parasitoid host. Leafroller densities will be monitored in each plot and parasitism levels determined in native leafroller populations through transect samples and by placing and recovering sentinel larvae. Sentinels will consist of laboratory reared *P. pyrusana* or *C. rosaceana* deployed directly on orchard trees (Brunner, unpublished).

In one-half of five apple orchards, rows of various commercial strawberry varieties and wild strawberry isolates and will be planted into the grass cover crop, the remaining half being only grass cover. In five other orchards half of the grass ground cover will be replaced with strips or sections of alfalfa. At all sites strawberries will be seeded with *Ancylis* and alfalfa with *X. pallorana* in spring. In midsummer of the same year and spring and midsummer of the following years, transects will examine the relationship between distance from rose/strawberry and parasitism of sentinel leafroller. Sentinels will consist of laboratory reared *P. pyrusana* or *C. rosaceana* deployed directly on orchard trees or potted apple trees as used previously (Pfannenstiel et al. 2000).

Near orchard habitat modification: Hedges of Wood's rose and plots of mixed varieties of strawberries will be planted on one edge of paired orchards during 2001 (5 paired replicates). During the season *Ancylis* will be established in one of the paired blocks, and persistence and parasitism of *Ancylis* will be monitored through the season on both rose and strawberry in both blocks. Also, both rose and strawberry will be sampled through the season to determine if they foster potential pests (see Obj. 3.3). In spring and midsummer of the following years transects will examine the relationship between distance from rose/strawberry and parasitism of sentinel leafroller as described above (Pfannenstiel et al. 2000).

Obj. 3.2: Identify alternative hosts (extra-orchard) for key natural enemies of pear psylla that are suitable for habitat manipulations.

At monthly intervals, orchards and native habitats adjacent to orchards in northern Washington (Wenatchee), central Washington (Yakima), and northern Oregon (Hood River) will be sampled. Beat trays will be used to sample tree and shrub species, and sweep nets will be used to sample understory. Orchards will be sampled by walking a circuit within the orchard so as to monitor all sections of the orchard. Non-orchard habitats will be monitored by extending transects 50-200 meters from the orchards into the neighboring non-orchard habitats. Common trees and shrubs along the transect will be sampled with beating trays; sweep net samples of ground cover will be taken at random intervals along each transect. In each transect, plant taxa sampled, distance from the orchard that the sample is taken, and numbers and types of common predatory arthropods will be recorded. Many years of sampling in the Pacific Northwest have familiarized us with the natural enemy community occurring in orchards (Westigard et al. 1968; Gut et al. 1982; Horton and Lewis 2000; Miliczky et al. 2000), and our samples in non-orchard habitats will be examined most closely for these species. If necessary, immature predators will be collected and reared to the adult stage for identification. The importance of these habitats as overwintering sites for natural enemies will be determined by placing cardboard bands and bundles in trees and shrubs during late autumn and then collecting the traps in mid- to late winter (Horton and Lewis 2000). Timing of movement among host plants or from non-orchard habitats into orchards will be inferred by monitoring seasonal patterns in counts of natural enemies on different host plants and in the orchard (Horton and Lewis 2000).

Obj. 3.3: Understand the role of extra-orchard elements as predictors of pest risk from true bugs, and use trap crops, attractants and other tactics to manage these pests.

Pheromones - Aggregation and sex pheromones to attract stink bugs to plants and/or traps will be evaluated using a method (capillary tube and reservoir, Landolt personal communication) that provides controlled release over a range of rates. Different release rates of stink bug pheromones (provided by Dr. Millar's laboratory) will be associated with "trap plants" and stink bugs counted and removed every other day. Treatments (release rates) will be rotated after each examination, and multiple sites will be used as replicates. Different dispenser types (rubber, plastic, wax matrix, etc.) will be evaluated in the laboratory for release rate characteristics that match optimized rates from previous experiments. Lures with optimized pheromone release rates will be used to evaluate different trap designs that provide desired performance, i.e., capture as many stink bugs as attractive plants (mullein) associated with lures. Different trap shapes, colors and configurations will be evaluated using the replicated design described above to evaluate optimum pheromone release rates.

The effect of plant volatiles will be evaluated using Y-tube olfactometer or wind tunnel behavior studies to document additive or synergistic effects. Different plants will be placed in the air stream to determine if they are attractive. In addition, a blend of "green leaf volatiles," a group of simple six-carbon compounds that are associated with the characteristic odor of most deciduous plants (Metcalf and Metcalf 1992), will be evaluated for attractiveness. Combinations of attractive plants, green leaf volatiles and pheromones will be evaluated alone and together to determine if behavioral effects are additive or synergistic. The number of stink bugs responding to various attractants will be compared to those responding to controls, no attractant or plant material.

Trap crops and attractants – An aggregation pheromone of *E. conspersus* (Aldrich et al., 1991) has been shown to be highly attractive when released from a polyethylene vial cap (Brunner, unpublished). The lure will be associated with plants in the field in a variety of ways to influence the populations of *E. conspersus.* Attractive plants (four species of drought tolerant legumes) will be planted in cultivated and irrigated garden areas near orchards. Three garden areas will be planted at 4 to 5 sites. Gardens will receive treatments of systemic insecticides (imidacloprid), contact insecticides and no insecticides. The number of stink bugs colonizing and life stages occurring in each garden treatment will be evaluated weekly. In addition, the number of parasitized eggs and nymphs will be assessed weekly. Similar studies will be conducted utilizing natural habitats to determine if stink bugs can be aggregated using pheromones and if biological control in these aggregations can be enhanced.

These studies will provide the basis for managing a pest that invades orchards from native habitats. Better monitoring tools will provide a means to assess risk of attack and trap crops could be used to reduce movement of stink bugs into orchards or to kill them prior to mass movements in the fall.

GOAL 4: Create an integrated educational plan to support the implementation and sustainability of a pheromone-based IPM system for western orchards.

Obj. 4.1: Conduct workshops and intensive courses, establish electronic information dissemination systems, and publish guidelines to support decision makers implementing selective IPM programs.

The two main types of workshops that will be used are grower meetings in a classroom setting where research results can be reported and thoroughly discussed, and in-field demonstrations utilizing the field plots in each region (see Obj. 1.1 and 2.1) to provide hands-on instruction in pest monitoring, evaluation of alternative tactics, and assessment of the impact of biocontrol agents. The regional field plots will provide "real world" examples of both the benefits and risks of pheromone-based IPM. Emerging pest problems associated with pheromone-based IPM, e.g. true bugs and leafrollers, vary in intensity from region to region, and the field plots will be utilized to train growers and consultants to identify and manage these potential pests. In-field training will emphasize recognition of key biocontrol agents, and information that is developed on determining the impact of natural enemies on the pest complex will be demonstrated.

A publication will be developed to facilitate the enhancement of biological control in western orchards. The publication will include brief details of the major parasitoids and predators associated with codling moth and secondary pests in pome fruit orchards. In addition, it will summarize the information available on risks to biological control associated with each of the currently registered and probable future products used in pome fruit management in the western region. The guidelines will be published in a grower-oriented journal and will be distributed throughout the western region through workshops, research and grower meetings.

A comprehensive set of tools, including web-based workshops, formal courses, and published management guidelines will be developed and distributed through the western region. Emphasis will be placed on facilitating the use of insecticides that are least disruptive to biological control in pome fruit orchards. Where appropriate, publications, web pages and workshop presentations will be published or presented in English and Spanish.

EVALUATION AND MONITORING

An industry Advisory Committee will be established to annually review progress towards goals and to make specific recommendations to the Executive Committee on changes in emphasis. These recommendations will be shared with industry groups providing matching funds for specific projects as a means of jointly setting research and educational priorities. After the second year of the project an external peer review team will be invited to evaluate the progress made towards goals and offer recommendation on adjustments in planning for years three and four. At the end of the project this same peer review team will be invited to evaluate the accomplishments of the project relative to stated goals and objectives and to submit an independent report that will be a part of the final project report. Specific criteria such as pesticide use reports available from State Agencies, use of pheromone based products from state surveys, and pest damage will be used in part to evaluate program acceptance and utility. Grower surveys have also proven successful tools for identifying program constraints and successes.

COLLABORATIVE ARRANGEMENTS

Several industry commodity groups have agreed to provide matching funding to this proposal (see attached letters). These include the Washington Tree Fruit Research Commission, Walnut Marketing Board (California), Fruit Growers' League (Medford, OR), and the California Pear Board. Funding for specific proposals will be determined through negotiations with the different commission. These commodity commissions have tentatively committed to provide matching of $2.4 million over the four years of this project. If this proposal is funded the commodity commissions above will be a part of the Consortium Executive Committee and help to determine how matching funding would be allocated to specific projects. An accounting of all matching funds will be kept by the commissions and included in annual reports of this project.

Discussions with the Center for Agricultural Partnerships have occurred and there is interest in this organization becoming involved in this project (see attached letter). There have also been discussion with the Winter Pear Control Committee, an industry commodity commission, that supports research on pest management. This board has not yet committed a dollar amount to match the IFAFS proposal but they are supportive of the project.

There will be considerable collaboration with fruit growers, crop consultants, and other industry personnel. Growers participating in this project will be contributing "in-kind" funding through the purchase and application of treatments associated with the "novel" regime outlined in Objective 1.1. The value of this contribution is difficult to assess at this time but will likely total at least $200,000 over the four years of the project.

MANAGEMENT PLAN AND ADMINISTRATION

An Executive Management Committee will be formed consisting of key project personnel from each of the four principal centers. Membership will include the following people; Jay Brunner, John Dunley, Steve Welter, Bob Van Steenwyk, Rick Hilton, Helmut Riedl, Pete Landolt, and Tom Unruh. These individuals represent campus-based faculty, government researchers, and extension specialists from each region. Representatives from industry providing matching financial support will be included as advisory stakeholders. The rough amounts allocated to different institutions (states) and to the different objectives was established in the budget process for the overall proposal. However, specific funding decision for individual projects to meet objectives will be based on detailed proposals submitted by project participants and will be approved by review of the Executive Committee depending on programmatic needs and proposal quality. Proposals that involve an Executive Committee member as lead PI will not have a decision in the funding of their own proposals. Annual reports of progress of individual projects will be required and continued funding based on successful progress towards goals.

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