Interim Report

Biological Control of Arthropod Pests in California Agriculture: Current Status and Future Potential

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Preface

California agriculture is a $32 billion industry and one of the state's leading sources of revenue and employment (2006, http://www.cdfa.ca.gov/files/pdf/card/AgResDirEntire06.pdf). Arthropod pests, both invasive and indigenous, have the potential to cause severe damage to California agricultural industry. Insecticides are commonly used to protect California's agricultural industry from arthropod pests. However, public concerns for contamination of food, water, the environment, and impacts on human health have brought insecticide use under increased scrutiny. Insecticides are among non-point source discharges that will be increasingly regulated and are currently under pressure from the EPA and State and Regional Water Quality Control Boards (under Cal EPA) as a result of implementation of the Food Quality Protection Act (FQPA) and the Clean Water Act (CWA). Thus, alternative control methods to the traditional insecticides must be developed and tested in the near future to maintain an economically viable agricultural industry in California.

Biological control offers a proven management alternative for many arthropod pest problems. Biological control is based upon a fundamental knowledge of the interactions of living organisms, makes use of living natural enemies for the control of pests, and provides a sound ecological basis for pest management in many of California's crop systems. Successful biological control programs can enhance farm and ecosystem sustainability, reduce fuel inputs, and reduce human risk and non-target organism exposure to toxic pesticides.

If biological control can offer clear economic and sustainable control solutions to many arthropod pest problems, then why has there not been greater adoption of potentially successful practices and more research funding to develop new programs?

The following interim report covers two broad areas. First, we attempt to identify organizational and legislative barriers to adoption of biological control with a view to targeting critical needs for research and implementation in California agriculture. Second, we sought to summarize the history and current status of biological control in selected California crops, as well as future constraints and opportunities for these crops.

1) To identify key barriers and opportunities for greater implementation of biological control in pest management in California

Biological, economic, institutional and social factors can be considered as barriers to natural enemy importation. Our ability to select the most effective natural enemy from the region of origin of an invasive pest will be considered, together with current and expected future changes in the federal and state permitting procedures for exotic natural enemies. We will also consider the consequences of FQPA and its impact on the registration of selective reduced risk insecticides. The changes over the last 50 years in California's research programs and personnel in biological control (UC, USDA, CDFA) will be documented, changes in levels of funding support for foreign exploration and quarantine operations will be analyzed from records (UC campuses, commodity funding), and adjustments to the priorities of the different agencies involved (UC, CSU, USDA, CDFA) will be determined. The recent change in social attitudes toward the environment, exotic species and non-target impacts of imported biological control agents will be considered, as well.

Barriers for successful application of mass reared natural enemies include the economies of scale, lack of a "patentable" product or methodology and thus economic sustainability, quality control of the natural enemies produced, linkages and partnerships required in moving from production to implementation, and the greater knowledge base required of all participants. The importance of these perceived barriers was

evaluated by gathering data from in-depth interviews with end users, particularly insectary producers (Association of Natural Biocontrol Producers), commodity research directors, the Organic Farming Research Foundation, and PCAs (particularly those affiliated with the Association of Applied IPM Ecologists). In addition, we analyzed changes in funding support (federal, state, and commodity boards grants) and research efforts (primarily personnel at the UC, CSU, USDA and CDFA) over the last 50 years for augmentative biological control.

One important variable that defines the backdrop for all pest management is the choice and frequency of insecticide applications for key pests. Insecticide programs have varied widely over time, and changes coming as a consequence of the implementation of FQPA and CWA and their impacts on insecticide development, have the potential to increase the opportunities for biological control. Previous assessments that examined the economic impact of the elimination of OP insecticides on California agriculture [Metcalfe et al. 2002. "The economic impact of organophosphates in California agriculture." California Department of Food and Agriculture Report, http://www.cdfa.ca.gov/publications.html] served as the platform for further analysis. Using data from the literature and from the Department of Pesticide Regulation's pesticide use database on historical trends in pesticide use and selectivity of pesticides, the changing pattern of past, present and future opportunities for conservation of natural enemies in production agriculture is being documented.

2) Document historical benefits in key commodities.

The academic and popular literature has been reviewed to document the history of biological control attempts and successes in key agricultural crops in California. The review considered natural enemy importation, periodic releases of mass reared natural enemies and management practices that have been adopted to enhance the activity of natural enemies in these crops. Crops selected for review include annual row crops (cotton and lettuce) and perennial crops (almond, grape, pome fruit, and stone fruit). Information was gathered from the scientific literature, commodity reports, the University of California Integrated Pest Management manuals and project database, the USDA ROBO database of biological control importations, and from the quarantine facilities of UC Berkeley, Davis and Riverside. This will provide a chronologically-organized list of biological control programs over the last 100 years targeting major arthropod pests attacking these key commodities in California.

Our future plans are to use the crop summaries to design a set of categorical descriptions including crop characteristics (value, perennial versus annual, damage tolerance), operational practices (insecticide use, timing, disturbance levels), pest characteristics (taxa, biological traits, phenology), and natural enemy characteristics (taxa, biological traits, past successes). These characteristics will be used as a basis for developing an overall rating of the future potential for biological control. The result will be a description of insect pests and commodities that have "high potential" as targets for biological control. For example, an aphid pest of lettuce that has a low economic injury threshold may be a poor target, while a scale pest in almonds may have greater potential. These ratings can then be used to identify funding priorities or allocation of resources within agencies to crops or target pests which either have the greatest opportunities for success or present the greatest challenges.

The Missing Metrics of Classical Arthropod Biological Control in the USA

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Increasing concerns about potential nontarget effects of classical biological control have prompted efforts to evaluate relative risks, costs and benefits of proposed introductions. This study reviews publicly available data collected to assess classical biological control projects targeting arthropods in the USA. After reviewing recent retrospective analyses of risks, it then examines the use of metrics used to evaluate classical biological control of arthropods. Available data are then presented on biocontrol introductions in 3 states since 1962. Existing record keeping systems were established prior to widespread concern about nontarget effects of introduced control agents, and offer incomplete and inconsistent data for evaluating risks, costs and benefits. No economic analysis of a classical biological control project targeting agricultural arthropod pests has been published in the USA within the past 30 years. Hawaii, California and Florida have been the states hosting the most projects, but rates of introductions in all 3 states have declined over the past 15 years. We discuss the implications of these data and its limitations, and propose strategies for making possible more complete cost/benefit/risk analyses.

Commodifying Insects? Challenges to the Commercialization of Augmentative Biocontrol in Agriculture

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Abstract

Augmentative biological control has been advanced by scientists as an alternative to agrochemical pesticides for many years (suggested by our respondents, and those interviewed by Ridgway and Inscoe 1998; Ridgway, King, and Carillo 1977; Justum 1988; Obrycki, Lewis, and Orr 1997). Parella, Heinz, and Nunney (1992) went so far as to title an article "biological control through augmentative releases of natural enemies: a strategy whose time has come." The cancellation of pesticide registration, rising threat of pesticide resistance, public distaste for pesticides, and expansion of organic agriculture have been proposed as factors favoring augmentative biological control (Ridgway and Inscoe 1998), especially in annual cropping systems (Obrycki, Lewis, and Orr 1997). Some have cited the increasing number of commercial distributors as evidence of growing supply and distribution (Cranshaw, Sclar, and Cooper 1996), and van Lenteren (2003) lists 125 species available worldwide. Economic analyses have determined that the benefit to cost ratio for augmentative biological control can be as high as 3:1 in outdoor settings (Reichelderfer 1981) and 31:1 in a greenhouse (Hussey and Scopes 1985). Our research suggests, however, that augmentative biological control has not, in general, fulfilled its potential – long espoused by biocontrol scientists -- in American production agriculture. Why is this?
In this paper, we conduct the first systematic commodity systems analysis of the stagnating North American commercial insectary industry. This analysis serves as a starting point for understanding biocontrol's unfulfilled potential in production agriculture as it illuminates factors shaping the behavior of the individuals and institutions engaged in commercial natural enemy production, release, and distribution. In doing so, it sheds light on barriers and opportunities to greater economic use of commercial natural enemies as an alternative to hazardous pesticides. Specifically, following on Friedland's (2001) methodological blueprint for commodity systems analysis, we explore the dynamic and synergistic interplay among the nodes of the natural enemy commodity chain, focusing on production, marketing and distribution, science and knowledge and consumption. We situate the entire commodity chain within the current political economic context of agriculture in the United States today.

This analysis allows us to address four fundamental research questions:

1. What are the biological barriers to successful natural enemy production, rearing and distribution and how have they affected the evolution of the commercial insectary industry in North America?
2. How have economic, social, and political factors shaped the contemporary commercial insectary industry in North America?
3. Where, along the natural enemy commodity chain, do we find the key barriers to augmentative biological control achieving its oft-proclaimed potential?
4. What kind of opportunities exist for public policy to assist the industry in this regard?

In answering these questions, we demonstrate the challenges to the commodification of biocontrol, which some have described as "more of an art than a science" and as "unruly and unpredictable" given its basis in nature. Indeed, the organizational and operational processes within the natural enemy commodity chain are constrained by biological forces (Bunker 1989), and as such, natural enemy production serves as an ironic counter-movement to capital's tendency to replace and substitute natural processes and to "squeeze biological constraints out of the production process" (Morgan et al 2006). We focus on empirical examples of challenges to Ridgway's (1977) three proposed biological characteristics for effective augmentation: an ability to rear predictable quantities of insects of known quality; an ability to store, transport, and release the natural enemy in such a manner that it can compete at the release site; and an understanding of the ecological conditions determining the relationship between the enemy and the pest.

More than just being a biological activity, however, the commercial production and release of natural enemies is simultaneously an economic, engineering and social activity, and as such, reflects scientific knowledge, technological know-how, market forces, and personal values. Whereas science and technology constitute one side of the insectary "coin," economic profit constitutes the other. And both perspectives are essential to understanding the functioning and status of this industry. In this paper, we demonstrate that commercial augmentative biological control works when its economic (production and marketing) and biological and engineering (production, handling, shipping and performance of the agent) factors are aligned so as to be simultaneously successful. We outline the major factors that must be coordinated for successful commercial augmentative biological control, and we describe how these factors are linked though social relations in the commodity chain of natural enemy production.

Additionally, we analyze the political economy of the natural enemy commodity chain. On the science and technology side, we found no evidence that any new insect species were being researched by US public agency or land-grant university scientists to be brought to market, nor were we able to identify any researchers devoting a significant portion of their time to the evaluation of new insects for commercialization of natural enemies. And we found no evidence of any institutional initiative to foster better collaboration between researchers and the insectary industry. We contextualize this glaring lack of an individual or institutional research agenda as it contrasts with significant effort and resources being poured into pesticide research, genetic engineering and other areas of pest management.

Our research suggests two overarching socio-economic trends constraining the commercial application of augmentative biological control in California agriculture. First, the economic structure of agricultural pest management is generally atomistic and individualistic. Arthropod pest control decisions are most often made in reference to individual pests, as opposed to an insect complex or agroecosystem, and made by individual growers without regard to the potential benefits of agroecological landscape management. This tendency mitigates against the collaborative and coordinated scientifically-informed approaches necessary for successful augmentative biocontrol strategies, and against a market structure that would support an economically successful commercial insectary industry. Second, the orientation of scientific institutions over the last few decades has turned away from the practical, applied research necessary to support a successful commercial insectary industry. In conclusion, we suggest strategies to counter these trends and to support the development of a more vital commercial insectary industry.

A Socio-Economic Analysis of the North American Insectary Industry and Implications for Augmentative Biological Control

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This article reports the first systematic and independent socio-economic study of the commercial insectary industry in North America, drawing from 62 interviews with insectary leaders, research scientists, retail distributors, and customers. The 22 North American insectaries produce 38 natural enemy species. Commercial natural enemies constitute less than 10% of the biologically based pest control market, with an estimated gross annual value of $25-30 million at the wholesale level. Over the past decade no new insectaries have been established, several insectaries have declared bankruptcy, and only two new species have been brought into production. Producers report that the market for commercial natural enemies generally appears to be static, with declining demand for some species. Prices for at least 6 species have declined since 1994, and several insectaries report having to abandon production lines due to economic losses. Industry leaders report serious difficulties in obtaining capital for investment, researchers who will address applied scientific questions in augmentative biological control, and moving commercial natural enemies across U.S. borders. Realizing the potential of augmentative biological control as a pest management strategy in North America will require new initiatives to address these challenges.

Biological Control of Key Pests in Cotton

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1. Introduction

The United States is one of the biggest growers and is the largest exporter of fine cotton in the world. One-third of world exports of fine cotton are grown in the San Joaquin Valley of California (Estur 2002). With an export value of $513.5 million in 2002, cotton is the number two export of California, second only to almonds (Bervejillo and Sumner 2003). In 2003, there were 700,055 acres of cotton planted in California, 671,555 acres in the San Joaquin Valley, 20,375 acres in the lower desert valleys (Coachella and Imperial) and 7,920 acres in the Sacramento Valley (Adamczyk and Burris 2004).

While many arthropod species inhabit Californian cotton fields, only some are plant feeding, and economic damage can be attributed to a small subgroup of these. In 2003, pest damage destroyed 58,829 bales of cotton, which translated into a $16,942,753 loss. The same year, insecticide applications cost growers $12,454,740 (Williams 2004). The major pest species are *Lygus hesperus* (Het.: Miridae), *Aphis gossypii* (Hom.: Aphididae), *Bemisia argentifolii* (Hom: Aleyrodidae), *Tetranychus* spp. (Acar.: Tetranychidae), and a complex of Lepidoptera including *Pectinophora gossypiella* (Gelechiidae), *Helicoverpa zea*, *H. virescens* and *Spodoptera exigua* (Noctuidae).

The soil inhabiting bacterium, *Bacillus thuringiensis* (Bt), is toxic to many lepidopteran pests. In 1990, Perlak *et al.* inserted genes coding for the proteins responsible for this toxicity into cotton plants. Bt cotton varieties first became available to California growers in 1996 and today, due to its effectiveness against *P. gossypiella*, account for 80% of the cotton grown in the Imperial Valley. However, this pest does not occur in the San Joaquin Valley, where a much smaller percentage of Bt-cotton is grown (Godfrey *et al.* 2005).

2. Generalist Predator Complex

Another important group of arthropods inhabiting cotton is the natural enemies of insect pests. While parasitoids tend to be more specific to pest species and will be discussed in more detail in later sections, the general predator complex attacks most of the key pest species in cotton. In California, beneficial insects range from 8 to 23 insects per 50 sweep samples in organic cotton fields during the growing season (Swezey and Goldman 2001).

2.1. Big-eyed bugs: In the desert valleys the most commonly found species is *Geocoris punctipes* (Het: Geocoridae), while *G. pallens* is more common in the San Joaquin Valley (Anon. 1996). Big-eyed bugs can be present throughout the season with populations peaking during mid-summer. Both nymphs and adults are predatory, but will also feed on nectar. Alfalfa fields are an important source of big-eyed bugs that colonize cotton.

2.2. Minute pirate bugs: *Orius tristicolor* (Het.: Anthocoridae) is the most commonly found species in California cotton. They appear early in the season with both nymphs and adults feeding on a variety of small insects and eggs, though their main food source is thrips.

2.3. Lacewings: Larvae of *Chrysoperla carnea, C. comanche* and *Chrysopa nigricornis* (Neur.: Chrysopidae) are the important lacewing predators in cotton. In the San Joaquin Valley large populations can also be found in alfalfa fields. However, in cotton, intraguild predation of lacewing larvae by other general predators prevents large populations from occurring (Anon. 1996).

2.4. Assassin bugs: The most common assassin bugs in California cotton fields are *Zelus renardii* and *Sinea diadema* (all regions), and *S. confusa* and *S. complexa* (desert valleys) (Het.: Reduviidae). Both nymphs and adults feed on insect prey, and assassin bugs can be found in cotton during mid and late-season (Anon. 1996), though high densities do not occur (Van den Bosch and Hagen 1966).

2.5. Damsel bugs: The damsel bug most commonly found in California is *Nabis americoferus* (Het.: Nabidae). In the desert valleys, *N. alternatus* is also commonly found. Adults and nymphs both prey on insects. (Van den Bosch and Hagen 1966)

2.6. Collops beetles: In the San Joaquin Valley, *Collops vittatus* occurs, while in the desert valleys *C. marginellus* (Col.: Melyridae) is common. Both species feed on moth eggs, aphids, mites and young caterpillars. While they can be found in cotton at any point during the season their populations do not build up until mid-season (Van den Bosch and Hagen 1966).

3. Lygus Bug: *Lygus hesperus* **(Het.: Miridae)**

3.1. Lygus Species and Damage

3.1.1. Description of pest

The four species of lygus bug inhabiting cotton in the western United States are *L. hesperus, L. elisus, L. desertinus* and *L. lineolaris. L. hesperus* occurs most often in California and as a result is the most damaging. Under field conditions a female lygus lays an average of 50 eggs (Cave and Gutierrez 1983), and typically three generations occur per year in cotton (Anon. 1996).

Lygus hesperus can feed on a wide variety of host plants, although it has a strong host preference for alfalfa, as well as other leguminous plants (Scott 1977). Other crop hosts include, but are not limited to, sugarbeet, tomato, beans and potato (Godfrey *et al.* 2005). When these other host plants become unsuitable (mature, dry or are harvested) for lygus, they will migrate into cotton. In California, safflower, alfalfa and weeds (including redroot pigweed, lambsquaters, knotweed, wild sunflower, shepherds purse, London rocket and black mustard) are important source populations for lygus infestations in cotton (Leigh and Matthews 1994, Anon. 1996).

Lygus can feed on apical meristematic tissues, squares, and developing seeds. Meristem feeding can stimulate secondary vegetative growth, giving plants a bushy appearance (Leigh and Matthews 1994). Economic damage usually occurs when smaller squares are fed upon causing them to abort (Anon. 1996, Leigh *et al.* 1988). In the San Joaquin Valley, 4th and 5th instars have been shown to have greater impact on square damage and square loss than adults (Zink and Rosenheim 2004). Feeding on larger squares can lead to boll deformation, and high lygus densities can lead to feeding on bolls and yellow staining of the lint (Leigh and Matthews 1994). Migrations of large lygus populations from preferred hosts usually occur in June when cotton plants are most vulnerable (Godfrey and Leigh 1994).

3.1.2. Damage

In 2003, lygus destroyed 26,862 bales of cotton and caused 268,222 acres to be treated with insecticides in California (Williams 2004). However, lygus damage can vary year to year as evident by the modest

amount of damage occurring the previous year (174 bales lost in 2002) (Williams 2003). The severity of lygus damage in cotton depends on rainfall patterns and availability of alternate hosts (Goodell 1998). Lygus can pose a threat to cotton in all growing regions of California, though it is usually a lesser problem in the desert valleys (Goodell and Toscano 2002).

3.1.3. Treatment thresholds

Current treatment thresholds in the San Joaquin Valley are based on sweep net counts and stage of crop development. Treatment is recommended for 2-4 lygus bugs per 50 sweeps during early squaring, 7-10 per 50 sweeps at mid squaring, and 10 per 50 sweeps at late squaring (Anon. 1996).

3.2. Lygus Biological Control

3.2.1. Current parasitoids, predators and pathogens

Anaphes iole (=*ovijentatus*, Hym.: Mymaridae), an egg parasitoid of lygus bug, is found in all cotton growing regions of the western United States (Anon. 1996). In Arizona cotton, mean monthly rates of egg parasitism by *A. iole* range between 0 and 36% (Graham *et al.* 1986). *Leiophron uniformis* (Hym.: Braconidae), a nymphal parasitoid, is found in the desert valleys (Anon. 1996). Monthly rates of parasitism by *L. uniformis* range from 0 to 10.6% in Arizona alfalfa (Graham *et al.* 1986).

The most important predators of lygus eggs and nymphs are the big-eyed bugs, other predators include damsel bugs and collops beetles. Crab spiders will also attack lygus adults (Anon. 1996). There is little information on the impact of the generalist predators, although Leigh and Gonzalez (1976) carried out field cage studies to evaluate predation of lygus in California cotton. They found *G. pallens* to be effective against eggs and nymphs, while *C. carnea* provided no control.

Surveys in the San Joaquin Valley found the entomopathogenic fungus *Beauveria bassiana* infecting *L. hesperus* populations. Infection levels were greater than 50% in some samples. Isolates of *B. bassiana* from this study are reported as currently in culture and under study for possible future release (McGuire 2002, 2003).

3.2.2. Classical biological control

In 1998, parasitoids from related lygus bugs in Europe began to be imported and released into California for control of *L. hesperus*. In the summers of 1999, 2000 and 2001 adults and larvae (in lygus nymphs) of *Peristenus stygicus* and *P. digoneutis* (Hym.: Braconidae), both nymphal parasitoids, were released in several California locations. Overwintering recoveries of *P. stygicus* were made in 2000 and 2001, though no *P. digoneutis* were recovered. At one release site a maximum parasitism rate of 34% was recorded (Pickett *et al.* 2002). PCR primers have been developed to aid the identification of parasites in lygus nymphs (Erlandson *et al.* 2003, Zhu *et al.* 2004), and although hyperparasitism is not yet known in California, it has been detected in the northern part of the continent where the parasitoid *P. pallipes* is dominant (Ashfaq *et al.* 2005).

3.2.3. Augmentative biological control

Although augmentative releases of *A. iole* have been shown to have some impact on lygus populations in strawberries in California (Udayagiri *et al.* 2000a), no comparable studies have been carried out in cotton. While lygus eggs may be more vulnerable in cotton than in strawberry (Udayagiri and Welter 2000b, Jackson 2003), and some elements of a mass rearing system have been developed (Jones and Jackson 1990, Riddick 2004), the cost of parasitoid production and their availability of sufficient material for

inundation of cotton fields may still be limiting. Smith and Nordland (2000) also point out that while there are several possibilities for augmentative biological control against Lygus bug, the rearing technologies necessary to mass produce these agents are absent.

3.2.4. Conservation biological control

Organophosphates have been found to reduce the natural enemy population by 25% two weeks after treatment (Godfrey *et al.* 1998). One of the most heavily used insecticides for lygus bug and cotton aphid in California cotton is chlorpyrifos, of which 221,695 pounds were applied to cotton in 2002 (DPR pesticide use database). Murphy *et al.* (1994) rated the toxicity of chlorpyrifos to be 1.87 for Heteroptera, 2.80 for Neuroptera, 2.03 for Coleoptera and 2.74 for Hymenoptera, using a scale of 1 < 30% mortality, 2 = 30-90% mortality and 3 > 90% mortality.

Godfrey *et al.* (2005) lists several recommended pesticides for lygus in order of their usefulness in an IPM program as alternatives to OPs. At the top of the list is aldicarb, a systemic carbamate applied to the soil, which is listed as having a high selectivity and a long persistence for lygus while having a low impact on natural enemies (Goodell and Toscano 2002). However, it may cause outbreaks of lepidopteran pests as the heteropteran predators are killed when they feed directly on plant fluids from the cotton plant, and it must be applied prophylactically before lygus becomes a problem (Goodell and Toscano 2002).

Pyrethroids are also listed as alternatives to OPs for lygus control. However, lygus resistance to bifenthrin was already detected in 1996 (Grafton-Cardwell *et al.* 1997), and in 1997 and 1998, surveys carried out in the San Joaquin Valley found resistance to bifenthrin in greater than or equal to 80% of the lygus populations tested (Grafton-Cardwell *et al.* 2000). Pyrethroids also destroy the natural enemy complex causing outbreaks of cotton aphids, spider mites and secondary lepidopteran pests (Godfrey *et al.* 1998). Pyrethroids can reduce beneficial populations by almost 50% two weeks after treatment (Godfrey *et al.* 1998).

Bifenthrin is known to cause high acute mortality of *Anaphes iole* (Udayagiri *et al.* 2000c) and parasitoids of *Helicoverpa* spp. (Tillman 1996), and has resulted in greater than 95% reduction of general predators in cotton fields (Keillor and Godfray 2000). Similarly, while lambda-cyhalothrin was found to have no acute toxicity effect on *Chrysoperla carnea* (Sterk *et al.* 1999) or *C. rufulabris* (Ruberson and Tillman 1999), it caused increased mortality in *Geocoris punctipes* (Ruberson and Tillman 1999, Tillman *et al.* 1998), *Orius insidiosus* (Studebaker and Kring 2002, Ruberson and Tillman 1999), *Cotesia marginiventris* (Ruberson and Tillman 1999), *Microplitis croceipes* (Tillman *et al.* 1998), *Trichogramma cacoeciae* (Sterk *et al.* 1999) and *T. pretiosum* (Ruberson and Tillman 1999, Ruberson *et al.* 2002). Finally, cyfluthrin was found to increase mortality of *C. carnea, Encarsia formosa* (Hym.: Aphelinidae), *Trichogramma cacoeciae* (Sterk *et al.* 1999), and *Anaphes iole* (Williams *et al.* 2003).

Chloronicotinyls are also potential alternatives to OPs for lygus control. A test of several registered and experimental insecticides belonging to the classes pyrethroids, organophosphates and chloronicotinyls, imidacloprid, a chloronicotinyl, was found to give good short term control while affecting the beneficial insect population the least (Keillor and Godfrey 2000).

However, it was found to cause temporary but high mortality of adults of *Anaphes iole* (Williams *et al.* 2003), and although it had no effect on population densities of *G. punctipes* (Kilpatrick *et al.* 2004), it has caused increased mortality of *O. insidiosus* in the field, as well as in lab studies (Ruberson and Fairbanks 2003, Studebaker and Kring 2002). In addition, recent laboratory studies have shown that imidacloprid is the most disruptive of the chloronicotinyl insecticides with short-term acute toxicity impacts on a broad range of parasitoids and predators (Mills, unpublished data).

3.3. Lygus Cultural Control

The affinity that lygus has for alfalfa makes alfalfa management important to lygus management in cotton, as well as providing an important mechanism for lygus control. Staggered planting and cutting of alfalfa fields can be used to minimize lygus migration into cotton (Stern *et al.* 1967, 1969*)*. Farm demonstration trials consisting of three different cutting patterns suggested that staggered cuttings of alfalfa, as opposed to strip cutting, was an easier method to adhere to (Goodell *et al.* 2000). By planting strips within cotton fields, alfalfa can also be used as a trap crop (Stern *et al.* 1969). Godfrey and Leigh (1994) examined the best cutting schedule for alfalfa strips interplanted in cotton to optimize natural enemy refuge and lygus management. They determined that strip-cut alfalfa should be cut on a 28 day cycle for the most efficient lygus management. Cowpea and lima bean can also be used as trap crops in cotton fields (Godfrey *et al.* 2005).

Other cultural variables can affect lygus abundance. In the San Joaquin Valley, higher populations of *L. hesperus* were found in well irrigated fields (Munk and Goodell 2002). High populations of lygus have also been correlated with excess nitrogen fertilization (Leigh *et al.* 1969).

4. Cotton Aphid: *Aphis gossypii* (Hom.: Aphididae)

4.1 Cotton Aphid Species and Damage

4.1.1. Description of pest

A. gossypii has a worldwide distribution, occurring in all regions that do not experience severe winters and is commonly referred to as the cotton or melon aphid. It has been reported on 200 different host plants in the United States (Leonard *et al.* 1971) and on 900 worldwide (Inaizumi 1981). Apterous cotton aphids occur in two different forms. One morph is yellow, smaller, and has a low reproduction rate. The other morph is green or black, larger, and reproduces rapidly. Nymphs developing into alate aphids have a more bluish color and appear to have a dusty waxy coating (Godfrey *et al.* 2005). Population shifts from the lighter morph to the darker morph can be induced by cooler temperatures coupled with shorter day lengths, crowding or heavily fertilized plants. The generation time of the cotton aphid is approximately 12 days. In California, cotton aphids migrate from orchard crops and weeds to cotton during May and June and can cause damage at any point during the season (Anon. 1996).

Cotton aphids feed on the underside of cotton leaves by piercing and sucking the tissues out of the phloem. Early in the season, heavy populations of cotton aphid can cause leaves to crinkle and cup, defoliation and stunted plant growth. Mid-season, during square and boll production, low aphid populations are not damaging. However, high populations can lead to stunted growth of plants and bolls, as well as cause square and boll drop. Late-season populations compromise the quality of the cotton by depositing honeydew onto the lint, creating sticky cotton (Anon. 1996). Sticky cotton can cause sooty mold growth and also disturbs fiber production processes (Leclant and Deguine 1994).

4.1.2. Damage

In 2003, 8,059 bales of cotton were lost because of cotton aphid, which infested 604,400 acres in California (Williams 2004). Cotton aphid primarily causes damage to cotton in the San Joaquin valley. Rosenheim *et al.* (1997) have shown that early season damage is not important. Leaf-area can be reduced by as much as 58% and the plant can still compensate for the damage by the end of the season. However, mid 1990 cotton aphid activity shifted to mid season and began to threaten both cotton yield and quality (Goodell and Toscano 2002).

4.1.3. Treatment threshold

The threshold for cotton aphid differs throughout the season. Mid-season, the threshold is 50 to 75 aphids per fifth main stem node leaf for 7 to 10 days. Later in the season, after the bolls have opened and sticky cotton becomes a threat, the threshold is considerably lower at 10 to 15 yellow aphids or 5 black aphids per fifth main stem node leaf (Godfrey *et al.* 2005).

4.2. Cotton Aphid Biological Control

4.2.1. Current activity of parasitoids, predators and pathogens

Early in the season, naturally occurring predators and parasitoids will suppress cotton aphid populations (Rosenheim *et al.* 1997). *Lysiphlebus testaceipes* (Hym.: Braconidae) is an important parasitoid of cotton aphid in California (Anon. 1996), but hyperparasitism by *Pachyneuron siphonophorae* (Hym.: Pteromalidae) and *Alloxysta bakeri* (Hym.: Cynipidae) can reduce populations (Colfer and Rosenheim 2001). In addition, predation on parasitized aphids by the predator *Hippodamia convergens* (Col.: Coccinellidae) has been found to significantly reduce parasitoid populations. However, in field cages, the presence of both *L. testaceipes* and *H. convergens* has been shown to provide the greatest control of cotton aphid (Colfer and Rosenheim 2001).

Important early season predators of cotton aphid are *H. convergens* and *Coccinella novemnotata franciscana* (Col.: Coccinellidae) (Anon. 1996). Over a 24 h period *H. convergens* can devour an average of 32.9 unparasitized aphids and 21.9 mummies (parasitized aphids) (Colfer and Rosenheim 2001). During mid and late-season the important predators are minute pirate bugs, big-eyed bugs, damsel bugs, and green lacewings (Anon. 1996). Considerable work has been done looking at lacewing larvae and their effectiveness as a cotton aphid predator. In field enclosures, lacewing larvae were able to suppress the small, yellow morph, but were unable to control populations of the larger, dark morphs (Rosenheim *et al.* 1993).

In California, *Linepithema humile* (argentine ants) and *Tetramorium caespitum* (pavement ants) (Hym.: Formicidae) have been found tending cotton aphid colonies (Colfer and Rosenheim 2001) and may limit the effectiveness of both parasitoids and predators.

Entomopathogenic fungi found attacking the cotton aphid in the San Joaquin Valley include *Pandora neoaphidis, Conidiobolus obscurus* and *Entomophthora planchoniana* (Zygomycetes: Entomophthorales). However, only 1.58% in 1997 and 0.35% in 1998 of aphids were found to be infected (Godfrey *et al.* 2001).

4.2.2. Classical biological control

In 1996, a joint project, involving CDFA, USDA and the University of Arkansas, was launched that would introduce natural enemies of the cotton aphid into California. Releases of two parasitoid species (*Aphelinus* nr. *paramali* and *A. gossypii* (Hym.: Aphelinidae)) were started in 2000. Though *A.* nr. *paramali* was found to overwinter successfully, Godfrey *et al.* (2004) suggested that it would probably not be an important bio-control agent of the cotton aphid. In fact, there are no examples in the biological control record, with the exception of the very specialized woolly apple aphid, showing *Aphelinus* spp. to be effective biological control agents. *Lipolexis oregmae* (Hym.: Braconidae) has also been imported into California for possible release pending study (Godfrey *et al.* 2004), and *Aphidius colemani* (Hymenoptera: Braconidae) was evaluated in cage trials as a possible biological control agent with inconclusive results (Godfrey *et al.* 2002).

The entomopathogenic fungus *Neozygites fresenii* (Entomophthorales: Neozygitacaea) was also considered for release under the above mentioned project (Godfrey *et al.* 2001). In Louisiana, where *N. fresenii* occurs naturally, the fungus can reduce peak aphid densities down to non-detectable levels within 10 days after infection (Jones *et al.* 2003). Releases of *N. fresenii* were carried out in the San Joaquin Valley of California in 1994 and 1995. Surveys carried out in 1997 and 2001 did not find any evidence of *N. fresenii* (Godfrey *et al.* 2001), and so the releases are not considered to have resulted in the establishment of this pathogen in California (Steinkraus *et al.* 2002). As the spore stage requires a sufficient period of close to 100% humidity to sporulate, it seems likely that the drier conditions in California cotton limit the potential of this fungal pathogen. Although the role of fungi could be important in the future bio-control of the cotton aphid, it is first necessary to find fungi that are adapted to California aphid populations and climate (Godfrey *et al.* 2004).

4.2.3. Augmentative biological control

In Texas, augmentative releases of the lacewing *C. rufilabris* did not control cotton aphid populations. High larval mortality, adult dispersal, and high cost are suggested to act as limiting factors on augmentative releases of lacewings (Knutson and Tedders 2002). Rosenheim and Wilhoit (1993) propose that naturally occurring, as well as released *C. carnea*, are limited in their abilities to suppress cotton aphid populations because of predation pressure from other generalist predators on young lacewing larvae.

4.2.4. Conservation biological control

The outcome of cotton aphid control by insecticides can be very hard to predict. This is partly due to resistance of cotton aphid to many different insecticides including types of organophosphates, carbamates and pyrethroids (Anon. 1996). In 1996, 40% of cotton aphid populations were resistant to chlorpyrifos (OP), 67% were resistant to endosulfan (carbamate), and 85% were found to be resistant to bifenthrin (pyrethroid) (Grafton-Cardwell *et al.* 2000). In addition, there are also the disruptive impacts of OPs, carbamates and pyrethroids on natural enemies that have already been noted above when discussing lygus bug. A reduction of organophosphate and pyrethroid use in the late 1990's was partially due to the introduction of the chloronicotinyls and resulted in a reduction in resistance by the cotton aphid (Grafton-Cardwell *et al.* 2000). Godfrey *et al.* (2005) gives resistance management guidelines for cotton aphid, as well as recommending imidacloprid, a chloronicotinyl with a higher selectivity, as a suitable alternative. As noted above under lygus bug, however, imidacloprid shows significant levels of short-term acute toxicity to a broad range of natural enemies. In addition, Goodell and Toscano (2002) consider endosulfan as an alternative to OPs for aphid control in cotton. Endosulfan shows high acute toxicity to parasitoids of *Helicoverpa* spp. (Tillman 1996) and to generalist predators, such as *Orius insidiosus* and *Geocoris punctatus* (Elzen 2001).

Early-season use of broad-spectrum insecticides for aphids destroys the control provided by natural enemies, which are abundant and effective at this time (Anon. 1996, Rosenheim *et al.* 1997). Rosenheim *et al.* (1997) stresses that early season use of insecticides for cotton aphid is not only unnecessary, but also can have serious consequences such as the large-scale aphid and spider mite outbreaks of 1995.

4.3. Cotton Aphid Cultural Control

Pima cultivars are prone to large aphid populations and associated damage, and the hairy leaf Acala varieties are more prone to aphids than smooth leaf varieties (Anon. 1996). Weathersbee and Hardee (1994) studied aphid abundance on six different cultivars of cotton and also found that abundance was greater on pubescent types than on smooth. In addition, cotton aphids prefer highly irrigated and highly

fertilized plants (Anon. 1996). High nitrogen levels have been shown to increase aphid fecundity and development rate (Godfrey *et al.* 2000).

5. Silverleaf Whitefly: *Bemisia argentifolii* (Hem.: Aleyrodidae)

5.1. Silverleaf Whitefly Species and Damage

5.1.1. Description of pest

Bellows *et al.* first described *B. argentifolii* in 1994, although it remains debatable whether it is a distinct species or merely a biotype of *B. tabaci* referred to as *B. tabaci* biotype b. *B. tabaci* was first described in Greece in 1889 (Gennadius, 1889), is currently considered a species complex rather than a single species (Perring 2001), with biotype b thought to have originated in the northeast Africa/ Middle east/Arabian peninsular region (Frohilich *et al.* 1999, De Barro *et al.* 2000). It did little economic damage in the USA until 1981 when outbreaks occurred in California and Arizona (Oliveira *et al.* 2001). The b biotype is thought to have been introduced into California in the 1980's and by the 1990's it had edged out the less destructive biotype (Ellsworth and Martinez-Currillo 2001). In this review, the pest will be referred to as the silverleaf whitefly or *B. argentifolii* rather than *B tabaci* biotype b.

More than 600 plant species have been found to host *B. tabaci* (Oliverira *et al.* 2001). The whitefly can reproduce year round and move between host plants as available (Anon. 1996). Zalom and Natwick (1987) calculated the degree-days needed for egg hatch and completion of each larval stage. In California, the summer generation time of the whitefly is 15 to 20 days (Anon. 1996). In the Imperial Valley, important overwintering host plants include sunflower, field bindweed and prickly lettuce (Butler and Henneberry 1984). Winter crops that whitefly can develop on include carrot, lettuce, carrot, broccoli, tomato and alfalfa (Coudriet *et al.* 1985). Whitefly populations start increasing on cotton from late June to September and, if conditions permit, can continue to increase throughout November (Meyerdirk *et al.* 1986).

Both the adults and nymphs feed by sucking the sap out of the plant, which deprives the plant of nutrients, causing stunted growth, defoliation, square and boll drop and lower yields. Feeding nymphs also deposit honeydew on the lint causing sticky cotton, resulting is a serious reduction in lint quality. Honeydew deposits also encourage the growth of sooty mold. In the lower desert valleys, the whitefly is a vector of cotton leaf crumple disease (Anon. 1996).

5.1.2. Damage

In 2003, whitefly infested 570,822 acres of cotton in California and was responsible for a loss of 7,611 bales (Williams 2004). The damage done by whitefly can be much higher, varying year from year, as evident by the loss of 18,512 bales in 2002 (Williams 2003). The risk of whitefly damage occurs in all growing regions of California (Godfrey *et al.* 2005).

5.1.3. Treatment threshold

The treatment threshold is 40% of the leaves infested with more than three adults or 40% of the leaves infested with large (3rd and 4th instar) nymphs (Godfrey *et al.* 2005).

5.2. Silverleaf Whitefly Biological Control

5.2.1. Current activity of parasitoids, predators and pathogens

The native parasitoids attacking whitefly in California are species of *Encarsia* and *Eretmocerus* (Hym.: Aphelinidae) (Anon. 1996). In the Imperial Valley, *Eretmocerus eremicus* can first be detected during the season in late June to early July (Gerling and Naranjo 1998). In field-cage evaluations *E. eremicus* reduced whitefly populations and increased cotton yield (Simmons and Minkenberg 1994). However, parasitism rates can vary tremendously year from year. In one year, parasitism averaged only 4.1% over the season and never exceeded 10%, but in the following year averaged 35% for the season with a maximum of 72% (Gerling and Naranjo 1998). Another study found that when insecticide use stopped after August, parasitism of whitefly could reach over 70% by mid-October (Natwick and Zalom 1984).

In Arizona cotton fields, predation is also considered to be an important mortality factor of the whitefly (Naranjo and Ellsworth 1999). Generalist predators in cotton that will attack whitefly nymphs include big-eyed bugs, lacewing larvae and lady beetles (Anon. 1996).

5.2.2. Classical biological control

Biological control of economically important whitefly species has been going on for the past 100 years (Gerling 1992). Gerling *et al.* (2001) gathered reports of 34 species of *Encarsia,* 12 species of *Eretmocerus*, 1 species of *Metaphycus* (Hym.: Encyrtidae) and 3 species of *Amitus* (Hym.: Platygasteridae) attacking *B. tabaci* nymphs worldwide. In addition, they reported 114 different predators of *B. tabaci* from 9 different orders and 31 families. Finally, worldwide, 11 species of fungi have been reported on *B. tabaci* (Faria and Wraight 2001).

The USDA-APHIS-PPQ, Mission Plant Protection Center (MPPC) in Texas has been carrying on a large-scale importation of parasitoids and predators of *B. tabaci.* Of these, Goolsby *et al.* (1998) evaluated 38 exotic and 2 native parasitoids in a variety of crops to determine which would be the most valuable to mass rear for field release. *Eretmocerus* sp. (Pakistan) not only achieved the highest parasitism rate of silverleaf whitefly in cotton, but also was consistently recovered in the field. Olfactometry and functional response studies suggested that *Eretmocerus mundus* (Spain) would perform better in the field than 8 other parasitoid populations and field-cage studies confirmed that *Er. mundus* could lower whitefly densities (Heinz and Parrella 1998). Exotic species of *Eretmocerus* and *Encarsia* were released in the Imperial Valley during 1994 to 1999. Surveys carried out in subsequent years showed that *Eretmocerus* nr. *emiratus*, *Er. emiratus*, *Er. mundus* and *En. sophia* (= *bemisiae, sublutea, transvena*) had become established (Roltsch 2001). *Er. emiratus, Er.* nr. *emiratus, Er. mundus, Er. hayati, En. sophia* were released in Californian citrus orchards adjacent to cotton during 1997 to 2000. *Er. mundus* was recovered in cotton fields two years after the last releases were made (Pickett *et al.* 2003). In other Southern California field-cage studies, whitefly mortality in cages that *Amitus bennetti* were released in was 82% higher than in non-release cages (Joyce and Bellows 2000). Different release methods for *Er.* nr. *emiratus* have been examined in Arizona cotton (Gould 2003). *En. formosa, En. sophia*, *Er. mundus* and *Er. queenslandensis* are commercially available parasitoids of silverleaf whitefly (Gerling *et al.* 2001).

5.5.3. Augmentative biological control

In 1992 and 1993, augmentative releases of the beetle *Delphastus catalinae* (Col.: Coccinellidae) were carried out in the Imperial Valley. While cage releases produced a significant decline in whitefly populations, open field releases did not (Heinz *et al.* 1999).

Myco-insecticides have been developed that are based on the fungi *Verticillium lecanii, Paecilomyces fumosoroseus* and *B. bassiana* (Faria and Wraight 2001). *V. lecanii* can infect *B. tabaci* nymphs and adults. *P. fumosoroseus* can infect eggs, as well as nymphs and adults (Osborne and Landa 1992). In the Imperial Valley, a single, high-rate application of a *B. bassiana* based product resulted in 80% control of whitefly (Jaronski *et al.* 1998). However, in Texas and the Imperial Valley, applications of Mycotrol, a

product based on *B. bassiana*, did not provide any whitefly control (Wraight *et al.* 1996, Liu *et al.* 1999). In Arizona cotton, three products containing strains of either *P. fumosoroseus* or *B. bassiana* suppressed whitefly nymph populations (Akey and Henneberry 1998). Faria and Wraight (2001) discuss the limitations and offer some recommendations on myco-insecticide use.

5.5.4. Conservation biological control

Important approaches for whitefly control include raising the treatment threshold and delaying the first insecticide treatment of the season in order to allow more time for predator populations to become established and allowing predation to play a significant role in whitefly suppression (Naranjo 2001, Naranjo *et al.* 2002). In addition, the most valuable insecticides for light to moderate populations of whiteflies are the IGRs, buprofezin or pyriproxyfen, which show high selectivity (Naranjo *et al.* 2004). In a 3 year study in Arizona, these IGRs did lead to decrease in the abundance of 8 out of 20 predator taxa examined, including *Geocoris punctatus*, *Nabis alternatus*, and *Chrysoperla carnea*. However, these reductions were more consistent with loss of prey availability than direct toxicity, compared to conventional insecticides that induced greater and more immediate reductions in all predator taxa. In addition, predator-prey ratios increased in plots treated with the IGRs in comparison with untreated control plots.

However, for moderate to heavy populations of whiteflies combinations of the following insecticides are recommended (Godfrey *et al.* 2005): bifenthrin and endosulfan; fenpropathrin and acephate; amitraz alone or with and adulticide. In general, applications of mixtures of fenpropathrin and acephate did not negatively affect parasitism rates of whitefly (Gerling and Naranjo 1998). The impacts of bifenthrin and endosulfan were discussed above for lygus bug and cotton aphids respectively, both having high potential for disruption of natural enemy control in cotton.

5.6. Silverleaf Whitefly Cultural Control

Anon. (1996) recommends planting cotton ½ mile upwind from alternate whitefly host plants. The shorter growing time of Acala varieties makes whitefly infestation less likely than on longer growing Pima varieties. Of Acala varieties whitefly densities are usually greater on hairy-leaf varieties than on smooth-leaf varieties (Anon. 1996). In the desert valleys, defoliation in late August, as opposed to October can be used to effectively prevent the occurrence of high populations of whiteflies (Meyerdirk *et al.* 1986).

6. Webspinning spider mites (Acari: Tetranychidae): Strawberry spider mite (*Tetranychus turkestani*), Pacific spider mite (*T. pacificus*), two spotted spider mite (*T. urticae*), carmine spider mite (*T. cinnabarinus)*

6.1. Spider Mites Species and Damage

6.1.1. Description of the pest

A complex of four spider mite species occurs in California cotton. Adult males and immature forms of all four species look very similar, but the females are distinguishable from one another (Anon. 1996). There are three larval stages, which alternate with three resting stages (Gutierrez 1994). The strawberry, twospotted and Pacific spider mites are found in the San Joaquin Valley. The strawberry spider mite, along with the carmine spider mite is found in the desert valleys (Anon. 1996). At 25° C, females can live up to three to four weeks, while laying 50 to 100 eggs (Sabelis 1985). In California cotton, spider mites can have ten generations a season. They are usually found on the underside of leaves, though Pacific spider mite can be found on both sides (Anon. 1996). On cotton plants, females typically form colonies

midway up the plant occupying the fifth to tenth main stem leaves below the plant terminal, but by the end of the season they will have moved up to the plant terminal (Carey 1982). In California, the strawberry spider mite is dominant early in the season (Leigh 1985) and is also the most destructive. These spider mites can also occur on a variety of other host plants, such as alfalfa, tree fruit and nuts, annual crops, and various weeds.

Spider mites feed on the leaves and cause a reduction in photosynthesis, resulting in stunted growth, decreased flowering and a decrease in yield (Gutierrez 1994). Heavily infested leaves will turn yellow and drop, and the squares and bolls can either be stunted or abort from the plant. Late-season infestations, when most bolls are already mature, are not as damaging as in early-season (Anon. 1996).

6.1.2. Damage

In 2003, spider mites damaged 8,059 bales and infested 604,400 acres of cotton in California (Williams 2004).

6.1.3. Treatment thresholds

Yield loss will occur when 80% of the leaves are infested. However, treatment is recommended when 30-50% of the leaves are infested because of the slow action of registered products (Godfrey *et al.* 2005).

6.2. Spider Mites Biological Control

6.2.1. Current activity of predators and pathogens

The most important naturally occurring, early-season predator of spider mites in cotton is *Frankliniella occidentalis* (Thys.: Thripidae), the western flower thrips, which feeds on spider mite eggs (Anon. 1996). In exclusion experiments *F. occidentalis* reduced spider mite populations by more than 50% (Colfer *et al.* 2000). However, spider mite webbing on the eggs and on the leaf can hinder predation by *F. occidentalis* (Trichilo and Leigh 1986). Western flower thrips are omnivorous and can also resort to herbivory when other food sources are scarce, as well as acting as a food source for other generalist predators (Trichilo and Leigh 1986, Wilson *et al.* 1991). Later in the season, big-eyed bugs and minute pirate bugs become important predators of spider mites (Anon. 1996). Exclusion tests in the San Joaquin Valley found that while an artificial *Orius/Geocoris* complex provided spider mite suppression, the natural predator complex, consisting of *Nabis* spp. , *Notoxus calcaratus* (Col.: Anthicidae)*, Z. renardii, Chrysoperla* spp. and spiders, as well as *O. tristicolor* and *Geocoris* sp., provided the greatest spider mite control (Colfer *et al.* 2000). Gonzalez and Wilson (1982) suggested that the role of mites as primary food source for the big-eyed bug and minute pirate bug, which also prey on other pest species, should be considered when setting treatment threshold levels for spider mites.

In Mississippi cotton, the pathogenic fungus, *Entomophthora* sp. was present in 92.8% of *T. urticae* collected and was found to suppress mite populations late in the season (Smith and Furr 1975). Field collections in Egypt found *Neozygites* sp., *Cephalosporium* sp., *V. lecanii, Alternaria* sp. and *Aspergillus* sp. to be associated with *T. urticae* (El-Naggar *et al.* 2004). In the same study, applications of *B. bassiana* reduced *T. urticae* populations by 75% on soybean after ten days. It is not known whether fungal pathogens affect spider mite populations in California cotton, but the drier climate may limit their occurrence.

6.2.2. Augmentative biological control

Augmentative releases of the western predatory mite, *Galendromus occidentalis* (Acari: Phytoseiidae), have been attempted for control of spider mites in California cotton, though they failed to establish (Colfer *et al.* 2003). Exclusion experiments suggested that this was a result of intraguild predation on *G. occidentalis* by other generalist predators (Colfer *et. al*. 2003).

6.2.3. Conservation biological control

Early-season applications of broad-spectrum insecticides for lygus and aphid control are often responsible for spider mite outbreaks in cotton (Grafton-Cardwell *et al.* 2000). In addition, twospotted and Pacific mites have shown significant resistance to a number of selective miticides including dicofol, propargite and abamectin (Goodell and Toscano 2002). Application of acaricides in June and July will select for resistance within the mite population. However, resistance will decline during the winter and will be low the following spring (Grafton-Cardwell *et al.* 2000). Godfrey *et al.* (2005) lists abamectin, a bacterial fermentation product, as the most useful in an IPM program, although it has been shown to be highly toxic to adult parasitoids (Tzeng and Kao 1999, Brunner *et al.* 2001), but the impact may be of short duration as indicated for *Anaphes iole* (Udayagiri *et al.* 2000c) and *Trichogramma cacoeciae* (Hassan *et al* 1998). Similar impacts have also been observed for the general predators, including *Orius insidiosus* (Studebaker and Kring 2003) and coccinellids (James 2003). However, abamectin does show greater toxicity to phytophagous than to predatory mites (Hardman *et al.* 2003), which would help to avoid miticide resurgence in spider mite populations.

6.3. Spider Mites Cultural Control

Water stressed plants usually cause spider mites to exhibit rapid population growth (Anon. 1996). Pima varieties seem more resistant to spider mites than upland varieties (Godfrey *et al.* 2005).

7. Pink Bollworm: *Pectinophora gossypiella* (Lep.: Gelechiidae)

7.1. Pink Bollworm Species and Damage

7.1.1. Description of pest

Pink bollworm, first recorded in India in 1842, was first detected as an invasive pest to California in 1965 (Ingram 1994). In the United States, it also feeds on okra, kenaf and hibiscus, okra being the only other crop host plant (Anon. 1996) and preferred over cotton (Noble 1969, Ingram 1981). Pink bollworm is primarily restricted to the lower desert valleys in California.

In California, pink bollworm can have three to five generations a year, with spring emergence of adults peaking in May, and larval population abundance reaching a peak in August and September (Anon. 1996). It overwinters as diapausing final instar larvae. Gutierrez *et al.* (1981) created a model to predict the induction and termination of diapause based on temperature and photoperiod. Pink bollworm can migrate north from the desert valleys to the San Joaquin Valley, but because of an aggressive IPM program, has never become established there (Anon. 1996). The success of this program, which has been in effect since 1967, relies heavily on large releases of sterile moths, plow-down restrictions, and occasional mating disruption by pheromones (Anon, no date).

In the spring, infested squares will flower and set fruit normally (Anon. 1996). Larvae can spin webbing in flower buds, preventing the bud from opening properly and causing a rosetted bloom (Ingram 1994). Larval feeding may occasionally cause squares to drop (Anon. 1996). Later in the season, as bolls become available, larvae feed on the seeds and lint. Several larvae may be in one boll and in a young boll all the seeds may be consumed, leading to total boll destruction. In a large boll, however, when all of the

seeds are not consumed, only part of the boll is lost (Ingram 1994). The exit holes made by larvae in the boll wall also encourage boll rot and the build up of aflatoxin (Anon. 1996, Henneberry *et al.* 1978).

7.1.2. Damage

In California, pink bollworm caused the loss of 68 bales and infested 20,375 acres of cotton in 2003. While this seems like a small economic loss, the same year, California spent $3,404,296 on pink bollworm eradication (Williams 2004). In addition, the seemingly small amount of damage can be attributed to two other factors. Firstly, the restriction of pink bollworm to the desert valleys, which represent only a small percentage of cotton grown in California. Secondly, a majority of the cotton grown in the desert valleys is Bt cotton, which provides effective control of pink bollworm (Godfrey *et al.* 2005). Field data collected from 1997 to 2002 in Arizona and California, detected some resistance to Bt though the frequency was so low that it is unlikely to be a problem in the near future (Dennehy *et al.* 2004).

7.1.3. Treatment threshold

The current threshold in California is set at 10% infested bolls (Godfrey *et al.* 2005).

7.2. Pink Bollworm Biological Control

7.2.1. Current activity of parasitoids, predators and pathogens

In cotton, pink bollworm spends most of its life buried in a boll, making it difficult for predators and parasitoids to reach it (Bartlett and Gonzalez 1970). The California native larval parasitoid, *Bracon platynotae* (Hym.: Braconidae) can be effective against pink bollworm larvae in squares early in the season, but not against those concealed in bolls later in the season (Anon. 1996). In addition, there are no reports of naturally occurring insect pathogens as being of importance in California.

The pink bollworm is most vulnerable to predation when it is an egg, a young larva (not yet in the boll) and a fully mature larva preparing to pupate (Orphanides *et al.* 1971). Indigenous predators such as lacewing larvae, big-eyed bugs, minute pirate bugs, collops beetles and lady beetles will prey on pink bollworm eggs and small larvae, but do not usually provide control (Anon. 1996). Under laboratory conditions, Orphanides *et al.* (1971) evaluated the efficiency of six Californian generalist predators against different stages of the pink bollworm. The egg stage was suggested as the most vulnerable to predation. The predators were ranked in the following order of most efficient to least efficient: 2nd instar *C. carnea,* adult *C. marginellus*, *G. punctipes*, *N. calcaratus*, *N. americoferus* and *O. tristicolor*. In field-cage tests, Irwin *et al.* (1971) had similar results, with *C. carnea, G. pallens* and *N. americoferus* being the most efficient egg predators out of an array of native Californian predators.

7.2.2. Classical biological control

Lists of worldwide parasitoids of pink bollworm can be found in Cheema *et al.* (1980), Pearson (1958), Noble (1969) Legner (1976), Menon and Thangavelu (1979), Sekhon and Varma (1983), Gordh (1984), and Naumann and Sands (1984). Jackson (1980) discusses early biological control introductions for the pink bollworm in the United States. In the years between 1969 and 1978, attempts were made to establish 14 egg-larval and larval parasitoids in the lower Colorado Desert and in Arizona. The egg-larval parasitoids released were *Chelonus blackburni, C. curvimaculatus* and *Chelonus* sp. (Hym.: Braconidae), and the larval parasitoids released were *Goniozus* sp. and *Parasierola emigrata* (Hym.: Bethylidae); *Apanteles angaleti, A. oenone, Bracon gelechiae, B. kirkpatricki*, *B. mellitor* (Hym.: Braconidae); *Exeristes roborator* and *Pristomerus hawaiiensis* (Hym.: Ichneumonidae). Field reproduction was

observed in *P. emigrata, A. angaleti, B. kirkpatricki, C. blackburni, Chelonus* sp. and *P. hawaiiensis* (Legner and Medved 1979). Byran *et al.* (1973) reported that Arizona releases of *B. kirkpatricki* lowered the number of pink bollworm larvae found in cotton blooms, and that *C. blackburni* was more effective than *B. kirkpatricki* at attacking larvae in bolls. In 1978 and 1979, field applications of host-searching kairomones in Arizona failed to increase parasitism by *C.* sp. nr. *curvimaculatus* (Chiri and Legner 1983). Further details of the biology of this species are provided by Hentz *et al.* (1997, 1998). In all cases, while recoveries of parasitoids occurred during the season of release, none were recovered the following year (Legner and Medved 1979). An additional larval parasitoid *Goniozus aethiops* (Hym.: Bethylidae) was released in southern California ca. 1970, though no attempts were made at recovery (Gordh 1984).

7.2.3. Augmentative biological control

An exotic egg parasitoid *Trichogrammatoidea bactrae* (Hym.: Trichogrammatidae), imported from Australia, is commercially available and has been considered for inundative release against pink bollworm control. Naranjo (1993) provides details of the biology of this species, which indicate that it is able to tolerate the high temperatures associated with cotton production in Arizona and the desert valleys of California. *Steinernema* spp., entomopathogenic nematodes, attack larvae that have dropped to the soil and have been considered for augmentative releases (Anon. 1996). Field trials of a nucleopolyhedrovirus failed to reduce field populations of pink bollworm in Arizona (Bell and Henneberry 1980).

7.2.4. Conservation biological control

Control of pink bollworm has relied on gossyplure, a sex pheromone of the pink bollworm, used for mating disruption with no adverse affects on natural enemies (Godfrey *et al.* 2005). However, the increased use of Bt cotton in the desert valleys in recent years has led to effective control and a decline in use of gossyplure (Goodell and Toscano 2002). Although Bt cotton has been shown to have sublethal impacts on *Orius tristicolor*, *Geocoris punctipes* (Ponsard *et al.* 2002) and noctuid parasitoids (Bauer and Boethel 2003), these effects are unlikely to be as disruptive as the use of conventional insecticides. Organophosphates, carbamate and pyrethroids are also effective against pink bollworm, though applications often lead to outbreaks and resistance in other pests (Anon. 1996, Ingram 1994).

7.3. Pink Bollworm Cultural Control

There are also some cotton plant varieties which show natural resistance to pink bollworm (Noble 1969, Wilson 1980, Jenkins 1989). Preventing large populations from going into diapause in the fall can help reduce populations the following year. One way to do this is by cutting off irrigation and harvesting early, destroying the larval food source. The plants also should be shredded immediately after harvest. Winter irrigation can also add to the mortality of the overwintering population (Anon. 1996). Early irrigation in the spring and late planting can increase suicidal emergence of moths (Anon. 1996, Ingram 1994).

8. Lepidopteran Defoliators (Lep.: Noctuidae): Cotton bollworm (*Helicoverpa zea*), tobacco budworm (*Helicoverpa virescens*), and beet armyworm (*Spodoptera exigua*)

8.1. Lepidopteran Species and Damage

8.1.1. Description of pest

The most important defoliators on cotton in California include the indigenous cotton bollworm and tobacco budworm and the exotic beet armyworm. Cotton bollworm and beet armyworm are found

throughout the cotton growing regions of California, while tobacco budworm is of importance only in the desert valleys (Anon. 1996). *H. zea* is commonly known as cotton bollworm, tomato fruitworm and corn earworm (King 1994). Among 49 host plants of economic significance are corn (preferred), cotton, tomato, sunflower, safflower and bean (Matthews 1987, King 1994, Anon. 1996). *H. virescens* is known as the tobacco budworm and is known to feed on 55 crop plants including tobacco, cotton, tomato, sunflower and soybean (Matthews 1987, King 1994). The origin of beet armyworm is uncertain, though it is thought to be a native of southern Asia (Ruberson *et al.* 1994). The first records in the United States are from 1876 (Harvey, 1876) and it has now been reported on over 90 plant species (Pearson 1982), including cotton, alfalfa, vegetables, sugarbeets and beans (Anon. 1996).

In all species, development time ranges from two weeks to a month, depending on the temperature (Anon. 1996, Ruberson 1996). In the San Joaquin Valley, the *Helicoverpa* enter into winter diapause, but in the desert valleys, depending of the environmental conditions, only a portion of the population enter diapause, while the rest continue development and move to winter hosts (Anon. 1996). In the San Joaquin Valley, there are only two generations of *H. zea* in cotton, while in the desert valleys there can be three to four generations of both *Helicoverpa* species. Populations usually do not reach damaging levels until August (Anon. 1996). There are typically three to five generations a year of *S. exigua* (Anon. 1996).

The *Helicoverpa* spp. are late-season pests. First and second instar larvae prefer to feed on small squares, while older instars prefer larger squares, flowers and bolls (Anon. 1996). A larva will chew a hole into a boll and empty out large sections. Humid conditions can lead to rot of the damaged bolls, while in drier conditions the damaged boll will dry. In contrast, *S. exigua* is an early-season pest and leaf feeding is usually only significant on small plants (Anon. 1996). Larvae feed mainly on the underside of leaves, though they will also feed on squares, flowers and small bolls. The plant usually compensates for early-season damage, though feeding can lead to a delay in fruiting. When boll damage occurs too late for the plant to compensate, loss of yield may occur.

8.1.2. Damage

Infestation and subsequent damage by cotton bollworm and tobacco budworm is occasional. No loss of yield caused by either species has been reported since 2000 when 59 bales were lost (Anon 2002, Williams 2003, 2004). In 2003, beet armyworm infested 470,089 acres of cotton resulting in a loss of 6,268 bales in California (Williams 2004). However, in 2002, infestations of 261,346 acres lead to no loss in yield (Williams 2003).

8.1.3. Treatment thresholds

There is no beet armyworm treatment threshold, though fields and adjacent weeds should be monitored to detect large infestations (Godfrey *et al.* 2005). The current threshold for *Helicoverpa* spp. in the desert valleys is 10 to 12 small budworm or bollworm larvae per 100 plants. In the San Joaquin Valley, the threshold is dependent on management of the cotton. In fields that have not been treated with broad-spectrum insecticides the threshold is 20 small bollworms per 100 plants. In fields that have been treated with broad-spectrum insecticides, the threshold is considerably lower – at 8 small bollworms per 100 plants (Godfrey *et al.* 2005). The larger larvae are the most damaging, but as they are difficult to kill treatment must be occur when 1st through 3rd instars are present (Anon. 1996).

8.2. Lepidopteran Biological Control

8.2.1. Current activity of parasitoids, predators and pathogens

Naturally occurring parasitoids of cotton bollworm found in California cotton include *Apanteles militaris, Cotesia marginiventris*, *Chelonus texanus* (Hym.: Braconidae); *Campoletis argentifrons, Hyposoter annulipes, H. exiguae* and *Therion californicum* (Hym.: Ichneumonidae); *Spilochalcis igneoides* (Hym.: Chalcididae); *Trichogramma* spp. (Hym.: Trichogrammatidae); *Eucelatoria armigera, Gonia capitata, Lespesia archippivora* and *Winthemia quadripustulata* (Dip.: Tachinidae) (van den Bosch and Hagen 1966, Henneberry *et al.* 1991). Of these parasitoids *H. exiguae* and *L. archippivora* were dominant (Henneberry *et al.* 1991). In desert valleys, naturally occurring populations of *Trichogramma* can destroy a majority of the cotton bollworm and tobacco budworm eggs in some fields (Anon. 1996).

Ruberson *et al.* (1994) compiled a list of parasitoids associated with the beet armyworm in the United States. The parasitoids reported as attacking beet armyworm in California cotton are: *Cotesia laeviceps, C. marginiventris, Chelonus insularis, Meteorus vulgaris* and *Cremnops haemotodes* (Hym.: Braconidae); *Campoletis argentifrons, Hyposoter exiguae, Rubicundiella perturbatrix, Therion longipes, Pristomerus spinator* and *Temelucha* sp. (Hym.: Ichneumonidae); *Trichogramma* spp. (Hym.: Trichogrammatidae); *Eucelatoria armigera, Eucelatoria* sp. nr. *armigera, Archytas californiae, A. apicifer, Voria ruralis,* and *Lespesia archippivora* (Dip.: Tachinidae). *L. archippivora*, *P. spinator*, *C. insularis*, and *C. marginiventris* (Cresson) are dominant (Henneberry *et al.* 1991). In Georgia cotton during 1992 and 1993, parasitism was found to be greatest in the 1st through 3rd instars with parasitism rates as high as 67.0% for 3rd instar larvae, but declining to 3.7% in 5th instar larvae (Ruberson *et al.* 1994).

Important indigenous predators feeding on eggs and small larvae of all three defoliators include big-eyed bugs, minute pirate bugs, damsel bugs and lacewing larvae, and to a lesser extent assassin bugs, spiders and collops beetles (Ruberson *et al.* 1994). Large populations of natural enemies can cause a 90% mortality of bollworm eggs and larvae in cotton fields (Falcon and van den Bosch 1978). In addition, using field cage studies, Lingren and Wolfenburger (1976) found that *Orius insidiosus* consumed 65% of tobacco budworm eggs. Similarly, native predators are considered to be able to keep populations of beet armyworm from causing economic damage (Godfrey *et al.* 2005). In Texas, mortality greater than 99% for immature beet armyworm was thought to be largely due to the natural enemy complex present in cotton fields (Summy *et al.* 1997).

Pathogens affecting cotton bollworm and tobacco budworm include a nucleopolyhedrovirus (HzSNPV), a granulovirus, *B. thuringiensis*, and the fungi *Nomuraea rileyi, Metarhizium anisopliae, Entomophthora aulicae* and *Beauveria bassiana* (King 1994). Beet armyworm also has a nucleopolyhedrovirus (SeMNPV) that causing epizootics of disease in larval populations (Anon. 1996) and it is known to be susceptible to the same range of fungal pathogens under laboratory conditions, although there are no reports of natural infection in the field.

8.2.2. Classical biological control

Reviews of biological control of cotton bollworm and tobacco budworm have been given by Johnson *et al.* (1986), King and Coleman (1989) and King and Jackson (1989). Some of the exotic parasitoids imported for classical biological control of pink bollworm were known to be able to develop successfully on other cotton pests and were considered for their potential as neoclassical biological controls for budworm, bollworm and armyworm. A larval parasitoid, *Palexorista laxa* (Dip.: Tachinidae), from India and Africa, parasitized 51% of bollworm and budworm larvae in field cage tests in Arizona (Jackson *et al.* 1976). Similarly, Fye and Jackson (1973) looked at the potential overwintering success of *Chelonus blackburni* for the control of budworm and bollworm populations in Arizona cotton.

8.2.3. Augmentative biological control

A field cage comparison between two predators of tobacco budworm found *C. carnea* most effective at reducing the number of budworm eggs and first instar larvae in field cages, while *Podisus maculiventris* (Het.: Pentatomidae) was found to be an effective predator on later instar larvae. This suggested that *P. maculiventris* had potential for augmentative release, since few other predators attack large budworm larvae (Lopez *et al.* 1976). Ridgeway *et al.* (1977) suggested that while augmentative releases of *C. carnea* could suppress populations, high costs restrict this method.

In California field cages, *Trichogramma* spp. parasitized as much as 80% of cotton bollworm eggs present (Ashley *et al.* 1974). In Texas, releases of *Trichogramma* spp. resulted in 51% egg parasitism of *Helicoverpa* spp. (Ridgeway *et al.* 1977). Stinner *et al.* (1974) reported 66 to 80% reduction in *Helicoverpa* larvae by *Trichogramma* releases. Despite these consistent impacts from mass released *Trichogramma* in cotton, the levels of parasitism achieved were not sufficient to provide adequate control of *Helicoverpa* spp. and the high costs of mass production were not competitive with the low cost and accessibility of insecticides (King *et al.* 1985). Greater success in the use of inundative releases of *Trichogramma* for the control of defoliators in cotton has apparently been achieved in Columbia, Mexico, and China, due in part to the lower costs of mass production in these regions.

Hayes and Bell (1994) suggest that NPV could be used to reduce populations of budworm and bollworm on weedy plants before they move into the cotton crop and that one early-season application could reduce moth emergence on weeds up to 38%. The results from an 11 year study in Mississippi showed that one or two well timed applications onto early season weeds could in fact reduce moth emergence by more than 70% (Hardee and Streett 1999). Hoover *et al.* (1995) also report on a fast acting recombinant baculovirus (AcAaIT), based on *Autographa californica* with an insect selective toxin derived from the scorpion *Androctonus australis,* that knocks budworm larvae off the plant before killing it, so dead larvae stuck on the plant do not compromise lint quality. Similarly, applications of SeMNPV directly in the cotton crop killed 60% of beet armyworms four days after treatment (Suszkiw 1998).

8.2.4. Conservation biological control

Control of defoliators has primarily been accomplished through use of OPs and carbamates. In addition, the use of broad-spectrum insecticides to control other cotton pests will destroy the natural enemies of budworm and bollworm and is often the cause of outbreaks (Anon. 1996), as shown by Eveleens *et al.* (1973) for beet armyworm. Alternatives to conventional insecticides for these defoliators include new formulations of Bt sprays, spinosad (fungal metabolite), tebufenozide (IGR) and indoxacarb (oxadiazine) (Goodell and Toscano 2002). While these insecticides are more selective than other classes, they may still have negative effects on natural enemy populations. Spinosad did not affect field densities of big-eyed bugs, assassin bugs, *Orius* sp. and *Scymnus* sp. one day after treatment (Sansone and Minzenmayer 2000).

However, it has been reported to show acute toxicity to *G. punctipes* (Ruberson and Tillman 1999), *C. marginiventris* (Ruberson and Fairbanks 2003), *Anaphes iole* (Williams *et al.* 2003) and *T. pretiosum* (Ruberson and Tillman 1999). Bt-sprays are more selective and have been found to have no effect on *C. carnea, C. marginiventris* or *T. cacoeciae* (Sterk *et al.* 1999). Similarly, tebufenozide shoes no acute toxicity to *O. insidiosus* (Pietrantonio and Benedict 1999, Elzen 2001), *G. punctipes* (Elzen 2001) or *C. marginiventris* (Pietrantonio and Benedict 1999).

8.3. Lepidopteran Cultural Control

Damage caused by the cotton bollworm and tobacco budworm occurs late in the season and therefore is more likely to become a problem in the desert valleys. Growing short season varieties can limit the

damage. Heavy fertilization and irrigation also encourage infestation (Anon. 1996). Bt cotton varieties also help control bollworm and budworm populations (Godfrey *et al.* 2005).

Bt cotton does not provide a high degree of mortality in beet armyworm, though it can increase larval development time (Ashfaq and Young 1999), as do plants grown in high potassium soil (Graham and Gaylor 1997). Beet armyworm damage usually occurs when the weather is hot and dry. Stunted, less robust plants (Ruberson 1996) or plants that are generally stressed (Smith 1989) seem to be preferred. Sandy soils also appear to be attractive to beet armyworm (Smith 1989).

9. Future directions

As detailed above, there are numerous arthropod pests and natural enemies in cotton. The largest hurdle to implementing better biological controls may not be the importation of a new natural enemy species or the development of a novel cultural practice for natural enemy conservation. Rather, the key for improved biological controls in cotton appears to be the conservation of the existing natural enemies through the reduction of broad spectrum insecticides. Short-term research goals should then be the continued reduction of disruptive materials through their replacement with more species-specific, short-residual materials whenever possible. Long-term research goals should be the development of better materials to replace key carbamates and OPs.

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Biological Control of Key Pests in Lettuce

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I. Introduction

Lettuce, *Lactuca sativa*, is a $1.5 billion/year industry in California; it is one of California's ten most valuable crops. The industry produces head lettuces such as iceberg, and leaf lettuces such as green leaf, red leaf, and romaine. In 2005, California growers harvested 250,000 acres, accounting for more than 75% of all U.S. lettuce production (California Department of Food and Agriculture 2006). Organic management practices are applied to approximately 5% of all California lettuce production acreage (California Department of Food and Agriculture 2006; Economic Research Service 2006). There are four major lettuce production areas in California: the central coast, which includes the Salinas Valley, the self-titled "Salad Bowl of the World"; the southern coast, which includes the Santa Maria Valley; the southern San Joaquin Valley, which includes portions of Fresno, Kings, and Kern counties; and the southern deserts, which include the Coachella and Imperial Valleys (Jackson *et al.* 1996a; Jackson *et al.* 1996b). Together, these four growing regions provide a range of climatic conditions that allows California to produce lettuce throughout the year. The lettuce cropping cycle consists of planting the seeds in raised beds, thinning the seedlings to reduce the crop density, and harvesting the plants before they bolt to produce flowering stems. The cropping cycle lasts from 9 to 16 weeks, depending on the region and the time of year (Jackson *et al.* 1996a; Jackson *et al.* 1996b).

The predominant arthropod pests of Californian lettuce are aphids, leafminers, and lepidopteran larvae. Additional pests (not discussed here) are thrips, whiteflies, and *Lygus* bugs. Because lettuce grows with a closed plant structure, direct contact of pests with insecticides is difficult. Two key tools available for suppressing pests in the plant interior are systemic insecticides and biological control. Biological control of the lettuce pest complex is provided by a range of beneficial organisms that includes generalist and specialist predators, parasitic wasps and flies, and pathogenic microbes and nematodes.

2. Aphids (Hemiptera: Aphidae)

2.1. Aphid Species and Damage

Lettuce aphid: *Nasonovia ribisnigri*
Green peach aphid: *Myzus persicae*
Foxglove aphid: *Aulacorthum solani*
Lettuce root aphid: *Pemphigus bursarius*

2.1.1. Description of pest

The lettuce aphid originates from Europe (Blackman & Eastop 2000; Parker *et al.* 2002). It became established in California in 1998 and arrived in other western states in 1999 (Chaney 1999; Palumbo 2000). Currently, the lettuce aphid is one of the most important arthropod pests of lettuce (California Lettuce Research Board 2003). In its native range the lettuce aphid passes through a sexual phase, mates, and overwinters in the egg stage on currant and other plants in the genus *Ribes*. However, in California the lettuce aphid does not pass through a sexual phase. Under optimal conditions, newly-born lettuce

aphids require 6 to 12 days to reach adulthood; adult females produce 3 to 5 nymphs per day (Diaz & Fereres 2005). The lettuce aphid's coloration varies from green to orange to pink. The adults have dark bands crossing the width of their bodies (University of California 2004).

Before the lettuce aphid appeared in California lettuce fields in 1998, the green peach aphid was the primary aphid pest (University of California 1985; Hinsch *et al.* 1991). The green peach aphid attacks many crops. Green peach aphids range from yellow to dark green. Under magnification, the green peach aphid can be identified by its converging tubercles at the base of the antennae.

The foxglove aphid is similar in appearance to the lettuce aphid. Its color may be green or orange or pink. However, adults have dark patches near the base of their cornicles, and do not have dark bands across their bodies.

The lettuce root aphid is distinct from other aphid pests of lettuce because it lives below the soil surface and feeds on the roots (Dunn 1960). Lettuce root aphids bear a white waxy coating, have short antennae, and undeveloped cornicles. Because lettuce root aphids pass the winter in the egg stage on Lombardy poplar trees, they cause the most damage in lettuce fields near these particular trees.

3.1.2. Damage

Aphids damage lettuce primarily by contamination: the presence of numerous insects in heads of lettuce renders the lettuce unmarketable. The lettuce aphid and the foxglove aphid are found near the center of the plant (MacKenzie & Vernon 1988; Liu 2004; University of California 2004). The green peach aphid is dispersed throughout the plant (University of California 2004). The lettuce root aphid does not occur on the leaves; rather, it damages lettuce by feeding on the roots. Large numbers of lettuce root aphids can cause lettuces to wilt, brown, and die. Aphids can also damage lettuce by transmitting viruses. The green peach aphid and the foxglove aphid are vectors of several viral diseases of lettuce, including the lettuce mosaic virus. The lettuce aphid does not appear to transmit viruses in California (Liu 2004).

2.2. Biological control

2.2.1. Current parasitoids, predators and pathogens

The complex of aphids in lettuce is attacked by a suite of predatory insects. Aphids are also killed by entomopathogenic fungi and parasitoid wasps.

Lady beetles (Coleoptera: Coccinellidae)
Lady beetles are active aphid predators both as larvae and as adults. Species found in lettuce fields include *Coccinella septumpunctata* and *Hippodamia convergens*. Lady beetles are most likely to contribute to aphid control in the spring.

Lacewings (Neuroptera: Chrysopidae)
Larval lacewings are generalist predators that include aphids in their diet. Lettuce fields are populated by both green lacewings (*Chrysopa* spp. and *Chrysoperla* spp.) and brown lacewings (*Hemerobius* spp.).

Syrphid flies (Diptera: Syrphidae)
A complex of more than ten species of syrphid flies provides a major contribution to aphid control (Smith & Chaney 2007). Syrphid flies have a number of characteristics that make them especially strong candidates for providing effective aphid control. Adults are highly mobile, enabling females to distribute eggs over large areas and exploit patchily distributed aphid colonies when overall aphid densities are low. As aphid densities range from low to high, some species of syrphids respond by increasing their

oviposition rate (Bargen *et al.* 1998; Scholz & Poehling 2000; Sutherland *et al.* 2001); this density-dependent response is unusual among aphid predators. Female syrphids exhibit a second behavior that distinguishes them from other aphid predators, such as lady beetles and lacewings: they will continue to deposit eggs into aphid colonies that already contain enough larvae to consume all of the aphids, resulting in accelerated and complete extinction of the aphids (Chandler 1967). Syrphid larvae are aphid specialists (Gilbert 1993; Dixon 1998) that have the capacity for short handling times and high killing rates.

2.2.2. Classical biological control

We are not aware of any classical biological control programs targeting these aphids in California agricultural fields.

2.2.3. Augmentative biological control

Green lacewings are readily available from commercial insectaries and augmentative releases of their eggs have been conducted in several crops (Olkowski 1999; Swezey 1999; Daane & Hagen 2001). An augmentative release of green lacewing eggs was conducted by Toscano (2000) in experimental lettuce plots in the Coachella Valley, but the additional lacewings provided no additional aphid control. Augmentative releases of green lacewings in central coast lettuce appeared to succeed in reducing lettuce aphid numbers, although this effect may have been partly due to a correlated increase in syrphid fly activity (Wunderlich & Chaney 2001). The UC IPM pest management guidelines suggest that by the time aphids are sufficiently abundant to support the development of larval lacewings, the aphid populations have already reached damaging levels and escaped control by predators.

Augmentative biological control has been applied to the green peach aphid in crops other than lettuce. For instance, inoculative releases of the predatory midge *Aphidoletes aphidimyza* served to control the green peach aphid in field-grown peppers in New York (Meadow *et al.* 1985).

The most promising biological control agents for controlling the lettuce root aphid are soil-dwelling entomopathogenic nematodes and fungi (Chandler 1992). Researchers in the UK have isolated a strain of fungus that consistently killed lettuce root aphids in laboratory trials (Chandler 1997).

2.2.4. Conservation biological control

To enhance syrphid-based control of aphids in lettuce, many growers of organic lettuce in the Salinas region include insectary plants in their fields (Smith & Chaney 2007). Some growers use sweet alyssum (*Lobularia maritima*) alone and others use multispecies blends. Thus, syrphid efficacy is apparently robust to temporal and spatial variation in insectary plant species composition, aphid pest pressure, syrphid species composition, and abiotic conditions. The practice of planting insectaries in lettuce fields is supported by two lines of research. First, the function of syrphids in aphid control was demonstrated by applying an insecticide to experimental plots of lettuce. The application of spinosad was at a rate that killed syrphid larvae without affecting aphids. Syrphid-excluded plants suffered aphid densities five to twenty times higher than occurred in syrphid-accessible plants (Smith *et al.* 2006). Second, transects running across rows of lettuce fields showed that syrphid egg densities were higher adjacent to the alyssum strips, and lower at distances greater than 50 feet away from the alyssum. Subsequently, lettuce aphid populations were reduced in the lettuce adjacent to the alyssum, and remained high at distances away from the alyssum (Colfer 2004) . Thus, existing evidence indicates that insectary plantings boost syrphid oviposition rates, that syrphids suppress aphid populations, and that control is sufficiently reliable and effective that insectary plants are an economical tool for growers.

2.3. Cultural control

Metalized mulch reduced colonization by alate aphids in the laboratory but did not work in the field (Chaney 2000). Metalized mulches have worked in other vegetable crops, including zucchini and squash (Johnson *et al.* 2004). Metalized mulches incorporate aluminum foil and are thought to function by altering the appearance of the field to the winged aphids, thereby disrupting the migrating aphids' ability to detect a host plant.

3. Leafminers: *Liriomyza* spp. (Diptera: Agromyzidae)

3.1.1. Description of pest

Leafminers in the genus *Liriomyza* are pests on a number of crops including peas, potato, celery, and lettuce (Martin *et al.* 2005). The principal leafminers attacking lettuce are the serpentine leafminer, *L. trifolii*, the vegetable leafminer, *L. sativae*, and the North American pea leafminer, *L. langei*. The pea leafminer was previously regarded as a single species throughout the world, named *L. huidobrensis*. However, a genetic analysis in 2001 revealed that the flies living in California that appear to be *L. huidobrensis* are genetically distinct and are now regarded as a separate species, *L. langei* (Scheffer & Lewis 2001). Further differentiation occurs within California: populations of *L. langei* in southern and central California are genetically distinct (Morgan *et al.* 2000). The adult flies are black or gray with a yellow mark between their wings. Larvae feed for 7 to 14 days before exiting their leaf mines to pupate elsewhere on the plant or in the soil (University of California 2004; Martin *et al.* 2005).

3.1.2. Damage

Leafminers cause cosmetic damage to lettuce. Larvae burrow through the mesophyll tissue of lettuce, leaving a whitish trail behind them. Adult females puncture leaves to insert eggs into the leaf tissue, and also to feed on plant sap (Nagata *et al.* 1998; University of California 2004).

3.2. Biological control

3.2.1. Current parasitoids, predators and pathogens

Options for leafminer control are strongly influenced by the feeding location of the larval leafminer. The larva's feeding location below the leaf surface protects it from many chemicals and also from many generalist predators. Parasitic wasps, however, are able to access leafminer larvae, and can maintain leafminer populations below economic thresholds. The parasitoid complex that attacks leafminers on California lettuce has not been fully documented, but it is likely to include genera recorded from leafminers on lettuce in Arizona and Ontario, Canada: *Opius*, *Diglyphus*, *Dacnusa*, *Chrysocharis*, and *Halticoptera* (Hills & Taylor 1951; Palumbo *et al.* 1994; Olivera & Bordat 1996; Bahlai *et al.* 2006). The UC IPM pest management guidelines state that *Diglyphus* wasps are of particular importance (University of California 2004).

Leafminers may also be controlled by sprays of entomopathogenic nematodes, *Steinernema* spp (Head *et al.* 2003). Nematodes enter leaf mines through oviposition holes and attack the leafminer larvae inside the leaf tissue. *Steinernema feltiae* was shown to suppress a *Liriomyza* infestation of lettuce in a commercial greenhouse (Williams & Walters 2000).

3.2.2. Classical biological control

Liriomyza leafminers are native to western North America; therefore, there have not been any classical biological control programs targeting *Liriomyza* leafminers in California agricultural fields. The complex

of parasitoids that attack *Liriomyza* leafminers has been well characterized, in part to identify biological control agents for importation to other countries where *Liriomyza* leafminers have become an invasive pest species (Murphy & LaSalle 1999).

3.2.3. Augmentative biological control

Liriomyza leafminers are serious pests of flowers and other greenhouse-grown crops. Parasitoids have been released to control leafminers in these closed environments (Heinz *et al.* 1993; Abd-Rabou 2006). At Florida's Disney World amusement park, leafminers in the landscaping are controlled by rearing and releasing *Opius* parasitoids (Petitt *et al.* 1996; Petitt 2004). However, we are not aware of any augmentative biological control programs targeting *Liriomyza* leafminers in open agricultural fields.

3.2.4. Conservation biological control

There are no reports of conservation biological control programs directed at the control of leafminers in California lettuce.

3.3. Cultural control

Because a wide variety of crops can support populations of *Liriomyza* leafminers, a first step to limiting leafminer damage consists of inspecting neighboring fields and locating new lettuce fields at a distance from other infested fields (University of California 2004). Jackson et al. (2004) tested for the effects of soil management practices on pest problems, and found that leafminer numbers were not affected by conventional versus minimum tillage regimes or by inputs of organic matter.

4. Lepidopterans: (Lep.: Noctuidae)

4.1. Moth Species and Damage

Beet armyworm, *Spodoptera exigua*
Cabbage looper, *Trichoplusia ni*
Alfalfa looper, *Autographa californica*
Corn earworm, *Heliothis zea*
Tobacco budworm, *Heliothis virescens*

4.1.1. Description of pest

Beet armyworms vary in color from light to dark olive green; they have a broad stripe along each side and many fine wavy lines along their backs. Beet armyworm eggs are laid on leaves in masses covered with fine cottony hairs. After hatching, beet armyworm caterpillars feed for 2 to 3 weeks before forming a cocoon. Adult armyworms are nondescript moths with brown and gray wings. Beet armyworms also feed on beans, sugarbeets, tomatoes, cotton, alfalfa, and certain weed species (Trumble & Baker 1984).

Looping caterpillars move by arching their backs to bring their rear legs forward. Cabbage loopers are green caterpillars with a narrow white line on each side of their bodies. The caterpillars feed for 2 to 4 weeks, and then pupate in cocoons attached to leaves. Adult cabbage loopers are moths with brown wings bearing a small silver figure eight. The cabbage looper is also an important pest of tomatoes, cotton, and cole crops.

Other damaging caterpillars that occasionally appear in lettuce are the alfalfa looper *Autographa californica*, which can appear in lettuce in spring in the central coast, and the corn earworm *Heliothis zea* and tobacco budworm *Heliothis virescens*, which can occur in the southern desert areas of California.

4.1.2. Damage

Lepidopteran larvae, also called caterpillars or worms, feed on all stages of the lettuce plant. Caterpillars contaminate the crop with their bodies and abundant frass. Caterpillars can destroy plants by skeletonizing leaves and by boring holes through the head, permitting access to diseases and rot.

4.2. Biological control

4.2.1. Current parasitoids, predators and pathogens

Biological control of caterpillars is provided by a variety of natural enemies. Minute pirate bugs, *Orius* spp., and big-eyed bugs, *Geocoris* spp., are generalist predators that pierce and ingest the contents of lepidopteran eggs and small larvae. *Trichogramma pretiosum* is a small wasp that parasitizes eggs of the cabbage looper, the alfalfa looper, the corn earworm, and the tobacco budworm; the parasitized eggs turn black (Harding 1976; University of California 2004). The parasitic wasp *Hyposotor exiguae* is notable for its ability to attack a variety of caterpillars, including the beet armyworm and the cabbage looper (Browning & Oatman 1984; University of California 1985; Henneberry *et al.* 1991). Beet armyworm caterpillars are also parasitized by another wasp, *Chelonius insularis*, and a tachinid fly, *Lespesia archippivora*. Additional parasitoids of cabbage looper caterpillars are the wasps *Copidosoma truncatellum* and *Microplitis brassicae*, and the tachinid fly *Voria ruralis* (Henneberry *et al.* 1991). Caterpillars are also attacked by nucleopolyhedroviruses that occur naturally in the field (Hall *et al.* 1961; Henneberry *et al.* 1991; Vail *et al.* 1999). Infected caterpillars become soft and dark, and their carcasses may ooze a dark fluid.

4.2.2. Classical biological control

The lepidopteran pests of lettuce are serious pests of other crops, including tomatoes, cotton, and corn. Because some of these crops are of major national economic significance, these pests have been the targets of several biological control efforts. For example, more than 17 species of parasitoids and predators have been imported into the United States with the goal of controlling species of *Heliothis*; however, none of these importations have resulted in establishment (King & Coleman 1989).

4.2.3. Augmentative biological control

Lepidopteran larvae are generally maintained below economic thresholds by applications of products containing the microbial insecticide *Bacillus thuringiensis* (Kerns 1996). *B. thuringiensis* sprays are organically acceptable and do not interfere with the activities of biological controls.

The release rates required to achieve control of *Heliothis zea* and *H. virescens* using two parasitoids (one hymenopteran and one dipteran) were calculated by the theoretical models of Knipling (1992). Augmentative biological control of *Heliothis* has been demonstrated, but grower adoption of augmentative strategies has been limited by the costs of producing the control agents. Mass rearing programs for two natural enemies of lepidopteran pests—*Trichogramma* wasps and lacewings—have been sufficiently developed that augmentative releases can be economically equivalent to chemical applications (King & Coleman 1989). *Trichogramma* wasps parasitize lepidopteran eggs, and have been used to control lepidopteran pests in cotton, corn, and tomatoes, among other crops (Ridgway *et al.* 1979; Ridgway *et al.* 1986). Lacewings have been released to control *Heliothis zea* and other noctuid lepidopterans in cotton and soya; however, they have reduced pest densities only in studies conducted inside experimental cages (Ridgway & Jones 1969; Daane & Hagen 2001).

Nucleopolyhedroviruses have been tested for efficacy against lepidopteran pests in a variety of crops, including lettuce (Kolodny-Hirsch *et al.* 1997; Vail *et al.* 1999; Farrar & Ridgway 2000). Under certain conditions, nucleopolyhedroviruses can be as effective as chemical alternatives, but their utility in commercial fields is restricted by their relatively short half-lives (King & Coleman 1989). The formulations of nucleopolyhedroviruses that have been developed for commercial application are marketed under the trade names GemStar and Spod-X.

4.2.4. Conservation biological control

Conserving the naturally-occurring complexes of consumers of lepidopterans is best achieved by delaying or eliminating applications of insecticides that affect beneficial insects (King & Coleman 1989). There have been several attempts to reduce lepidopteran pests by planting flowers near the crop to provide parasitoid wasps and other beneficial insects with nectar and/or pollen resources, but results have been mixed (Lee & Heimpel 2005).

4.3. Cultural control

The UC IPM Pest Management Guidelines recommend that lettuce fields be disked soon after harvest to destroy the larvae and pupae of lepidopteran pests (University of California 2004).

5. Future directions

Every cropping system poses its own unique set of challenges for pest control. Biological control efforts in California's lettuce fields must account for the short crop cycle by using agents that can colonize the crop, increase their population, and suppress the target pest within the narrow time window between the time the pest appears and the date the lettuce is due to be harvested.

Many of the pests in lettuce are also major pests in other, more economically significant crops. Thus, one avenue for developing biological control programs in lettuce is to co-opt parasitoids and predators that have provided biological control in other agricultural systems.

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Biological Control of Key Pests in Grapes[1]

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1. Introduction

Testimonials from farm managers, pest control advisers, and University personnel on the implementation of successful organic farming systems for California vineyards will range from "quite easy" to "nearly impossible." What is the current status of organic grape production in California? Here, we describe the current status and potential for greater adoption of organic management practices through a discussion of arthropod pest management. Because biological and cultural controls are a foundation of organic farming, we discuss the current status of these non-pesticide approaches for the three most important groups of vineyard arthropod pests: leafhoppers, mealybugs, and mites. We also highlight how grape commodity and growing region can influence pest density and damage. We begin with a description of three common pest management approaches in vineyards – organic, sustainable and integrated pest management (IPM).

1.1. Pest management systems.

There is not a universal definition of organic vineyard management, but generally it implies that use of synthetically produced fertilizers, pesticides, and growth regulators are prohibited (CCOF 2005). Soil fertility relies on applications of amendments that include composts of rock phosphate, animal manure and green manure crops, with most organically managed vineyards receiving compost made of pumice and animal manure (1:1), Arthropod pest control is achieved through a combination of biological controls, cultural controls, and approved pesticides. Weeds are controlled primarily through the selection of seeded cover crops, mulches, tilling, and flaming.

Are vineyard managers adopting the available organic farming tools? California's grape acreage in 2003, as reported by the California Agricultural Statistics Service, is estimated at 882,000 acres, and is largely composed of wine and juice grapes (529,000 acres, 60%), followed by raisin grapes (260,000 acres, 29.5%), and table grapes (93,000 acres, 10.5%) (California Agricultural Statistics 2003). Of this, about 1% is organic. What limits the successful development of organic vineyard management practices? Clearly, there is a considerable market for organic grape products, with California seeing a relatively steady increase in organic agriculture from 1992 to 2002 and a double-digit average annual growth in

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registered acreage and sales (Klonsky 2002). In fact, growth of organic agriculture using these measures was considerably faster than in California agriculture as a whole.

One aspect of growing "organic" grapes as opposed to utilizing "organic" or "sustainable" pest management practices is the certification process. Vineyard managers can select from a number of different organic certification agencies (National Organic Program 2005); however, new since 2002, the USDA National Organic Program has set standards for practices and products labeled "organically grown". For table and raisin grapes, the organic certification is based on how the grapes are handled in the field. The rewards are commonly increased sales prices, which helps offset the increased labor costs for vineyard management (Klonsky 2002). For wine grapes, the recent changes in the certification process require wine labels to include an "ingredient statement." These changes were made to help consumers determine whether they were buying wine made according to organic regulations, or whether just the vineyard management practices conformed to organic standards. Kennedy (2003) summarized how these labeling changes impact organic wine production. Briefly, the USDA's National Organic Program regulations define three levels that require certification: "100% Organic," "Organic," and "Made with Organic Grapes." A fourth category is for products with <70% organic ingredients. These changes greatly impact winemakers because "100% Organic" wine can only be made from organic grapes and organic ingredients post-harvest. This prohibits the addition of yeast for fermentation. Those making "Organic" wine may add yeast, certain acids, and a few other non-organic ingredients and processing aids, but they may not add sulfites, a common addition to many wines. If a vintner adds sulfites, the wine must be labeled "Made with Organic Grapes." For the fourth category, when the only organic claim is in the ingredient statement, the winemaker does not need to be certified, and may use any ingredients that are used in non-organic wine.

The level of complexity in the labeling is certainly lost on most consumers, who will not distinguish between different levels of organically grown. This may remove much of the market value for producing "100% Organic" wine. For this reason, many grape growers, especially for wine grapes, have adopted "sustainable" farm management rather than organic. This is an important market issue as wines made without sulfites may appeal to people with sulfur allergies (about half the population). However, these wines are notoriously unstable and frequently spoil more readily. Secondly, the 'healthy food market" for organic wines has been limited as there is considerable pressure in most markets to stock wines that cost $9-12 per bottle. For many organic producers, this is not a profitable niche as their wines are hand-crafted and more costly to produce.

Sustainable agriculture integrates three main goals – environmental health, economic profitability, and social and economic equity (SAREP 2005). For all management practices used, the stewardship of both natural and human resources is of prime importance. However, unlike the organic label, there are no regulations that govern what is or is not sustainable vineyard management. Moreover, achieving sustainability on any farm may, in fact, be a moving target as the pest problems encountered and available materials change constantly and will vary among vineyards and regions. Therefore, a systems perspective is essential to place the vineyard management practices in context with the local ecosystem, and to communities affected by the selected farming practices.

To help set a working definition for sustainable vineyard management a joint effort by the California Association of Winegrape Growers, the Wine Institute, and the Lodi-Woodbridge Winegrape Commission (LWWC) produced a workbook, *Code of Sustainable Winegrowing Practices Self–assessment Workbook* (Ohmart 2004). There are now a few third party certification programs for the sustainable production of winegrapes. For example, LWWC launched a program called "*The Lodi Rules for Sustainable Winegrowing*" and the third party certifier is Protected Harvest (www.protectedharvest.org). This is a unique program because in order to qualify for certification a vineyard must achieve a minimum number of farming practices points and not exceed a maximum

number of pesticide environmental impact units calculated using a multi-attribute, pesticide impact model developed by Dr. Chuck Benbrook. Another third party sustainable certification program for winegrapes in Oregon is called "*Oregon Live*" and the third party certifier is IOBC.

In the IPM systems approach, pests or their damage are controlled through a combination of techniques that emphasize biological and cultural controls, the use of resistant varieties, and the selective use of pesticides (Mills and Daane 2005). Work in California vineyards has received worldwide recognition for the development of IPM techniques. In fact, the early development of IPM theory relied on "case studies," used to advance and verify some of the foundation principles and, key among these case studies were examples from California vineyards (Hoy and Herzog 1989). However, programs developed in the 1950-1960s and highlighted in the 1970s have undergone dramatic changes as new, exotic vineyard pests arrived and required alterations to the IPM systems developed. The repeated scenario of newly invasive vineyard pests has its most profound impact on the ongoing biological control programs when broad-spectrum pesticides are used to control the invasive pest (Flaherty *et al.* 1992a). This also increased the growers' reliance on timed pesticide sprays rather than an IPM systems approach.

2. Adopting organic vineyard practices

2.1. California market

California agricultural markets reached 27.8 billion in cash receipts in 2003, or 13% of the gross agricultural receipts in the U.S.A. (California Agricultural Statistics 2003). Grapes constitute one of the more valuable agricultural commodities, with ≈880,000 productive acres valued at ≈2.5 billion dollars (U.S.). California ranks fifth worldwide in productive grape acres and third in yield, indicating California's importance in this market. Beyond its agricultural value, California grape production has provided consumers a visible and positive image of the systems approach used in organic farming, sustainable agriculture, and IPM.

It is difficult to assess the level of adoption of sustainable or IPM farming practices, however, the acreage of organic farms can be monitored, as well as the kinds and amounts of pesticides used in vineyards. California law requires all growers marketing organic agricultural products to register with the California Organic Program, run by the California Department of Food and Agriculture, and to report sales and acreage by commodity. Registration data for the California Organic Program showed a substantial ($330 million) market for organically grown commodities. Organic agriculture represented approximately 1% of the total cash income from all California agriculture in 2003 (excluding livestock and poultry), with organic fruits and nuts representing 1.4% of the state total.

Organic grapes led all other commodities in sales (Table 1, after Klonsky [2002]) and comprised over 10% of the organic market in California (excluding livestock and poultry). There were more than twice the sales of organic wine grapes than raisin or table grapes although the percentage of organic wine grapes, based on the total wine grape sales, was actually smaller than that for raisins or table grapes. Part of this can be explained by the lack of clear premiums for organic wine. This percentage may continue to shrink, as a result of the new labeling regulations for 100% Organic wine. Organic wine prohibits the common practice of sulfite addition in the fermentation process. For this reason, the bulk of winegrapes grown using organic farming practices is used in wines labeled as "Made with Organic Grapes." Sulfites are used in these wines. We should also note that wine grape farmers are using organic or sustainable farming practices, but not marketing their grapes as such because the cost premiums are based on the overall quality of the fruit and wine. For example, a ton of Zinfandel grapes in Lodi can sell from $400 to over $2000, depending on the quality. Any organic premium pales in significance to this variation in price.

2.2. Commodity and regional differences

Production of the different grape commodities (wine, raisin, table and juice) is spread over a wide geographic range within California. Within each region, different commodities tend to predominate: table grapes are produced in the San Joaquin Valley and Coachella Valley; raisin grapes in the San Joaquin Valley; and the major wine grape regions include the North Coast, Central Coast, Central Interior, Sierra Foothill, and Southern California.

The wide geographic range in grape production disperses the economic gains to many regions, but can also dramatically alter the pest problems encountered and needed management system used. When applicable, we will indicate when and how regional influences impact the kinds, abundance and type of pest damage. We believed such regional differences would profoundly impact the vineyard managers' ability to farm using organic practices, resulting in more organic acreage in the coastal regions, where there is less pest pressure. However, the distribution of organic vineyard production follows the typical location patterns for other commodities. For example, about 33% of the state's total organic acreage was located in the San Joaquin Valley in 2002 (Klonsky 2002). The Sacramento Valley recorded 17% of the state's organic acreage, and the Central Coast about 13%. Part of this difference is explained in the crops produced in each region: 70% of the San Joaquin Valley income was split evenly between fruit and vegetable crops and another 23% was from field crops. In contrast, the Central Coast generated $63 million in sales but 94% were from fruits and vegetables and less than 1% from field crops. There is also considerable difference within each region of the amount of organic acreage compared with total grape acreage. For example, while 33% of the organic grape production was located in the San Joaquin Valley, this was a fraction (<0.25%) of the total grape acreage in this area. In the Northern Coast wine grape region, 18% of wine grapes grown in Mendocino County are organic, compared with only 2.4 and 0.7% in the neighboring counties of Napa and Sonoma.

Along with regional differences, there are also different levels of acceptable economic injury thresholds – for the same pest – among wine, table, raisin commodities. Generally, wine and raisin grapes can tolerate more pest damage than table grapes, in which the cosmetic quality of the grape cluster impacts market value. It is not surprising then to find most organic vineyards are managed for wine grapes. Therefore, developed pest management systems will not work for all regions or all commodities. For example, the level of pest reduction by biological control agents in a raisin vineyard may not be acceptable in a neighboring table grape vineyard.

2.3. Arthropod pests

In the following presentation we will highlight the biological and cultural controls currently available and the new controls needed for three groups of pests: leafhoppers, mealybugs, and mites. There are excellent summaries of the available scientific literature for vineyard biological control programs (Flaherty and Wilson 1999), vineyard pest management (Flaherty *et al.* 1992a), and vineyard cover cropping (Ingels *et al.* 1998), which we have drawn upon here. Pesticide use patterns are discussed in a separate section. Clearly, one of the best methods to improve natural enemy presence in the vineyard is the elimination of broad-spectrum, long-residual pesticides, which is a requirement of organic certification.

3. Leafhoppers: *Erythroneura* sp. (Hem.: Cicadellidae)

3.1. Leafhopper Species and Damage

3.1.1. Description of pest

Two leafhopper species are of primary concern: the western grape leafhopper, *Erythroneura elegantula* Osborn, and variegated leafhopper, *Erythroneura variabilis* Beamer (Daane and Costello 1998, 2000, Wilson *et al.* 1992a, Wilson *et al.* 1992b). While these leafhoppers are closely related, there are important biological and regional differences that result in the disparate effectiveness of key biological control agents and, thereby, different control measures may be required.

The western grape leafhopper (WGLH) has been a pest of California vineyards since the 1870s and can be found in most regions. In the San Joaquin Valley, the WGLH is usually found at its highest densities early in the season and declines thereafter – its low abundance is due, primarily, to biological controls (described below). In the Central Interior, Central Coast and North Coast regions, WGLH populations occasionally reach damaging levels and pesticide treatments are required. The variegated leafhopper (VLH) was first reported in southern California in 1929; in the 1980s VLH moved north into the San Joaquin Valley and displaced WGLH as the primary vineyard pest (*Settle and Wilson 1990b*). At present, VLH is commonly found in the Coachella Valley and San Joaquin Valley, and in isolated Central Coast and Central Interior regions.

3.1.2. Damage

Leafhopper nymphs and adults cause direct damage to grape leaves as they feed, puncturing individual leaf cells and reducing the leaf's photosynthetic capacity (Daane and Costello 2000, Wilson *et al.* 1992a, 1992b). Untreated leafhopper populations can build to such high densities that all leaves are dry and damaged, resulting in sunburned clusters and severe crop loss. Adult leafhoppers are also a nuisance pest when they fly into the eyes, ears, noses, and mouths of workers (Wilson *et al.* 1992a). During field operations, especially hand-harvest, this lowers worker productivity and, for this reason only, short residual pesticides are often used at harvest-time. The accumulation of small droplets of leafhopper excretion on grape clusters, and the associated sooty mold, also results in indirect or cosmetic damage.

The extent of damage varies with leafhopper species and density, vine condition, and commodity. For example, leafhopper development and feeding injury is closely tied to temperature, such that vineyards located in warmer regions (e.g., southern San Joaquin Valley) typically have higher leafhopper densities and damage than vineyards in cooler regions (e.g., Central Coast) (Wilson *et al.* 1992a, Wilson *et al.* 1992b).

Vine condition also impacts leafhopper density and direct damage, with well-watered watered vines (e.g., table grapes) able to support a higher leafhopper population densities with less direct damage than water-stressed vines (e.g., raisin or wine grapes) (Daane and Williams 2001). The extent of indirect damage also varies among the different grape commodities. Firstly, adult leafhoppers as a nuisance pest become less important when mechanical harvesters are used in wine, juice or raisin vineyards. Secondly, the berry spotting resulting from leafhopper excretion is a concern for table grapes and will prompt farm managers to apply pesticides at relatively low leafhopper densities. In contrast, berry spotting is not as great a problem for wine, raisin, juice grape quality.

3.1.3. Treatment thresholds

Studies that correlate leafhopper density to yield have been conducted on only a limited number of grape cultivars, and typically in the San Joaquin Valley. In a Thompson Seedless vineyard reductions in yield or sugar did not occur even when populations of first and second broods reached peaks of 20 and 25 nymphs per leaf, respectively, using conventional sampling methods (Daane and Costello 2000). Part of the reason that grapevines are able to tolerate such apparently high-leafhopper populations is because:

(1) Leafhoppers are small insects and are not able to cause much injury relative to total leaf area of a vine.

(2) As leafhoppers prefer to feed on shaded leaves in the interior of the canopy, much of the damage is to photosynthetically less active leaves.

(3) During each season, vines can lose up to 20 percent of their leaves without any yield or maturity loss, provided the leaves are not removed until about a month after fruit set. Generally, one leafhopper results in a 1 percent leaf loss per vine during its lifetime.

(4) As with most perennial crops, grapevines store energy in the form of remobilizable carbohydrates, primarily in their trunks and roots. This provides vines with a buffering capacity. Although leafhopper damage may be extreme during a season, the vines are able to compensate by remobilizing these stored carbohydrates. Repeated high levels of damage over a 2- or 3-year period may, however, affect a vineyards long-term vigor and productivity.

Treatment thresholds vary for raisin, wine and table grapes. These thresholds are suggestions as management decisions will be based not only on leafhopper density but on commodity, region, and vine vigor, as well as each manager's personal comfort with some level of leafhopper damage. Moreover, work in a Thompson seedless vineyard, in the San Joaquin Valley, showed that the same leafhopper counts (e.g., 15 nymphs per leaf) had very different levels of vine damage depending on the amount of irrigation water provided. Vines with more vigor and more shoot growth had less vine damage, while water-stressed vines had more leaf damage with the same number of leafhoppers per leaf.

For raisin and wine grapes, tolerance levels are set by either the amount of damage to the vine and the resulting decline in yield, or adult leafhoppers reducing worker productivity during harvest operations. Treatment thresholds for the variegated leafhopper typically range from 15 to 20 nymphs per leaf during the second or third brood, which is a bit lower than that for the grape leafhopper because the variegated leafhopper damage is more severe and biological controls are less effective.

For table grapes, as adults and nymphs feed, their excretions fall on the tops of the berry clusters and cause cosmetic damage. Excessive spotting or leafhopper droppings determine the economic damage level on table grapes because this cosmetic damage will occurs long before any reduction in sugar or yield can be measured. For these reasons, economic injury levels for second brood leafhoppers are typically set between 5-10 nymphs per leaf, using the conventional sampling program.

Grape-growing regions impact the levels of damage caused by leafhoppers variegated leafhopper. For example, warmer regions have a longer growing season for both the vine and its leafhopper pest, resulting in more broods per year and higher leafhopper densities, if the pest is not controlled. For examples, in the Coachella Valley, variegated leafhopper has as many as six broods annually, and levels of natural control are relatively poor. This can results in large and damaging populations. In the San Joaquin Valley and those coastal and upland regions where variegated leafhopper is found, overwintered leafhopper adults typically begin to move into the vineyard in March (warmer areas) and April (cooler areas) and begin to deposit eggs after the first flush of vine growth.

The first nymphs are commonly seen in early May, depending on seasonal temperatures. It is not recommended to treat vines to kill overwintering adults or first brood nymphs, unless these populations themselves are so damaging as to require treatments. First, in most of these regions, the grape leafhopper can also be found and it is important to consider both grape and variegated leafhopper populations when making treatment decisions. While both leafhopper species have a high reproductive potential, predators and parasites can negate most of the potential of grape leafhopper, but they can affect only part of the reproductive potential of variegated leafhopper.

3.2. Leafhopper Biological Controls

3.2.1. Current parasitoids, predators and pathogens

Egg parasitoids. The most important natural enemies of variegated leafhopper eggs are the tiny mymarid wasps (*Anagrus* species). Parasitoids recovered from variegated and grape leafhopper eggs form a complex of related species. Currently, three different *Anagrus* species are known to attack leafhopper eggs in North American vineyards. Recent work has provided better identification of these parasitoids, which were formerly called *Anagrus epos* Girault but are, in fact, a complex of closely related species. Currently, four different *Anagrus* species are known to attack grape leafhopper eggs in North America. The two most common in California are *Anagrus erythroneurae* Triapitsyn and Chiappini and *Anagrus daanei* Triapitsyn. A third species is *Anagrus tretikoviae* Triapitsyn, which is found in warmer regions (Arizona, New Mexico, Mexico). *Anagrus epos* does attack grape leafhopper eggs, but it is more typically found in colder regions (Colorado, Canada, Illinois), although this species is currently being investigated as a parasitoid of the glassy-winged sharpshooter

These parasitic wasps are able to locate and attack a high percentage of the grape leafhopper eggs (Daane and Costello 2000, Wilson *et al.* 1992b). However, their effectiveness against the variegated leafhopper has not been nearly as good (Settle and Wilson 1990a, Wilson *et al.* 1992a, Wilson *et al.* 1992b). As a comparison, in the San Joaquin Valley, parasitism of grape leafhopper eggs often exceeds 90 percent early in the second brood, but rarely exceeds 40 percent at that time for variegated leafhopper eggs. Lower parasitism levels of variegated leafhopper, compared with grape leafhopper, is thought to result from the egg location in the leaf. Variegated leafhopper oviposits most of its eggs adjacent to or within leaf veins. Also, while the eggs are laid under a single layer of leaf epidermal cells, they are clearly deeper in the leaf tissue than the grape leafhopper eggs. As a result, the variegated eggs are apparently more difficult to find by the adult *Anagrus*. Observations reveal that the adult female *Anagrus* spends most of her time in the interveinal areas, searching for leafhopper eggs. When she encounters the grape leafhopper egg blister, near the leaf surface, she usually stops to quickly insert her ovipositor and deposit an egg, and then immediately resumes the search for other leafhopper eggs. The variegated leafhopper egg is also more slender than the grape leafhopper egg, which might make it a less desirable host.

Larval parasitoids. *Aphelopus albopictus* Ashmead is a dryinid wasp that attacks grape leafhopper nymphs. In Central Valley vineyards, parasitism rates from 0 to 77 percent have been reported. The adult female parasitizes the larger leafhopper nymphs (third, fourth, and possibly fifth instars) by placing an egg under the leafhopper abdominal segments. The egg does not hatch until the leafhopper nymph molts to the adult stage. The *Aphelopus* larva then starts to develop, appearing as light colored, oval mass protruding from the adult leafhopper's first abdominal segment. Eventually, the *Aphelopus* larva eviscerates and kills the adult leafhopper. The fully developed parasite larva then drops to the soil, spins a cocoon, pupates, and after about 20 days emerges as a sexually active adult. There are no known effective parasitoids of variegated leafhopper nymphs. Unfortunately, *Aphelopus* rarely attacks the variegated leafhopper nymphs, even when confined with them in a small cage.

Generalist predators. Several generalist insect predators prey on variegated leafhopper nymphs and adults. Among the most abundant insect predators are *Chrysoperla* spp. (green lacewings), *Orius* spp. (minute pirate bugs), *Nabis americoferus* Carayon (damsel bug), *Hippodamia convergens* Guérin-Méneville (ladybird beetle), *Geocoris pallens* Stål (big-eyed bug), *Hemerobius* spp. (brown lacewings), and tiger flies (*Coenosia humilis* Meigen and *Coenosia tigrina* Fabricius). The tiger flies are predaceous in the adult stage, catching their prey in flight, and spend their larval period in the soil as predators of earthworms. Therefore, their role is both beneficial (as adults) and potentially destructive (as larvae). For most of these predators, there is little known about their impact on variegated or grape leafhoppers. While

they are considered to attack leafhopper and other vineyard pests, none have been shown to be directly responsible for leafhopper control.

First instar leafhopper nymphs have also been observed being attacked by the predaceous mite, *Anystis agilis* (Banks), in the San Joaquin Valley (Wilson *et al.* 1992a, Wilson *et al.* 1992b). In most surveys, spiders comprise more than 90% of the leafhopper predators found in the vineyard (Costello and Daane 1995, 1999). There are more than 50 spider species in San Joaquin Valley vineyards; however, less than 10 species comprise most of the spiders found on the vines. Spiders are often grouped by their mode of hunting prey. There are the large nocturnal hunters that locate prey by tarsal contact, these include two species of *Cheiracanthium*, *C. mildei* Koch and *C. inclusum* (Hentz) (Miturgidae), *Trachelas pacificus* (Chamberlin and Ivie) (Corinnidae), *Anyphaena pacifica* Banks and *Hibana incursa* Chamberlin (both Anyphaenidae). These spiders are commonly found in grape bunches in summer and under the bark in fall and winter. There are medium sized, diurnal spiders that are visually oriented towards their prey and can jump many times their body length to pounce on and capture leafhoppers. These include *Oxyopes scalaris* Hentz (Oxyopidae) and *Platycryptus californicus* (Peckham and Peckham) (Salticidae). The most obvious spiders on the vine are often the sit-and-wait web-builders, such as the small cobweb weavers (*Theridion dilutum* Levi and *Theridion melanurum* Hahn) (Theridiidae) and lyniphiids (*Erigone dentosa* [O.P.-Cambridge]) (Lyniphiidae), which construct a fine, irregular network of webbing, typically on the underside of leaves. A more obvious sit-and-wait web-builder is a funnel weaver (*Hololena nedra* Chamberlin and Ivie) (Agelenidae), which constructs a large, funnel-shaped web. One of the largest spiders is an orb weaver (*Neoscona oaxacensis* [Keyserling]) (Araneidae); small, immature *N. oaxacensis* spin webs on the grape foliage or trellis wire, but as this species matures, it strings its web between grapevine rows.

All spiders are predators, but what and how much they eat is quite variable among species. Each species has a distinct life history, feeding behavior and habitat preference. Therefore, the spider species complex and the extent of leafhopper control can vary dramatically between vineyards. For example, most spider species kill leafhoppers, but their effectiveness varies. In the laboratory, *Trachelas* and *Cheiracanthium* each ate an average of 12 leafhoppers per day, while the small cobweb weavers killed only 1-2 nymphs per day, the funnel weaver fed only on leafhopper adults, and a common jumping spider *Metaphidippus vitis* (Cockerell) would not feed on leafhoppers. Exclusion experiments (removing spiders from the vines) have shown that spiders can reduce leafhopper numbers. Nevertheless, there is little evidence that spiders can be relied upon for consistent economic control leafhopper populations.

Pathogens. Reports of diseases, such as the fungus, *Beauvaria bassiana*, as mortality agents of variegated leafhopper are sketchy and need confirmation. It is conceivable that this pathogen may exert some control over both leafhoppers.

3.2.2. Classical biological control

To improve biological controls of the variegated leafhopper, an importation program was conducted from 1985 to 1992 (Gonzalez *et al.* 1988). Vineyards in northwestern Mexico and southwestern USA were sampled and three different genera of egg parasitoids were imported. The egg parasitoids were in the families Mymaridae, which included *Anagrus* species and biotypes (Picket *et al.* 1987, 1989) and Trichogrammatidae (*Itysella* sp. and *Paracentrobia* sp., which did not apparently establish in the San Joaquin Valley). A thorough taxonomic analysis of the *Anagrus* species found that these parasitoids, which were formerly clumped as *Anagrus epos* Girault, were a complex of different species that include *A. epos*, *A. erythroneurae* Triapitsyn & Chiappini, *A. tretikoviae* Triapitsyn, and *A daanei* Triapitsyn (Triapitsyn 1998). More important than changes in nomenclature is a better understanding of biological differences. For example, *A. erythroneurae* is the most common parasitoid reared from VLH, while *A. daanei* is more commonly reared from leafhopper species collected in riparian areas.

Similar with the grape leafhopper, the Achilles' heel of these egg parasitoids may be their overwintering requirement – spending the winter months in leafhopper eggs, while the variegated leafhopper overwinters in the adult stage. Because no newly deposited variegated leafhopper eggs are found in the vineyard from October to March, the adult parasitoid numbers drop dramatically in the fall when emerging adult *Anagrus* must search outside the vineyard for alternate leafhopper hosts, such as the prune leafhopper, (*Edwarsina prunicola* [Edwards]), that overwinter in the egg stage.

3.2.3. Augmentative biological control

One problem with spiders as natural enemies is that the species present and their numbers are difficult to manipulate. Although increasing diversity with cover crops may favor predators such as *Trachelas* at certain sites, what makes *Trachelas* the dominant species at one site but other spider species dominant in nearby vineyards will depend on many factors - vine cultivar, trellis system, soil type, regional climate, and management practices (e.g., pesticide use). Another problem is that spider density tends to remain fairly stable with respect to leafhopper density. In other words, when leafhopper populations increase or decrease rapidly, there is not a corresponding change in spider density. This results, in large part, because most vineyard spiders have only 1-3 generations per year, resulting in a slow response. Spiders are also commonly territorial, reducing the numbers on any vine through competition with other spiders – either through avoidance, competition for food and shelter, or "spider on spider predation" (spiders are commonly the best predator of other spiders). One group of spiders that does seem to respond numerical to leafhopper densities is the small cobweavers (*Theridion* spp.). Unfortunately, these spiders tend to build to large numbers at the end of the season, in response to large numbers of leafhoppers, rather than earlier in the season when their predation might help suppress damaging leafhopper densities.

Lacewing larva kill >250 large leafhopper nymphs in laboratory studies (Daane, unpublished data). In part, because of the availability of commercially produced lacewings, releases of lacewing eggs are used to suppress leafhoppers in organically managed vineyards. However, field studies showed that lacewing releases reduced leafhopper densities in only 9 of 20 trials (Daane *et al.* 1996a). Further, the average reduction of leafhoppers in lacewing release plots was only 9.6%, as compared with no-release plots. One reason for this poor performance was the release methodology, which led to high lacewing egg mortality and poor dispersal (Daane and Yokota 1997). Commercial producers and researchers are currently investigating improved release methods, including the release of adult lacewings.

3.2.4. Conservation biological control

Cover cropping. Cover crops are popularly associated with the attraction of natural enemies and lower pest densities (Bugg and Waddington 1994). Maintenance of a season-long cover crop in vineyards has been shown to reduce late-season leafhopper densities, on average at about 20% (Costello and Daane 1998b, 2003, Daane and Costello 1998, 2000). In most instances this level of reduction was too small to be economically important. Further, the mechanism(s) leading to this reduction remains unclear because the addition of cover crops did not consistently lead to higher predator densities. One off-shoot of cover cropping that has been utilized in a few North Coast vineyards is the establishment of a "refuge corridor" or strip of annual and perennial plants that provide pollen, nectar and alternative prey throughout the season. Only one study has looked at the impact of refuge corridors and the authors report a reduction in leafhopper densities (Nicholls *et al.* 2001). We note here that most cover cropping trials have focused on leafhopper control. We suggest that natural enemies attracted to cover crops might have a greater impact on other vineyard pest species, such as mites.

Blackberry and prune refuges. Both the WGLH and VLH overwinter as adults in or near the vineyard, while the *Anagrus* egg parasitoids overwinter in an immature stage inside a leafhopper egg (Wilson *et al.*

1992a, Wilson *et al.* 1992b). Therefore, *Anagrus* must find alternate leafhopper host species that overwinter in the egg stage in order to survive in each region. Doutt and Nakata (1965, 1973) demonstrated that *Anagrus* (at that time referred to as *A. epos*) overwinter in the eggs of the blackberry leafhopper, *Dikrella californica* (Lawson). Eventually, researchers found that other leafhopper species also serve as overwintering hosts, most notably, the prune leafhopper, *Edwardsiana prunicola* (Edwards), the rose leafhopper, *Edwardsiana rosae* (L.), and the white apple leafhopper, *Typhlocyba pomaria* (McAtee) (Kido *et al.* 1984, Wilson *et al.* 1989, Triapitsyn 1998).

In the 1970s, researchers attempted, unsuccessfully, to increase the number of *Anagrus* overwintering near the vineyard by planting blackberry refuges to increase blackberry leafhopper abundance (Williams 1984, Wilson *et al.* 1992a). In the 1990s, French prune tree refuges were similarly planted to increase prune leafhopper abundance (Murphy *et al.* 1996). Corbett and Rosenheim (1996), using rubidium marking to follow *Anagrus* movement, concluded that vineyard colonization by *Anagrus* was related to the distance of prune refuges from vineyards. Nevertheless, recent surveys of commercial vineyards with prune refuges found no increase in *Anagrus* densities (Daane, unpublished data). The primary failure is the refuge's small size, relative to the vineyard, which produces a correspondingly small number of prune leafhoppers. During the summer and early fall, there are millions of *Anagrus* in the leafhopper-infested vineyard and, as the egg source on the vines diminishes, the onslaught of parasitoids overwhelms the relatively small numbers prune leafhoppers. The refuge works in the wrong direction – resulting in nearly complete control of the prune leafhopper from *Anagrus* coming from the vineyard! With no prune leafhoppers, the refuge has no impact.

3.3. Leafhopper Cultural Control

Vine vigor. Trichilo *et al.* (1990) first reported that lower amounts of applied water, and the associated reduction in vine vigor, resulted in lower leafhopper densities. Later studies showed vine vigor could be lowered to reduce leafhopper densities, fecundity, and adult immigration, without reducing crop yield (Daane and Williams 2003). This brought to question the role of cover crops in the suppression of leafhopper populations. Some cover crop species, especially grasses, can reduce available water and nutrients, resulting in lower vine vigor (Wolpert *et al.* 1993). Therefore, a portion of the observed leafhopper reduction found in vineyards with cover crops may result from lowered vine vigor rather than an increase in natural enemies (Costello and Daane 1998a, 1998b, 2003). Given these results, we suggest that cover cropping can be an important tool for vineyard management, but cover crop species selections should considered first for their impact on soil health and vine growth, rather than as a primary tool for pest management.

Sticky barriers. Six-inch wide bands of yellow sticky tape have been used to trap adult leafhoppers that are moving from overwintering habitats into the vineyard. Typically, the sticky tape is rolled out as a single strip down 3-4 of the edge rows, placed at mid-trunk level height. We found only one study of the efficacy of yellow sticky tape, where a 40-50% reduction of first generation leafhoppers was reported (Klonsky *et al.* 1998). For yellow sticky tape to be promoted, studies are needed to follow leafhopper populations up to harvest-time.

Leaf removal. Basal leaves are often removed on wine and table grape to reduce humidity and increase airflow and temperature; the result is lowered powdery mildew incidence (Willocquet *et al.* 1998). In the San Joaquin Valley, leafhopper nymphs, during the first generation, are found primarily on these basal leaves and it is commonly believed that when leaf removal for mildew control is properly timed to coincide with the leafhopper egg hatch, leafhopper densities are also reduced. No studies have been published confirming this observation. Furthermore, egg hatch of first generation of WGLH in the North Coast is in mid-May, which is too early for leaf removal.

3.4. Future for Organic Leafhopper Controls

Leafhoppers are the most common vineyard pest. In the recent past, from the 1970s to mid-90s, a number of highly toxic HCL, OP, and carbamate materials were used for the control of leafhoppers. In the mid-1990s, a nicotinoid (imidacloprid) was registered for use and was soon widely adopted for leafhopper control. Imidacloprid has few of the negative impacts associated with the carbamates and organophosphates.

Are there organic farming techniques for leafhoppers that are as effective and inexpensive as the new synthetic pesticides? Firstly, the more damaging VLH is not found in all vineyard regions and, when present, leafhopper densities (and damage) can vary depending on vine vigor, regional temperature, and management practices. Secondly, natural enemies provide excellent control of WGLH, which is the more widespread species. Thirdly, wine, raisin and juice grape commodities have a higher tolerance for leafhopper damage. We therefore suggest that leafhopper populations encountered in the North Coast and Central Coast regions can be effectively managed without synthetic pesticides. In regions where VLH predominates and pesticides are needed, there are organically approved botanicals, oils, and soaps. All of these materials are reported, in grower testimonials or industry advertisements, as providing leafhopper control. There are few scientific studies that verify their impact, although Bentley *et al.* (2000) showed that horticultural mineral oils, applied prior to bloom, suppressed both WGLH and VLH populations. Some negative aspects of these materials are that some wineries do not like soap-based products and restrict their use to early-season applications. Similarly, oils can change the cosmetic appearance of the fruit. The most effective products are the botanicals; as mentioned, the botanicals are rather broad spectrum materials and control has been inconsistent reported with different formulations. These concerns also need to be addressed.

If any of these organic materials are to be used, the following suggestions are provided to maximize pesticide effectiveness and minimize impact on biological controls (Daane and Costello 2000). Firstly, for all arthropod pests the farm managers should utilize effective monitoring programs and record pest populations in each block and from year to year. Many pesticide applications are made before leafhopper nymphs reach damaging thresholds. Secondly, avoid use of the botanicals for the overwintering adult generation. Only treat the first generation nymphs when the population is very high as little damage is caused during this time of the season, and delaying applications until the later generations allows time for natural enemies to establish. These botanicals are broad-spectrum and can have a negative impact on natural enemies. Thirdly, time the application to the most appropriate leafhopper stage. Most of the conventional pesticides kill by both contact and a systemic or fumigation action and, therefore, can be effective against adult and nymph stages. Soaps and oils kill by contact only, and may be most effective against the smaller nymphal development stages.

4. Mealybugs: *Pseudococcus* and *Planococcus* species (Hem.: Pseudococcidae)

4.1. Mealybug species and damage

There are four mealybug species that cause economic damage in California vineyards – grape mealybug, *Pseudococcus maritimus* (Ehrhorn), obscure mealybug, *Pseudococcus viburni* (Signoret), longtailed mealybug, *Pseudococcus longispinus* (Targioni Tozzeti), and vine mealybug, *Planococcus ficus* Signoret (Godfrey *et al.* 2005).

4.1.1. Description of pests

Adult female mealybugs are about 4 mm; the body shape is an elongated oval that is somewhat flattened from top to bottom. After each molt, wax secretion from hundreds of small pores on the dorsum (top)

begins to cover the mealybug. This gives it a white, cotton-like appearance, even though the mealybug's body color actually ranges from faded pink to purple. Along the lateral margin the wax secretion forms filaments, which look like small spines, with a pair of longer posterior "tail" filaments near the anus. These posterior filaments may help flick the honeydew away from the mealybug.

Just before eggs are laid, gravid adult females begin to secrete wax to form a shelter for the egg mass, called an "ovisac". The ovisac resembles loose cotton threads and can be 1 cm long, appearing larger than the female. Eggs are deposited underneath the ovisac. Over 1000 eggs have been recorded in a single female's ovisac, although most contain between 100 and 400 eggs. The ovisac helps to cluster the developing eggs and protect them from natural enemies as well as desiccation. The deposited ovisac sticks to the vine substrate and will remain there long after the eggs hatch and the crawlers leave – especially those ovisacs deposited under the bark. The first instar nymph hatches from the egg and leaves behind a white, collapsed egg shell. The newly hatched mealybug is small, about 0.6 mm long, elongate-oval in shape and extremely flat. It moves quickly to find a feeding spot, hence its common name "crawler." There are three molts, resulting consecutively in the second instar, third instar, and the "immature" adult. Each of these stages resembles the previous except for an increasing size and amount of wax secretion that results in a thicker cotton pelt or covering.

Male vine mealybugs have a different life-cycle than the females. From egg to third instar, the males generally resemble the females, with the exception that the males are slightly more elongate and narrow. Then, after the third instar, the male develops to a pre-pupa, next to a pupa, and finally to a winged adult male that emerges – the only mealybug stage with wings. The adult male is about 1.5 mm (1/15 inch) long, with a brown colored body and many segmented antennae that are about half the body length. Most evident are the long opaque wings that cover the body and extend well beyond the abdomen, which has a long pair of wax filaments. The adult male is fragile, not a strong flyer, does not feed, and lives for only hours or a few days in the heat of the summer months.

All of the *Pseudococcus* species have long been resident in California. In contrast, the vine mealybug is a newly invasive species that was first collected on Coachella Valley table grapes in the early 1990s. Each mealybug species has different biological attributes, resulting in different development and reproductive rates, honeydew excretion and feeding locations. These biological attributes determine the amount of damage each mealybug can cause, and the grape growing regions they infest. Generally, the obscure and longtailed mealybugs are restricted to coastal vineyards, the grape mealybug most often found in the North Coast region, the Central Interior, and San Joaquin Valley, and the vine mealybug can now be found in most California vineyard regions, although in most regions the infestations are isolated.

4.1.2. Damage

All of the vineyard mealybugs can feed on the vine's trunk, canes, leaves, or fruit (Flaherty *et al.* 1992b). Additionally, the vine mealybug can feed on vine roots (Godfrey *et al.* 2003). Damage is primarily caused by the accumulation of mealybugs, their excretion (honeydew), and sooty mold fungi in the grape clusters. Of the four species, the vine mealybug is the most damaging, with untreated populations often resulting in complete crop loss and even vine death. Transmission of leafroll viruses is another aspect of mealybug feeding (Golino *et al.* 1999).

4.1.3. Treatment thresholds

Economic injury levels for mealybug infestations vary among grape commodities. Certainly, table grapes have the least tolerance because any level of cluster infestation will lower crop quality. In comparison, small mealybug infestations in wine, juice or raisin grape clusters have little impact on crop quality. The grape growing region will also impact control decisions. For example, leafroll viruses are more common

in North Coast vineyards, prompting some growers to treat the grape mealybug even when the population density is quite low. Even the grape cultivar grown will influence mealybug damage. Mealybugs overwinter under the bark of the trunk or spurs; the offspring of subsequent generations move up the vine and into the grape clusters (Geiger and Daane 2001, Geiger *et al.* 2001). For this reason, grape clusters on cultivars that are harvested earlier in the growing season, such as Perlette cv., have a shorter period of exposure than clusters on cultivars, such as Flame Seedless cv., that are harvested later in the season.

4.2. Mealybug Biological Control

4.2.1. Current parasitoids, predators and pathogens

The grape mealybug is considered native to North America and has the largest and most effective complex of associated parasitoid species. Clausen (1924) reported >80% parasitism of grape mealybugs collected in San Joaquin Valley vineyards; the most common parasitoids were *Zarophalus corvinus* (Girault), *Anagyrus yuccae* (Coquette), *Acerophagous notativentris* (Girault), *Pseudoleptomastix squammulata* (Girault), and *Anagyrus clauseni* (Timberlake). More recent surveys found lower parasitism levels and a change in the parasitoid species complex, with *A. notativentris* and *Pseudaphycus angelicus* (Howard) as the dominant parasitoids and *Z. corvinus* rarely recovered (Daane *et al.* 1996b). It is not known whether changes in vineyard cultural practices, cropping patterns, pesticide use, or parasitoid activity resulted in these shifts in parasitoid complexes.

The longtailed mealybug, which is the most geographically restricted of the four mealybug species, shares many of these same parasitoid species with the grape mealybug. However, it is poorly controlled by natural enemies where it is found in Central Coast vineyards (Daane, unpublished data).

Lacewings are also commonly found on vines infested with mealybugs. Surveys of coastal vineyards infested with mealybugs found *C. carnea*, *C. comanche*, an unidentified *Chrysopa* Leach, and the brown lacewing *Hemerobius pacificus* Banks (Daane *et al.* 1996b). In pear, *C. carnea* were reported to suppress the grape mealybug populations (Doutt and Hagen 1949, 1950) and, in coastal vineyards, the brown lacewings *Sympherobius californicus* and *S. barberi* were observed feeding on mealybugs and considered to be important predators in the cooler times of the year when other natural enemies were not active. Cecidomyiid flies are frequently found preying on mealybug eggs and small larvae in the ovisac (Flaherty *et al.* 1992b). Charles (1985) reported one cecidomyiid fly species, *Diadiplosis koebelei* Koebele, reduced adult longtailed mealybugs by about 30% in New Zealand. However, like the lacewings, there are no studies of their impact in California. The most common in California is *Dicrodiplosis californica* Felt. Unfortunately, very little is known about the effectives of this predator. Midge eggs and larvae are commonly found in mealybug ovisacs. The fly typically pupates in the ground and the adult is not predatory.

Lady beetles closely associated with mealybugs include *Scymnus* species. Larvae of these lady beetles are also covered with wax and are, for that reason, often mistaken for the mealybug destroyer. In some North Coast vineyards, *Scymnus* were more common than the mealybug destroyer on mealybug infested vines. However, there is no data on effectiveness of these lady beetles - even to the extent that most beetles are assumed, incorrectly, to be the mealybug destroyer.

Several generalist insect predators prey on mealybugs. Among the most commonly observed in the vineyards are green lacewings (*Chrysoperla* spp.) brown lacewings (*Hemerobius* spp.), minute pirate bugs (*Orius* spp.), damsel bug (*Nabis americoferus* Carayon), ladybird beetle (*Hippodamia convergens* Guérin-Méneville), big-eyed bug (*Geocoris pallens* Stål), and European earwig (*Forficula auricularia* Linnaeus). Two groups of vineyard predators are predaceous mites and spider. In the laboratory, predaceous mites have been observed feeding on mealybug eggs and crawlers. Little is know, however,

about their impact in vineyards. Spiders comprise more than 90% of the insect predators found in the vineyard. While some spiders, such as *Theridion* species, have been observed feeding on mealybugs in vineyards, there are no studies of their impact on mealybug populations and, most likely, their primary prey are leafhoppers and other spiders.

4.2.2. Classical biological control

The obscure and vine mealybugs are considered non-native and have been the target of recent biological controls programs. However, one of the most effective predators was imported long ago for control of the citrus mealybug.

For all of the vineyard mealybugs, the most effective predator is the mealybug destroyer, *Cryptolaemus montrouzieri* Mulsant. This lady beetle was collected from Australia in 1892 and imported into California to help control mealybugs on citrus. While a voracious predator, the mealybug destroyer populations often drop sharply during the winter in California's cooler vineyard regions. In 1996, a "cold-hardy" strain of the mealybug destroyer was collected in southern Australia and released in California (K.S. Hagen, unpublished data). Material from these releases has established and, currently, the mealybug destroyer is found throughout the coastal wine grape regions (Daane, unpublished data). One aspect of the mealybug destroyer that makes it particularly effective is that the larvae have wax-like filaments similar to the mealybugs. This "camouflage" allows these beetle larvae to feed amongst mealybugs without too much disturbance from the mealybug-tending ants.

The most important natural enemies of mealybugs are parasitoids (Dean et al. 1979, Meyerdirk et al. 1988, Neuenschwander and Herren 1988) and these natural enemies have been the focus of recent importation efforts for the obscure and vine mealybugs. Prior to 1993, there were no effective parasitoid species of the obscure mealybug found in California. For this reason, the encyrtids *Pseudaphycus flavidulus* (Brethes) and *Leptomastix epona* (Walker) were imported from Chile in 1996, where they are considered an important part of the successful mealybug management. Both *L. epona* and *P. flavidulus* were initially recovered at the Central Coast release sites (Daane *et al.* 2004a). However, foraging Argentine ants, *Linepithema humile* (Mayr), diminished the success of these natural enemies (Daane *et al.* 2004a, 2007). For this reason, ant controls may be a necessary component of mealybug biological controls – in both organically and conventionally managed vineyards.

As mentioned, the vine mealybug has become the most serious mealybug pest (Daane *et al.* 2006a), in part, due to a lack of effective natural enemies. From 1995-1999, encyrtid parasitoids were imported from Spain, Israel, and Turkmenistan and included *Anagyrus pseudococci* (Girault), *Leptomastidea abnormis* (Girault), *Coccidoxenoides perminutus* (Timberlake), and *Leptomastix dactylopii* Howard. These parasitoid species were previously imported and established in California, as part of control efforts on the citrus mealybug in the 1930-50s (Noyes and Hyatt 1994), but only *A. pseudococci* is widely established, as discussed below.

The encyrtid wasp *Anagyrus pseudococci* (Girault), accounts for more than 85% of the parasitoids recovered from vine mealybug (Malakar-Kuenen et al., 2001, Daane et al. 2002, 2003, 2004), and has been reported as a vine mealybug parasitoid in Israel (Berlinger 1977), Egypt (Daane, unpublished), Europe (Duso 1989), Argentina (Trjapitzin and Triapitsyn 2002), and South Africa (Walton 2003). Other parasitoid species in California include the encyrtid wasps *Leptomastidea abnormis* (Girault) and *Leptomastix dactylopii* (Girault), and *Coccidoxenoides perminutus* Girault; and the platygastrid *Allotropa* sp. (Daane et al. 2003, 2004, 2005, 2006). Together, these species typically account for <15% of the parasites recovered. Other parasitoids reared from mealybugs include *Chartocerus* species, which are hyperparasitoids, probably attacking *Anagyrus pseudococci*.

The importance of *Anagyrus pseudococci* is most likely related to its ability to rapidly reproduce during the summer months. Researchers studied the parasitoid's development at different temperatures and showed that a constant 34°C (93°F), *Anagyrus pseudococci* completed development (from egg to adult emergence) in just over 10 days. This suggests that there can be 2-3 parasitoid generations to each vine mealybug generation (Daane et al. 2004). Temperature can also negatively impact parasite effectiveness and it appears that *Anagyrus pseudococci* has an overwintering requirement that may reduce its presence early in the season.

Overwintering studies show that *Anagyrus pseudococci* emergence was concentrated over a 15 day period in early May, regardless of when vine mealybugs were exposed (October 2001 to March 2002) (Daane et al. 2004). Results suggest that cues are used to synchronize overwintered *Anagyrus pseudococci* adult emergence with field availability of vine mealybug. There is also the problem of getting to the mealybug under the bark or on the roots, where the pest finds a "spatial refuge" from most natural enemy species, extreme temperatures (Daane et al. 2003, Gutierrez et al. 2007) and insecticide applications (Walton 2003). It also has a "temporal refuge" created when tending ants reduce natural enemy efficacy (Daane et al. 2006b). Ants tend mealybugs for their honeydew and, in return, protect them from most natural enemy species.

4.2.3. Augmentative biological control

While development of one of the first commercial insectaries in North America, in 1916, was for the rearing of the mealybug destroyer, there have been no scientific reports on the effectiveness of this program in either citrus or vineyards. This is quite surprising as one of the more commonly advertised strategies for organic mealybug control is the release of these predaceous beetles. Similarly, research on the augmentation of lacewings targeted leafhopper pests, while mealybugs may be more suitable prey (Daane *et al.* 2002). On pear trees, Doutt and Hagen (1950) reduced grape mealybug infestation levels from 65% to 12%, with multiple releases of lacewing eggs and larvae, although the release rates used were not economically sustainable.

Experimental studies found that releases of *P. angelicus* and *A. pseudococci* suppressed the grape and vine mealybugs, respectively (Daane *et al.* 2006a). However, at this time there are no commercial insectaries producing these parasitoids.

4.3. Mealybug Cultural Control

Cluster thinning. Most mealybugs overwinter under the bark (Flaherty *et al.* 1992b, Daane *et al.* 2004b). As the season progresses, the population typically moves upward and onto the grape clusters. For this reason, clusters that come in direct contact with the vine crown or cordon tend to have higher mealybug infestation (Stafford and Kiddo 1955, Geiger and Daane 2001). Table grape growers will commonly remove bunches in contact with the woody portion of the vine in order to reduce the infestation level. However, bunch manipulations are not always feasible in raisin and wine grape production because of the trellising systems used, the cost of thinning, and the need for optimal yield.

Vine cultivar. The grape cultivar and associated pruning systems also influence mealybug infestation levels. As mentioned, the mealybugs typically overwinter under the bark and then move up the vine, towards the leaves and clusters, as the season progresses. Therefore, early-harvested cultivars often have lower infestation levels than late-harvested cultivars because the clusters are exposed for a shorter period - and harvest is often before the later, and greater density, mealybug generations move into the clusters. Similarly, most clusters on cane pruned cultivars (e.g., Thompson Seedless) develop further from the crown and this, similar to thinning clusters in contact with the trunk, reduces the mealybug's direct access

to the clusters. In contrast, clusters on spur pruned cultivars, which include the majority of wine grapes, are situated closer to the cordon and this often results in higher infestation levels.

4.4. Future Organic Mealybug Controls

Pesticides. A recent on-line discussion of mealybug control materials, by members of the Association of Applied Insect Ecologists, suggests that mealybugs could be controlled by a number of organically approved materials. We could find no scientific studies on the use of oils, lime-sulfur, or soaps, which might be more conducive to natural enemies, and the botanicals have not yet been tested. Trials should be conducted with organically approved pesticide materials to determine their effectiveness.

Biological controls. There is effective biological control for the grape mealybug and there is no need for renewed importation efforts. Instead, the vineyard must be properly managed to reduce ants and pesticides treatments that can disrupt grape mealybug biological control. In contrast, biological control of the obscure, longtailed, and vine mealybugs is incomplete. Furthermore, there are numerous parasitoid species that have been identified as potential obscure or vine mealybug natural enemies which have never been released in California vineyards. We suggest that renewed foreign exploration efforts should be a primary goal for these pests. Also, there have been no studies on the biological controls or population dynamics of the longtailed mealybug and this work should be conducted to assess needed biological controls for the longtailed mealybug.

While the mealybug destroyer and green lacewings are used in commercial augmentation programs, there are no studies that have evaluated the impact of these programs. For example, lacewing larvae were observed to be effective predators of immature mealybugs, although they have had a more difficult time feeding on eggs in the mealybug ovisac or on mealybug adults, suggesting that synchronizing release to mealybug development stage may be critical. In contrast, experimental studies found that releases of *P. angelicus* and *A. pseudococci* suppressed the grape and vine mealybugs, respectively, but at this time there are no commercial insectaries for these parasitoids. Recently, there has also been grower-generated interest in testing augmentative releases of predaceous mites and cecidomyiid flies, and yet the biologies of these natural enemies, as mealybug predators, are relatively unknown and there is no information on their use in an augmentative release program. It appears that there is still much to be accomplished in the development of mealybug biological controls.

Monitoring and control decisions. Early detection of mealybug infestations, when the population is small and isolated in a few vines, would improve efficacy of control treatments (Geiger and Daane 2001). However, visual sampling of vineyard mealybugs, especially at low densities, is labor intensive (Geiger *et al.* 2001). The use of sex pheromone-baited traps, for the winged adult male mealybugs, offers a more effective sampling tool. Grimes and Cone (1985) demonstrated the presence of a sex attractant for the grape mealybug, and currently identification of sex pheromones for the four vineyard mealybug species is almost complete (Millar, unpublished data). Already, the identification and synthesis of vine mealybug sex pheromone has resulted in a highly successful commercial monitoring program (Millar *et al.* 2002, Walton *et al.* 2004). Still not yet determined is the relationship between pheromone trap counts and mealybug damage.

Mating disruption. The synthetic vine mealybug sex pheromone proved so effective that it is being tested for use in mating disruption programs (Daane *et al.* 2006a). If this proves to be a viable option, mating disruption may be the primary alternative to pesticide treatments for control in organic vineyards.

Ant controls. As mentioned previously, ants can exacerbate mealybug pest problems by disrupting natural enemy activity in vineyards (Daane *et al.* 2004a, 2006b, Phillips and Sherk 1991). Unfortunately,

pesticide controls for ants are often more disruptive than those materials applied for the mealybugs. Therefore, if biological control is to be developed, ants must also be controlled with pesticide materials that fit into the IPM and/or organic programs. Currently, researchers are working with different protein and sugar ant baits to deliver small amounts of pesticides (Daane *et al.* 2006b, Klotz *et al.* 2003, Tollerup *et al.* 2005). This work will be a crucial development for the implementation of mealybug biological control, including the use of boric acid in sugar baits, which could be used in organically farmed vineyards.

Mealybugs as vectors. While laboratory studies have shown that mealybugs can transmit these viruses, there is little information on the natural infectivity level of mealybugs collected in California vineyards, or their transmission efficiency.

5. Spider Mites (Acarina: Tetranychoidea)

5.1. Mite species and damage

5.1.1. Description of pests

Two spider mite species are common vineyard pests in California. Pacific spider mite, *Tetranychus pacificus* McGregor, which deserves serious consideration, and Willamette spider mite, *Eotetranychus willamettei* (McGregor), whose populations can become large enough in San Joaquin Valley, Central Interior, and North Coast regions to cause concern (Flaherty *et al.* 1992c, Welter *et al.* 1991). A third species, the two-spotted spider mite, *Tetranychus urticae* Koch, rarely causes damage. These pests feed on grape leaves, puncturing individual leaf cells. When the vine and environmental conditions are conducive to population growth, mite population densities can rapidly increase resulting in leaf "burning" and eventual defoliation.

Mite pest problems and the effectiveness of their natural enemies appear to be highly dependent on regional differences and vineyard cultural practices. For example, Pacific spider mite outbreaks are common in San Joaquin Valley raisin grapes, but rarely encountered in North Coast wine grapes. For this reason, vineyard location and possibly the commodity may be the most important determinants of successful organic management practices. Still, why these regional and commodity differences exist and the mechanisms resulting in mite outbreaks or adequate biological control are not clearly understood.

5.1.2. Damage

Pacific spider mite damage begins as yellow spots. As damage progresses, dead (necrotic) areas appear on the leaves. High populations can render the leaves unfunctional with leaf burning and bronzing and copious amounts of webbing. Damage is worse along the shoulder and tops of the vine canopies. Willamette spider mite feeding in mid- or late season causes foliage to turn yellowish bronze, but usually no burn occurs unless vines are weak. In red varieties, infested leaves may turn reddish.

5.2. Mite Biological Control

Predaceous mites. The most important natural enemy of spider mites is the phytoseiid *Galendromus* (=*Metaseiulus*) *occidentalis* (Nesbitt) (Flaherty *et al.* 1992c). Other phytoseiid species include *Amblyseius californicus* (McGregor), commonly found in the Central Coast region, and *M. mcgregori* (Chant), commonly found in the San Joaquin Valley and Central Interior regions. In most organically managed vineyards, the action of these predators is enough to hold mite pest populations below damaging levels.

Insect predators. The six-spotted thrips, *Scolothrips sexmaculatus* (Pergande), a lady beetle, *Stethorus picipes* and chrysopids will feed on mites, but are considered less effective than predaceous mites because they appear too late in the growing season or increase in abundance too slowly (Flaherty *et al.* 1992c, Flaherty and Wilson 1999). However, their contribution to natural control in vineyards should not be discounted.

5.2.2. Classical biological control

There have been few attempts at classical biological control of spider mites. Most of the mite predator species in California grapes were either already present or a result of previous accidental introductions.

5.2.3. Augmentative biological control

Predaceous mites can be easily reared at high quality and large densities, which is a primary component of a successful augmentation program (Daane *et al.* 2002). They have been used successfully in vineyards and other crops to control spider mites (Flaherty and Wilson 1999). Work conducted in cotton fields showed mite control with predator release ratios (phytoseiid mites: spider mites) ranging from 1:20 to 1:10, although studies in vineyards showed that release timing, rather than rate, may be critical as the late-season predator activity is an essential ingredient in spider mite balance (Flaherty and Wilson 1999). For example, fall releases of phytoseiid mites provided excellent control of spider mites the following season, while summer releases had little impact on the current season's mite densities (Flaherty and Huffaker 1970). The impact of release timing may be associated with a required late-season diapause induction for successful overwintering of the predaceous mites (Hoy and Flaherty 1975).

5.2.4. Conservation biological control

Food for predators. One possible method to support pollen-feeding tydeids is through pollen applications or planting cover crops (Flaherty and Hoy 1971). Another possibility is to release the less harmful mites along with the predaceous mites. Phytoseiid mite populations are better able to build to high numbers and control the more damaging mite pests, such as the Pacific spider mite, when they have available food early in the season, such as the less-damaging two-spotted mite or tydeid mites (Flaherty 1969, Flaherty and Hoy 1971). Karban *et al.* (1994) and Hanna *et al.* (Hanna *et al.* 1997a) showed that predatory mites were more effective when released in conjunction with low levels of Willamette spider mite. The combination of "prey-in-first" and pollen augmentation was tested by strip-planting of alfalfa within a cotton field, followed by releases of two-spotted mites as a food source and *G. occidentalis* as a predator, and resulted in the suppression of spider mite populations below damaging levels (Corbett *et al.* 1991). We note, however, that in some regions – such as the North Coast and Central Interior – the Willamette mite is the primary mite pest.

5.3. Mite Cultural Control

Dust control. Along with dry conditions, there has long been an association between mite outbreaks and dusty roads (Flaherty *et al.* 1992c). It is a common cultural practice to apply a material to seal roads and require crews to drive slowly in order to reduce dusty conditions. We have observed there are fewer adherences to this practice in San Joaquin Valley vineyards where dusty conditions often cannot be avoided and where miticides are routinely used.

Vine stress. There is a standing recommendation that to reduce mite outbreaks vineyard managers should maintain vine vigor as Pacific spider mite outbreaks are often associated with dry conditions and vine stress (Flaherty *et al.* 1992c, Hanna *et al.* 1997b). In fact, it is not uncommon to observe late-season mite damage in San Joaquin Valley raisin vineyards, where irrigation is discontinued in July, while

neighboring table grape vineyards, which are irrigated throughout the season, have little or no damage. However, the impact of water-stressed vines on spider mite densities or the mechanisms behind any observed changes in mite density are not well understood (*Trichilo and Wilson 1993*, Costello pers. comm.). For example, the influence of water stress on the two-spotted spider mite may be negative or nonlinear (English-Loeb 1989, 1990).

Sulfur treatments. Just as irrigation amounts have been implicated in mite outbreaks, so has the application of sulfur (dust), used to control mildew, *Uncinula necator* Burrill. Sulfur applications were first implicated in changes in mite species composition – *G. occidentalis* was the dominant spider mite predator in commercial vineyards with sulfur sprays, while *Amblyseius* sp. nr. *hibisci* was commonly found in wild grapes where sulfur was not applied (Flaherty and Wilson 1999). Furthermore, English-Loeb *et al.* (1986) showed that *A.* sp. nr. *hibisci* was the dominant phytoseiid in commercial vineyards where sulfur was not applied and maintained lower numbers of Willamette spider mites than *G. occidentalis* where sulfur was used. Other research suggests that sulfur applications reduce densities of predatory mites (Hanna *et al.* 1997c); however, the mechanisms underlying any observed differences are not understood (Costello, pers. comm.).

Grape cultivar. Characteristics of the leaf surface may impact mite abundance, with cultivars having pubescent leaf undersurfaces supporting higher populations of predaceous mites (Camporese and Duso 1996). For example, Duso (1992) reported that *Amblyseius aberrans* Oud. and *Typhlodromus pyri* Scheuten were more abundant on cultivars with hairy leaf undersurfaces and concluded that predaceous mite abundance was largely independent of prey density, but rather was more closely associated with host plant suitability. In another study of 20 grape (*Vitis*) species, 25% of the variability in abundance of the phytoseiid *Typhlodromus caudiglans* Schuster was determined by leaf characteristics, such as the presence of leaf domatia (tiny tufts of hair on the underside of the leaves), rather than spider mite abundance (Karban *et al.* 1995). However, Flaherty and Wilson (1999) suggest that prey (spider mite) densities in that study were too low to influence predator (phytoseiid) abundance. Moreover, studies with higher population densities of spider mites showed that phytoseiid abundance is clearly associated with prey abundance rather than grape cultivar (Hanna and Wilson 1991, Hanna *et al.* 1997a, Wilson *et al.* 1991a, 1991b). The impact of grape cultivar on either predaceous or phytophagous mites remains open for debate.

6. Future Organic Mite Controls

Pesticides. For organically managed vineyards, soaps, oils, neem, and botanicals all are popularly reported to have some impact on mite abundance, although we could find no scientific studies that document their effectiveness. As mentioned previously, the botanically-based pyrethrums are broad-spectrum materials. These organically-approved pesticides should be handled similar to synthetic pesticides with respect to their negative non-target impacts. Before incurring the expense of developing new materials for mite control, these materials should be tested and the results published to provide clear guidelines.

Biological controls. There are many effective biological control agents of spider mites present in California and further foreign exploration for new natural enemies is not warranted unless new exotic phytophagous mites are found. To improve the presence of natural enemies in the vineyard, a systems approach needs to be considered to balance vine vigor, pesticide sprays and cultural practices.

What is surprising is that augmentation of phytoseiids has not become a more popular practice. Research in California, as well as in vineyards in Italy and Switzerland has demonstrated the effectiveness of this program (Flaherty and Wilson 1999). It would appear that most vineyard managers chose miticides for their immediate impact on pest populations and their suitability to “timed” applications. In contrast, most

augmentation programs require more labor – especially in sampling pest and natural enemy populations – to knowing when and what to release (Mills and Daane 2005). Predatory mite releases will become cost-effective if targeted to augment naturally occurring predation, with the number of predators released dependent on the abundance of the naturally occurring predators rather than dependent on prohibitively costly inundative releases. Moreover, the costs and effectiveness of mite releases should be verified in commercial programs, and in different grape growing regions.

To improve pest control decisions, such as augmentation, binomial sampling techniques using early-season ratios of predator: spider mites have been developed (Flaherty and Wilson 1999). However, practical use of this technique needs better adoption by vineyards managers. There also needs to be a better understanding of the importance of the "secondary" mite pests – the Willamette mite and the two-spotted spider mite, as well as their associated natural enemy complex and the impact of vineyard management practices on their densities. As discussed with leafhopper controls, proper sampling and treatment decisions will greatly reduce unnecessary pesticide applications.

Cultural controls. The presence of leaf domatia can increase the abundance of fungal feeding mites, leading to a discussion of engineered or selected grape cultivars with leaf domatia. However, there has not been a similar interest in breeding cultivars that increase the presence of phytoseiid mites.

7. Future Organic Vineyard Management

7.1. Pesticide Trends

Pesticide use reports for California vineyards show changes in pesticide materials used. Here, we group insecticide and miticide materials by category as follows: organophosphates (acephate, azinophos methyl, chlorpyrifos, diazinon, dimethoate, disulfoton, fenamiphos, malathion, methidathion, methyl parathion, mevinphos, naled, parathion, phorate, phosmet), carbamates (carbaryl, carbofuran, forthante hydrochloride, methiocarb, methomyl), chlorinated hydrocarbons (methoxychlor, endrin, endosulfan, lindane), bacterial-based (avermectin, *Bacillus thuringiensis*, *Beauveria bassiana*, spinosad), botanical (azadirachtin, neem, rotenone, pyrethrins), oils, inorganic (kaolin, kryoside), insect growth regulator (buprofezin, tebufenozide), miticide (bifenazate, clofentezine, dicofol, fenbutatin-oxide, propargite, pyridaben), nicotenoid (acetamiprid, imidacloprid), pheromone, pyrethroid (cyfluthrin, esfenvalerate, fenpropathrin, permethrin). We use these data to discuss trends in pesticide use from 1993 to 2003, emphasizing materials applied for leafhoppers, mealybugs, and mites.

Over the past decade, there has been a steady increase in wine grape acreage, while table and raisin grape acreage has decreased (Fig. 1A). This fact alone may account for some of the reduced pesticide use in California grapes as there are less pesticides (lbs per acre) used on wine grapes than table and raisin grapes (Fig. 1B). Arguably, comparison of the total pounds (a.i.) per acre of pesticides does not distinguish between materials applied. For example, most of the "weight" difference between wine and table/raisin grapes is from the application of inorganics (cryolite) for control of moth pests, and this material is not commonly used in wine grape production (Fig. 1C). More important is the downward trend of pesticide material applied in all grape commodities (Fig. 1B).

The general reduction in "pounds per acre" may also result from the use of more toxic or effective materials that requires less amounts of product (in weight) to achieve control. For that reason, a comparison of pesticide groups provides a clearer portrait of the reduction. The three pesticide groups most often targeted for removal in sustainable or IPM systems are applied to control leafhoppers, mealybugs or mites and are the chlorinated hydrocarbons (CHC) (Fig. 2A), organophosphates (OP) (Fig. 2B), and carbamates (Fig. 2C), and a fourth group would be the miticides (Fig. 2D). CHCs, once the most material applied, are now rarely used; endosulfan is the only CHC frequently applied – typically for mite

pests in the San Joaquin Valley. While the use of OPs declines over the 10 year period, some materials are still commonly used for leafhoppers and mealybugs – chlorpyrifos, dimethoate, disulfon, fenamiphos, malathion, and naled. Carbamates are primarily represented by two materials – carbaryl and methomyl. Use of these two products is more common in coastal vineyards, primarily for mealybugs, because these products can result in secondary mite outbreaks in the interior valleys.

The ten year decline in the application of CHCs, OPs, and carbamates may be directly related to improved pesticide chemistry and IPM practices. For example, the increased use of imidacloprid, a nicotenoid, for leafhopper control has largely replaced the carbamates and organophosphates that were used in the 1980s (Fig. 3A). Buprofezin, an insect growth regulator (IGR), was recently registered and also provides excellent control of both leafhoppers and mealybugs – leading to a sharp increase in product use (Fig. 3B). By reducing the application of carbamates for leafhopper control, there are fewer secondary outbreaks of mite populations, requiring additional pesticide applications. Moreover, the miticide of choice is avermectin, which is a bacteria-based material. In contrast to these novel materials, there has been no consistent use pattern for the bacterial-based (Fig. 3C), botanical (Fig. 3C), or oils (data not shown), which are materials most commonly used by organic farmers.

Currently, the problem pests with respect to targeted pesticide material are the mealybugs. Historically, mealybugs have been difficult to control with short-residual, narrow-spectrum pesticides. One problem is that some portion of the population is always located in protected areas, such as underneath the bark, where pesticide coverage is incomplete (Geiger and Daane 2001). For this reason, some of the pesticide treatments initially used for mealybugs included fumigation with potassium cyanide and sodium cyanide. From the 1950-80s, highly toxic organophosphates and chlorinated hydrocarbon pesticides were used for mealybug control (Frick 1952, Stafford and Kiddo 1955). Eventually, it became evident that these pesticide disrupted biological controls (Flaherty *et al.* 1982) and pesticide treatments for mealybugs sharply decreased. In the 1990s, there were improvements in the application timing and available materials. Research in the San Joaquin Valley showed that a delayed dormant (February) application of an organophosphate (chlorpyrifos) provides control and applies the pesticide during a period when most natural enemies are not active. An in-season application(s) of a systemic nicotenoid (imidacloprid) or an insect growth regulator (buprofezin) can provide season-long mealybug control (Daane *et al.* 2006a). Chlorpyrifos, imidacloprid, and buprofezin can have non-target impacts, and there is still a need for pesticide-based tools for mealybug control in organically-managed vineyards.

7.2. Invasive Species

One of the most pressing threats to the continued growth of organic vineyard management is from invasive species. Each new pest species changes the established IPM program as the arrival of exotic pests is initially met with synthetic pesticide treatments. In contrast, development and testing of biological controls often takes years.

An example of the temporarily disruptive impact of invasive pests is found in the sequence of three moth species that damaged San Joaquin Valley grapes. The omnivorous leafroller, *Platynota stultana* Walsingham, the grape leaffolder, *Desmia funeralis* (Hübner), and the western grapeleaf skeletonizer, *Harrisina brillians* Barnes and McDunnough (Coviello *et al.* 1992) were considered to be primary pests in the 1960s and 1970s. When these pests first arrived in the San Joaquin Valley, growers typically employed the best available control options: CHCs and OPs. These applications disrupted biological controls of the WGLH, grape mealybug and Pacific mite. For each moth pest, research sought better biological and cultural controls, and improved pesticide materials and application timing. Today, there is a better understanding of pest biology and the needed control tools. Some of the more sustainable control options include the stomach poison sodium aluminum fluoride, which comes in a synthetic (kryocide) or organically-approved (cryolite) forms. Other organically-approved material includes applications of

Bacillus thuringiensis (Bt). A form of spinosad (a bacterial by-product) is also considered organic and somewhat effective against all but grapeleaf skeletonizer.

One of the more interesting situations is the biological control program for the western grapeleaf skeletonizer. During the 1960-80s, a number of parasitoids were introduced to suppress the western grapeleaf skeletonizer (Clausen 1961, Guerra-Sobrevilla 1991). Only the braconid *Apanteles harrisinae* Muesebeck and the tachinid *Ametadoria miscella* (Wulp) established, and neither provided effective control in the San Joaquin Valley. During this period, an extremely virulent granulosis virus, which kills skeletonizer larvae, was accidentally introduced into California. The virus was found to be associated and moved by the tachinid parasitoid (Stark *et al.* 1999) and this association of insect and pathogenic biological control agent was thought to help disseminate the pathogen. Today, grapeleaf skeletonizers are rarely a problem. Anecdotally, a popular story suggests that a proponent of the virus may have acted as a modern-day Johnny-apple-seed by spraying small amounts of such a virus-laden mixture throughout San Joaquin Valley vineyards in the 1980s.

Currently, there are two exotic pests of immediate concern. We previously described the vine mealybug as a new pest requiring new IPM techniques and organic pest control solutions. A far more threatening pest may be the glassy -winged sharpshooter (GWSS), *Homalodisca vitripennis* (Say). This leafhopper vectors *Xylella fastidiosa* (Xf), a xylem-limited bacterium that, in highly susceptible host plants, will clog the xylem and result in severe water stress or Pierce's disease (PD) (Redak *et al. 2004*) [<-- italics?]. GWSS may not be a more "efficient" vector of Xf than the native sharpshooters (Almeida and Purcell 2003), but it is certainly a more important vector (Blua *et al.* 1999). The arrival of GWSS has dramatically changed the epidemiology of PD in California, as clearly demonstrated in the Temecula Valley (Riverside County) (Perring *et al.* 2001). If and if it establishes in other grape regions will not make organic farming impossible, but it will make IPM efforts more complicated and control cost higher.

7.3. Future Directions

Here, we have detailed the current status of organic farming tools for three key vineyard pests. We have also described needed research to further improve the arsenal of IPM tools. What can be done immediately to improve adoption of organic farming practices and through the biological and cultural control of arthropod pests? The answer may be even more extension, on-farm outreach, and grower-participatory programs. For most arthropod pests, the needed IPM tools are available. If not farming by organic standards, vineyard managers can certainly farm using good IPM practices.

The University of California has placed viticulture Farm Advisors in Cooperative Extension offices located in key grape growing regions. Additionally, personnel in the University of California Sustainable Agriculture Research and Education Program (SAREP) (http://www.sarep.ucdavis.edu) and the University of California IPM Program (http://www.ipm.ucdavis.edu) have played a role in the development and extension of most of the IPM tools described previously. Commodity organizations for wine (American Vineyard Foundation), table (California Table Grape Commission), and raisin (California Raisin Marketing Board) grapes fund both research and extension activities. Additionally, supporting groups, such as the California Alliance for Wine Grapes (http://www.cawg.org), and regional programs, such as the Lodi-Woodbridge Winegrape Commission (http://www.lodiwine.com) and the California Central Coast Vineyard Team (http://www.vineyardteam.org/bifs.php), provide outreach programs that utilize on-farm and grower participatory education formats – often in collaboration with University extension programs. These, and other, organizations provide the needed grower support. Still, farmer-to-farmer communication and demonstration of research proven IPM techniques appears to be one of the best forms of extension, exemplified by the success of the Lodi-Woodbridge Winegrape Commission (Klonsky *et al.* 1998). Other successful on-farm demonstration projects have been joint efforts with University personnel and Community Alliance with Family Farmers (http://www.caff.org),

the Department of Pesticide Regulation (http://www.cdpr.ca.gov), and SAREP's Biologically Integrated Farming Systems. From this incomplete list, there is clearly an available network to help guide farm managers along the continuum of pest control decisions that range from conventional to organic farming practices. The final decision of how to farm rests with individual growers fitting their goals to the pest species and damage encountered in each grape commodity and region. Because of the variation described among commodity, regions, and vineyards – each manager is encouraged to conduct their own on-farm research to determine which of the available IPM tools is best suited for their vineyard ecosystem.

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Table 1 Sales of top five organic commodities in California in 2002 shows the importance of the grape market, and the dominance of organic wine grape sales. For the top ranked organic commodities, the data are categorized by total organic sales for each commodity, the percentage of total sales for all organic commodities, and the percentage of total sales (organic and non-organic) for each commodity (from Klonsky 1998)

Rank	Commodity	Organic Sales ($)	% of Total Organic Sales	% of Total Commodity Sales
1.	Grapes—all	26,768,000	10.3	1.1
	wine	14,557,000	5.6	0.8
	raisin	4,072,000	1.6	1.1
	table	8,139,000	3.1	1.8
2.	Lettuces	21,945,000	8.5	1.6
3.	Carrots	14,268,000	5.5	3.2
4.	Strawberry	12,525,000	4.8	1.5
5.	Tomato	10,126,000	3.9	1.3

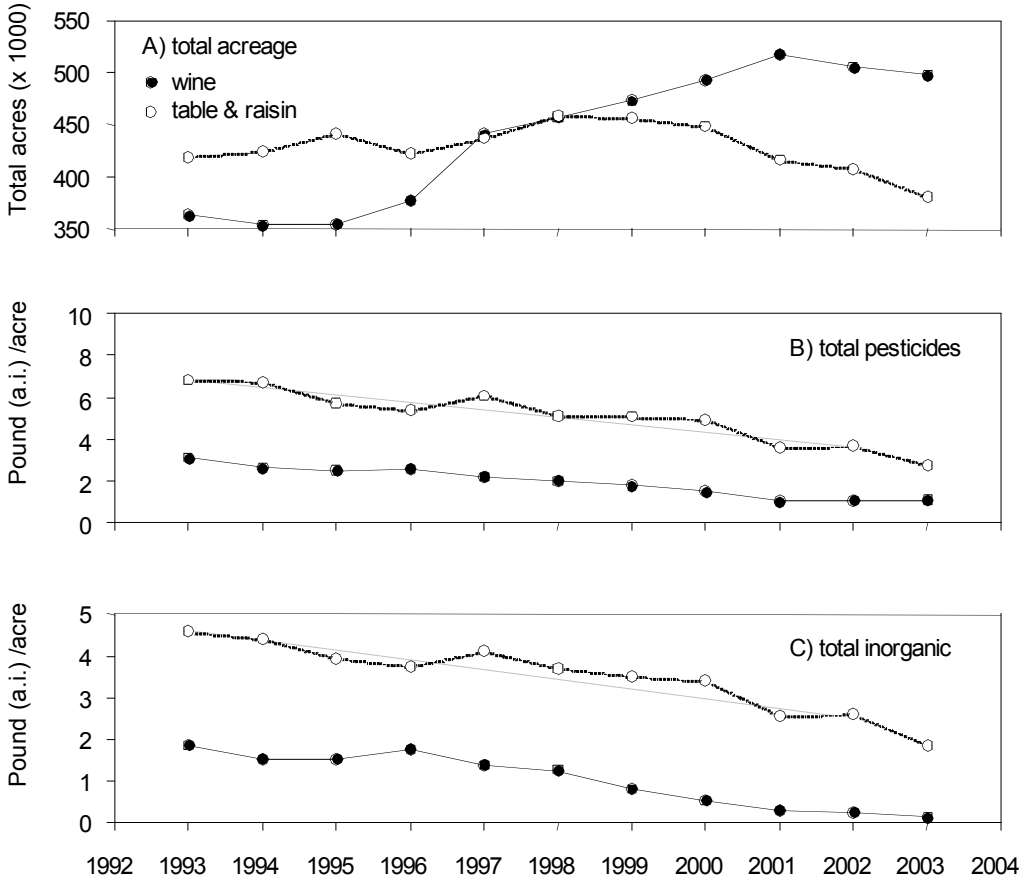

Fig. 1. California pesticide use reports for 1992 to 2003 for A) total grape acreage, B) total insecticide and miticide applied, and C) inorganic insecticides (mostly Cryolite). Data are separated for wine grapes and the combination of table and raisin grapes; on graphs B and C, data are total pounds active ingredient applied per total grape commodity acreage.

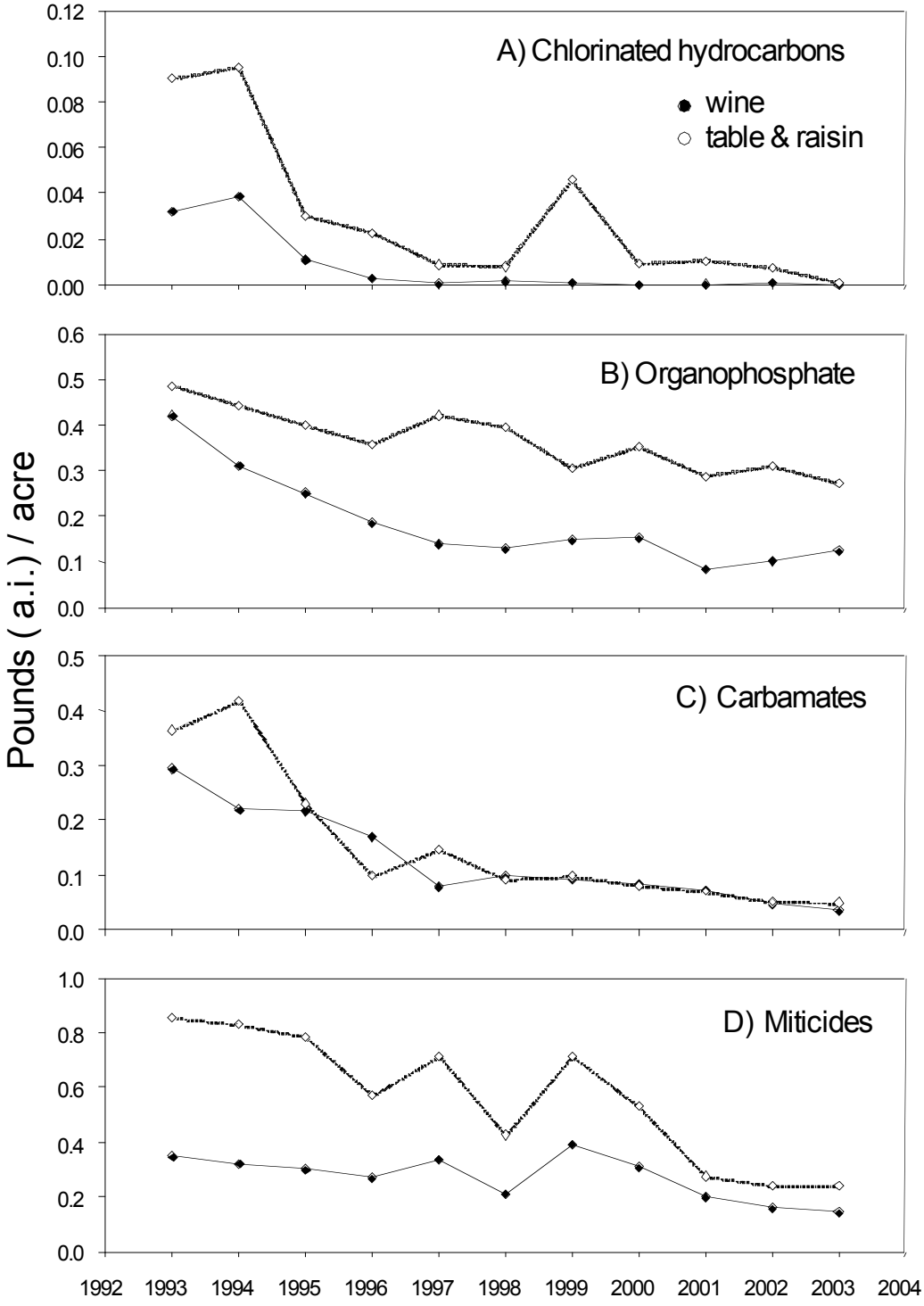

Fig. 2. California pesticide use reports for 1992 to 2003 for applied materials grouped as A) chlorinated hydrocarbons, B) organophosphates, C) carbamates, and D) miticides. Data are separated for wine grapes and the combination of table and raisin grapes; on each graph data are total pounds active ingredient applied per total grape commodity acreage.

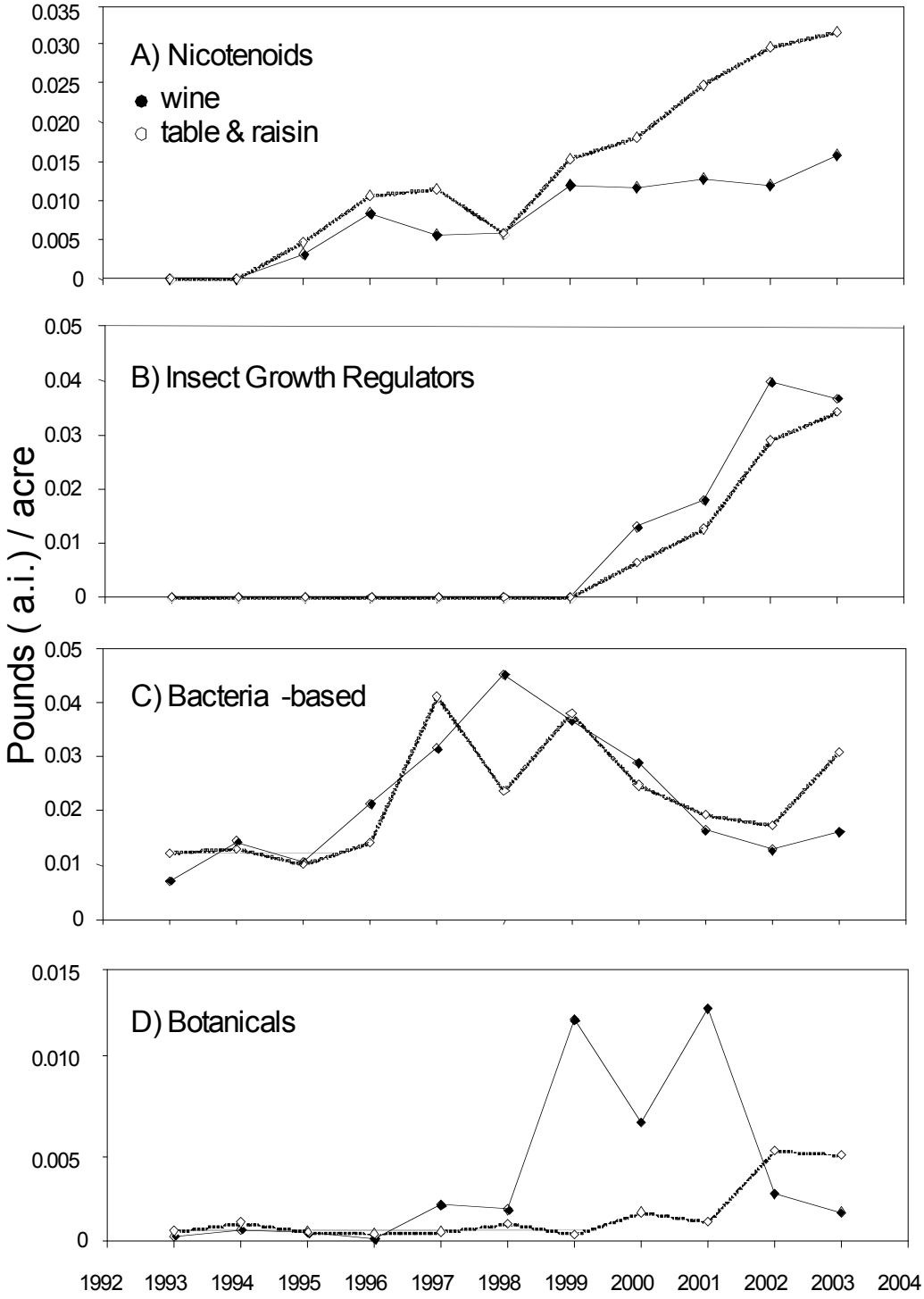

Fig. 3. California pesticide use reports for 1992 to 2003 for applied materials grouped as A) nicotenoids, B) insect growth regulators, C) bacterial-based, and D) botanicals. Data are separated for wine grapes and the combination of table and raisin grapes; on each graph data are total pounds active ingredient applied per total grape commodity acreage.

Biological Control of Key Pests in Apples and Pears

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1. Introduction

Apple production in California occurs on over 26,000 acres and was valued at $62,235,000 in 2004. The same year, pear production was valued at $80,432,000 and occurred on 17,000 acres, with the Bartlett variety grown on over 75% of this acreage (Anon 2005b).

California has five distinct apple and pear growing regions. The North Coast includes the apple growing counties of Sonoma and Mendocino. Pears are also grown in Mendocino County as well as Lake County (Anon 2005a). The Central Coast includes the apple producing counties of Santa Cruz, Monterey, San Benito and San Luis Obispo. Currently, economic pear production does not occur in this region of California (Ohlendorf 1999). As the major agricultural area in the state, the Central Valley supports both apple and pear production, with the greatest apple production occurring in San Joaquin, Kern, Stanislaus and Fresno Counties. The counties of Sacramento, Fresno and Tulare support pear production (Anon 2005a), with a high concentration of production occurring in the Sacramento delta (Ohlendorf 1999). Along the eastern side of the Central Valley are the Sierra Foothills, where apples are grown in eastern Tehama County down to eastern Tulare County. Additionally, the counties of El Dorado and Placer grow pears. The fifth growing region in the state is located in the southern California mountains, with the highest production occurring in San Diego, Riverside and San Bernardino Counties (Anon 1999, Ohlendorf 1999, Anon 2005b)

A similar pest complex is found on apple and pears in California, though susceptibly differs between crops. Additionally, pest pressures can vary across the diverse growing regions of California. However, codling moth is the primary pest in both crops, as it attacks fruit directly and lacks effective natural enemies. Other major pests include pear psylla, aphids, mites, scale, leafrollers and leaf miners (Caprile 2001). In 2003, statewide insecticide use in both pome crops totaled 2,928,267 lbs (Anon 2004).

2. Generalist Predator Complex

In addition to supporting pest arthropod species, pome orchards also support beneficial species. One beneficial group is the generalist predator complex. As their name suggests, these predators are not specialized and will feed on insect eggs, small insects and mites. If beneficial populations are not disturbed by pesticide use, they can provide partial control, or in some cases, complete control of pest species. In pear and apple orchards, greater numbers of beneficial insects are generally found in the cover crop on the orchard floor than in the tree canopy (Horton *et al.* 2003). However, if there is a substantial food source in the canopy, the generalist predators will migrate up into the tree (Caprile *et al.* 1994).

2.1. Spiders: Members of the order Araneae were the dominant group found in collections made of overwintering arthropods in Washington apple and pear orchards (Horton *et al.* 2002). Miliczky and Calkins (2001) found that the webspinning spider *Dictyna coloradensis* (Araneae: Dictynidae) caught significant numbers of small active pests in their webs. In apple orchards, spiders were found equally on the orchard floor and in the canopy (Caprile *et al.* 1994).

2.2. Lacewings: *Chrysopa* spp. and *Chrysoperla* spp. (Neur.: Chrysopidae) are the green lacewings found in California orchards. Brown lacewings, *Hemerobius* spp. (Neur.: Hemerobiidae), may also be found. Larvae of all species, as well as adults of *Chrysopa* and *Hemerobius*, feed on soft bodied arthropods and their eggs (Thacher and Flint 2005). Overwintering in orchards, lacewing populations can be active early in the season, as opposed to other beneficial species that might not migrate into orchards until later in the season (Horton *et al.* 2002). Additionally, several lacewing species seem to prefer the tree canopy over the cover crop (Caprile *et al.* 1994).

2.3. Big-eyed bugs: *Geocoris* spp. (Het.: Geocoridae) are predators of small insects, insect eggs and mites (Thacher and Flint 2005). However, in orchards they are found more often on the orchard floor than in the tree canopy (Caprile *et al.* 1994), so their importance as a biological control agent is probably greater in field crops than in orchard systems.

2.4. Minute pirate bugs: *Orius tristicolor* (Het.: Anthocoridae) feeds on spider mites, thrips, aphids, scale, pear psylla and insect eggs (Beers *et al.* 1993). *O. tristicolor* were found to represent the greatest proportion of predatory Anthocoridae overwintering in orchards in Washington (Horton *et al.* 2002). Additionally, their level of activity is similar in the tree canopy and on the orchard floor (Caprile *et al.* 1994).

2.5. Lady beetles: Adults and larvae of *Hippodamia* spp. and *Coccinella* spp. (Col.: Coccinellidae) prey on soft bodied insects, preferring the orchard floor over the tree canopy (Caprile *et al.* 1994). Ladybird beetles are well known in agricultural settings for their voracious appetite for aphids.

2.6. Damsel bugs: *Nabis* spp. (Hem.: Nabidae) feed on small insects, including moth larvae, insect eggs and mites (Beers *et al.* 1993). However, damsel bugs seem to prefer the orchard floor to the tree canopy (Caprile *et al.* 1994).

3. Codling Moth: *Cydia pomonella* **(Lep.: Tortricidae)**

3.1. Species and Damage

3.1.1. Description of pest

While originating in Central Asia, the infamous codling moth is currently found infesting apples in most apple growing regions worldwide (Beers *et al.* 1993). In North America, codling moth has been a pest in apple and pear for 200 years (Beers *et al.* 1993), establishing in California around 1872 (Essig 1938). Other codling moth host include: walnut, prune, quince, hawthorn, plum, peach, and apricot (Anon 1999). However, it is only an economically important pest species on apple, pear and walnut, preferring apple over other hosts (Beers *et al.* 1993). In California, as the key pest species, codling moth control is the foundation upon which pest management programs in apple and pear are built (Anon 1999).

Codling moth overwinter as diapausing larvae and pupate February through March. First flight occurs mid-March through early April (Anon 1999). Peak emergence usually occurs 17 to 21 days after the first moths emerge and may continue for six to seven weeks (Beers *et al.* 1993). Females from the overwintering generation lay between 30 and 70 single eggs on leaves or on fruit, with females from later generations having a higher fecundity. Dependent on location and temperatures, codling moth has between two to four generations per year in California. Young first generation larvae feed on terminal leaves and shoots, but enter fruit within 24 hours after hatching, while later generation larvae enter fruit immediately (Anon 1999). Early in the season, pears are not suitable codling moth hosts, as the hardness of young pears can cause first generation larvae to experience mortalities as high as 55% (Barnes 1991). However, as the pear matures and softens, increasing numbers of larvae are able to successfully enter the fruit (Beers *et al.* 1993) with 85% of larvae entering through or in the area around the calyx (Barnes

1991). In apples, the larvae may also enter the fruit through the calyx, though many enter through the side of fruit. The first instar is spent just under the skin of the fruit, while later instars are spent eating seeds at the core. Larvae burrow out of the fruit and find a secluded place under tree bark or in ground debris at the base of the tree to pupate (Anon 1999). Later in the season, shorter day lengths trigger diapause (Carde and Minks 1995, Anon 1999).

3.1.2. Mating disruption

Research on mating disruption of the codling moth has been occurring since 1973 (Carde and Minks 1995) and today is a vital component of an IPM program for codling moth (Caprile *et al.* 2002). Mating disruption is implemented by flooding an orchard with synthetic pheromones similar to those released by a female to attract a male. The male, not able to pick up a real "trail", is unable to find a female, hence mating will not occur and no viable eggs will be laid. All this is accomplished at a low environmental cost. However, there are constraints that must be considered. Mating disruption is not effective when used alone against high population densities, as the probabilities of a male encountering a female increase as the population density increases. Successful disruption also depends on a broad blanket of the synthetic pheromone; therefore disruption has a greater potential in orchards that are flat and free from strong winds. The orchard should also be a relatively uniform, square orchard that is at least five hectares in area.

Additionally, to prevent migrating populations, the orchard should be isolated from other possible codling moth hosts or mating disruption should take place in all surrounding orchards (Anon 1999). Still, even with these limitations, mating disruption has shown great promise, demonstrated by an 80% reduction of hard pesticide use in orchards incorporating mating disruption into their pest management program (Calkins and Faust 2003).

Several methods are used to make pheromone applications. Hand dispensers were the most commonly used between 1995 to 2000, though puffers were used on over 1,300 acres in Lake County pear orchards (Welter *et al.* 2005). Welter *et al.* (2005) estimates that in 2001, mating disruption occurred on 45 to 50% of pome fruit acreage from the Sacramento Valley to the Pacific Northwest. However, in more southern locals, mating disruption is less relied upon because of higher pest densities caused by a greater number of generations per year in these growing areas (Welter *et al.* 2005). Less reliance on broad-spectrum insecticides for codling moth suppression presents an excellent opportunity for increased biological control of other pests in pome fruit systems.

3.1.3. Damage

Codling moth can damage fruit from April through harvest (Anon 1999). Damage by codling moth is placed into two categories. The first type of damage, referred to as a sting, is formed when the larva chew through the skin and only shallowly, if at all, into the flesh. The larva then dies or goes elsewhere, leaving an area that will eventually scar over. The second type of damage is a deep entry. Deep entries occur when the larva burrows through the flesh to the center of the fruit to consume the seeds (Beers *et al.* 1993, Anon 1999). As the larvae feed, they push excrement (frass) to the outside of the hole making their presence inside the fruit evident.

While stings might seem more innocuous that deep entries, both types of damage make fruit unmarketable. Furthermore, when codling moth larvae attack young fruit, some infested apples and all infested pears will fall from the tree. In cold storage, deep entries can encourage fungi and bacteria growth that lead to rot (Beers *et al.* 1993). In one study, codling moth damage in apples ranged from 0.1 to 29% in organic orchards using mating disruption, 0 to 10% in conventional orchards using organophosphates plus pheromone treatments and 4.3 to 49% in untreated orchards (Vossen *et al.* 1994).

3.1.4. Treatment thresholds

Codling moth control requires a monitoring program that uses pheromone trap counts in conjunction with degree-day models to predict flight times. Thresholds given on the UC Davis IPM website presuppose the use of mating disruption and are dependant on the method of pheromone application. In orchards using hand dispensers, if traps with 10 mg (supercharged) pheromone lures contain more than 10 moths in two consecutive weeks or if 15 moths are caught in one week, then fruit monitoring is required. In orchards using puffers, if there are high moth catches (number not specified) or if moths are caught continually in traps for more than one week, then fruit should be monitored (Caprile *et al.* 2002, Elkins *et al.* 2002).

In apples, fruit monitoring should occur towards the latter half of each codling moth generation, as well as when indicated by trap counts. Supplemental spraying, preferably spot treatment, is recommended when fruit damage reaches 0.5% (Caprile *et al.* 2002). In pears, fruit should also be monitored when moths are found in traps, as well as 800 to 900 degree days from the biofix. If damage is over 0.25%, treatment is recommended in susceptible areas and hot spots (Elkins *et al.* 2002).

3.2. Codling Moth Biological Control

3.2.1. Current activity of parasitoids, predators and pathogens

While natural enemies are able to provide complete control of some pome fruit pests, alone they are unable to suppress populations of codling moth below economic levels (Anon 1999). Lloyd (1944) reported the following codling moth larval and pupal parasites from apple, pear and walnut orchards in California: *Ascogaster quadridentatus* and *Macrocentrus ancylivorus* (Hym.: Braconidae); *Mastrus* (*Aenoplex*) *carpocapsae, Mastrus* (*Aenoplex*) *betulaecola, Ephialtes sanguineipes* and *Ischnus* n. sp. (Hym.: Ichneumonidae); *Lixophaga orbitalis* and *Erynnia* (*Anachaetopsis*) *tortricis* (Dip.: Tachinidae). *Dibrachys cavus* **(**Hym.: Pteromalidae) is also known as a hyperparasitoid of several of the primary parasitoid cocoons. However, corresponding parasitism rates were low for all species, with parasitism of overwintering and first generations equaling 5.8% and 6.3% respectively (Lloyd 1944). More recent survey efforts did not find tachinid parasitoids or *M. betulaecola*, but did find *Coccygomimus hesperus* (Hym.: Ichneumonidae) and *Trichogramma platneri* (Hym.: Trichogrammatidae) (Mills 2003, Mills 2005). The *Trichogramma* complex attacking codling moth eggs in the Pacific Northwest has the following species composition: *T. minutum* complex (86%), *T. deion* (1.9%), *T. aurosum* (4.2%), *T. californicum* (3.3%), *T. sibericum* (2.2%), *T. alpha* (<1 %), *T. cacaeciae* (<1%), *T. itsybitsi* (<1%), *T. pretiosum* (<1%) (Pinto *et al.* 2002).

Glen (1982) reported that in unsprayed orchards in England, 25 to 62% of codling moth eggs were taken by Heteroptera and earwigs. However, Knight *et al.* (1997) found that while codling moth egg mortality was greater in orchards with greater predator abundance, no one predator density was correlated with egg mortality. Lloyd (1944) found *Cymatodera ovipennis, Cymatodera* sp., *Hydnocera scabra* (Col.: Cleridae) and an unidentified raphidiid larva predating cocooned and pupated codling moth. Carabid and staphylinid beetles are reported to predate codling moth larvae that have left the fruit (Glen 1982). The dominant carabid ground beetle inhabiting Central Valley apple orchards is *Harpalus pensylvanicus* (Col.: Carabidae). Other carabids active in Central Valley orchards include: *Anisodactylus californicus, Chlaenius* spp. , *Pterostichus* spp. , *Agonum punctiforme* and *Calathus ruficollis* (Col.: Carabidae) (Riddick and Mills 1994). In lab studies, *Pterostichus* spp. and *H. pensylvanicus*, predatory ground beetles, located and killed overwintering codling moth larvae (Epstein *et al.* 2001). Also in lab studies, *Pterostichus lustrans, Pterostichus cursitor* and *Pterostichus* (*Hypherpes*) spp. were found to be adept at destroying fifth instar larvae (Riddick and Mills 1994). In a California apple orchard, *H. pensylvanicus* and *Pterostichus* (*Hypherpes*) spp. were observed devouring tethered codling moth (Riddick and Mills

1994). However, in Washington, Horton (1998) found that ground beetle densities were not correlated with sentinel codling moth disappearance, while earwig densities were.

Birds have been suggested as important predators of overwintering larvae (Glen 1982). In a multi-year study taking place in California apple orchards, predation by birds on cocooned codling moth was estimated to range from 11 to 99% (Baumgartner 1999).

The entomopathogenic nematode *Steinernema carpocapsae*, which carries a symbiotic bacterium capable of killing its host within 24 hours (Poinar 1991), has been found infecting codling moth in California (Poinar 1985). However, infection of codling moth by *S. carpocapsae* is limited, as the nematode only searches for hosts on the ground or on the very lower regions of tree trunks (Poinar 1991). Fungal infection also can depress codling moth populations, with *Verticillium lecanii* reportedly killing between 5 and 30% of overwintering larvae (Glen 1982), and *Beauveria bassiana* killing up to 10% of overwintering larvae (Jaques & MacLellan 1965).

3.2.2. Classical biological control

LeRoux (1971) summarizes classical biological control attempts made against the codling moth in North America in the first half of the 21st century. The following were introduced into California to control codling moth: Liotryphon (*Ephialtes*) *caudatus* (Hym.: Ichneumonidae); *Perisierola emigrata* (Hym.: Bethylidae) (Clausen 1956); *Trichogramma* spp. (Flanders 1930).

While early attempts of biological control against codling moth relied on imported parasitoids from Europe, the focus of more recent attempts shifted east to central Asia. In Kazakhstan, the possible origin of the codling moth, parasitism ranges from 13 to 29 % (Mills *et al.* 1996). Parasitoids of codling moth collected from Eurasia between 1991 and 2003 included: *Apechthis* sp., *Liotryphon caudatus, Liotryphon* sp., *Mastrus ridibundus, Pristomerus vulnerator* and *Trichomma enecator* (Hym: Ichneumonidae); *Ascogaster quadridentatus, Microdus* (*Bassus*) *conspicuus* and *Microdus* (*Bassus*) *rufipes* (Hym.: Braconidae); *Hyssopus pallidus* (Hym.: Eulophidae); *Dibrachys cavus* (Hym.: Pteromalidae); *Perilampus tristis* (Hym.: Perilampidae); *Trichogramma spp.* (Hym.: Trichogrammatidae) (Mills *et al.* 1999, Mills *et al.* 2001, Mills 2005). Attempts to culture *T. enecator, B. conspicuus* and *B. rufipes* proved difficult at best. The difficulties encountered during the rearing of *B. rufipes* were especially unfortunate, for in Kazakhstan, this solitary endoparasitoid parasitizes 40 to 60% of codling moth larvae (Mills *et al.* 1995). Because *B. rufipes,* along with *M. ridibundus*, is one of the most important parasitoids of codling moth in Central Asia (Zlatanova 1970, Abdullaev 1972, Makarov 1985), small scale field releases were carried out despite the rearing constraint. However, recoveries were never made (Mills *et al.* 2001).

The two cocoon parasitoids *L. caudatus*, a solitary ectoparasitoid, and *M. ridibundus,* a gregarious ectoparasitoid, were successfully reared under laboratory conditions and substantial releases took place in pear, apple and walnut orchards from 1991 to 2000 in both California and Washington. Both species were found during non-release years and are considered established in California, although only the latter species has been recovered in Washington. Parasitism by *L. caudatus* in years of release was found to be as high as 25%. However, *L. caudatus* was infrequently found during years when no releases were made. Parasitism rates for *M. ridibundus* were more promising, with a parasitism rate as high as 57% in one overwintering population (Mills *et al.* 2001). Field studies suggest that while *M. ridibundus* does display an aggregative response to host density, its behavior does not indicate a density-dependent aggregation of parasitism (Bezemer and Mills 2001). Further studies suggest that though depriving *M. ridibundus* of hosts before release leads to an initial spike in reproduction, overall lifetime fecundity is reduced when compared to parasitoids that receive hosts continuously (Hougardy *et al.* 2005). *H. pallidus*, with a high life time fecundity (Zaviezo and Mills 1999) and the ability to locate larva inside of fruit (Mattiacci *et al.* 1999), was another biological control agent considered. However, as this species was found to acquire a

considerable fitness gain when attacking larvae already parasitized by *A. quadridentatus* (Zaviezo & Mills 2001) they effectively function as cleptoparasitoids and so were excluded from introduction.

3.2.3. Augmentative biological control

Ohlendorf (1999) recommends releases of the egg parasitoid, *T. platneri* to supplement mating disruption, suggesting that releases are made at each tree every or every other week. McDougall and Mills (1997) propose that in order to achieve effective parasitism levels, one of the following should also occur: releases every three days, continuous emergence over several days, or an increase in parasitoid longevity. Releases have been found to be more effective in walnut and pear than in apple, and optimal release rates in California were estimated to be 200,000 parasitized eggs per acre (Mills *et al.* 2000, Mills 2003). In apple orchards undergoing sterile moth releases, Cossentine and Jensen (2000) found that *T. platneri* released at a rate of 3000 wasps per hectare during egg oviposition of either the first or the second generation of codling moth was able to significantly reduce damage at the time of harvest. In Santa Cruz county, a local female-only strain of *T.* nr. *platneri* has been identified, mass reared and released (Swezey *et al.* 1999). However, *T. platneri* also attacks green lacewing eggs (Mansfield and Mills 2002), potentially reducing the general predator complex.

Methods for releasing the entomopathogenic nematode *S. carpocapsae* in order to control codling moth populations have also been investigated. Unruh and Lacey (2001) found pre- and post wetting can increase infection rate, causing close to 100% larval mortality. One of the greatest problems for treating overwintering codling moth cocoons in orchards with entomopathogenic nematodes is to maintain a wet enough environment and recently trials using mulches have shown greater promise in achieving better control (Lacey *et al.* 2006). However, the best use of the nematodes remains the treatment of overwintering cocoons in fruit bins (Lacey *et al.* 2005). In Washington, applications of codling moth granulovirus made against the first generation of codling moth significantly reduced damage by the second generation (Arthurs and Lacey 2004). Control with the bacteria *Bacillus thuringiensis* has also been attempted with unexceptional results as larvae feed very little on the surface before boring into the flesh of the fruit (Madsen and Hoyt 1958, McEwen *et al.* 1960).

3.2.4. Conservation biological control

Carabid beetles have been shown to be important predators of codling moth larvae descending to the ground in high density orchards to pupate (Riddick & Mills 1994). Ground predator densities can be enhanced through use of compost mulches that provide sources of alternative prey. However, this does not necessarily lead to greater predation rates on sentinel codling moth larvae, suggesting that habitat structure may be more important influence on predation than availability of alternative prey (Mathews *et al.* 2004)

Natural enemy activity against codling moth in pome fruit orchards can also be enhanced through reduced use of broad spectrum insecticides, and the adoption of alternative management strategies such as pheromone mating disruption.

3.3. Codling Moth Cultural Control

The UC Davis IPM website stresses the importance of cultural control in a codling moth management program. Nearby abandoned orchards containing host trees should be removed, as should any fruit from nearby unsprayed host trees. Infested fruit on the ground and on trees should be removed while the larvae remain inside (Caprile *et al.* 2002). Sanitation removal of fruit after harvest in early season pears has also been shown to reduce levels of codling moth infestation the following season (Van Steenwyk 2001).

Individual fruit can also be protected by enclosing them in brown paper bags during the growing season, but this approach has proved to be uneconomical due to the extent of labor involved (Caprile *et al.* 1994).

Removing tree props and fruit bins from orchards is also important, as both can be a source of overwintering codling moth the following spring (Caprile *et al.* 2002) and can facilitate population dispersal if the bins are moved to another orchard (Higbee *et al.* 2001). Higbee *et al.* (2001) found that use of plastic bins, as opposed to wooden, would greatly reduce codling moth overwintering in bins. Bin infestation could also be reduced by waiting until immediately before harvest to place bins in orchards (Higbee *et al.* 2001).

4. Obliquebanded leafroller: *Choristoneura rosaceana* **(Lep.: Tortricidae)**

4.1 Species and Damage

The leafroller complex attacking pome fruit in California includes the orange tortrix, apple pandemis, fruittree, omnivorous, and obliquebanded leafrollers. The orange tortrix and apple pandemis leafrollers occur coastally, while the omnivorous leafroller is found inland. Both the fruittree and the obliquebanded leafroller are found throughout California (Anon 1999). As the obliquebanded leafroller has two generations a year, with the second generation occurring immediately before harvest, it has a higher pest potential than the fruittree leafroller (Zanobini 1999).

The obliquebanded leafroller is indigenous to North America. Its primary hosts belonging to the family Rosaceae (Chapman and Lienk 1971), though it is also found on poplar, willow and birch (Powell 1964, Prentice 1965). Important economic hosts include: almond, blueberry, cherry, pear (Chapman *et al.* 1968), apple (Chapman *et al.* 1968, Reissig 1978), filbert (AliNiazee 1986), pistachio (Rice *et al.* 1988), and raspberry (Schuh and Mote 1948, Li and Fitzpatrick 1997).

The obliquebanded leafroller overwinters as a third instar larva under tree bark. In spring, as buds begin to open, larvae exit their hibernacula and move into cluster buds to feed. Larvae will also attach terminal leaves together for shelter. Later, when larvae are mature, they will create a single leaf roll to pupate in, emerging 10 to 12 days later. Emergence of the overwintering generation starts in late April and continues through May, peaking mid to late May. Emerging females lay egg masses containing up to 300 eggs on leaves (Anon 1999).

4.1.1. *Damage*

Economic damage is rarely caused by foliage feeding, but instead occurs when leafroller larvae attack fruit. Early in the season, attacked fruit can become deformed and scarred or wither and fall from the tree. Later in the season, larvae tie fruit and leaves together, creating shallow tunnels on the fruit surface. Larvae will also chew holes in fruit, causing the area around the hole to dry or decay when stored (Beers *et al.* 1993, Anon 1999).

Historically, broad-spectrum insecticides used for codling moth control have suppressed leafroller populations. However, with the increased use of mating disruption specifically targeting codling moth, leafrollers are more likely to become an economic pest.

4.1.2. Treatment thresholds

In apple orchards, treatment might be needed if two or more live larvae are found in a 100 fruit cluster sample in the spring or if four or more larvae are found during the summer (Caprile *et al.* 2002).

For pears the treatment threshold also differs with season. If during cluster bud, one larva is found in a 100 cluster bud sample, treatment should be considered at the beginning of the first summer flight. If more than one larva is found, then treatment is recommended immediately. In August, treatment is needed if more than two leafrollers are found in 100 shoots taken from the tops of the trees (Elkins *et al.* 2002)

4.2. Obliquebanded Leafroller Biological Control

4.2.1. Current activity of parasitoids, predators and pathogens

Parasitism of leafrollers (obliquebanded and three-lined) in organic apple orchards in British Columbia was found to range between 5.6 to 24.7 % for the overwintering generation and 0 (low leafroller density) to 67.9% for the first generation (Cossentine *et al.* 2004). In California, obliquebanded leafroller larval parasitism in pistachio orchards was around 15% in April, increasing to 40 to 60% in July and reaching 80 to 100% later in the season. *Macrocentrus iridescens* (Hym.: Braconidae) was found to be the dominant parasitoid with season-long parasitism ranging from 18 to 37% (Daane *et al.* 2001). *M. iridescens* can be found attacking obliquebanded leafroller in pear and apple orchards in the Central Valley, North Coast and Central Coast Regions of California (Anon 1999). Parasitism by *Exochus nigripalpis*, *Enytus eureka* (Hym.: Ichneumonidae) and a tachinid fly has been observed in North Coast apple orchards (Anon 1999). Many other parasitoids have been recorded from the Pacific Northwest and from obliquebanded leafroller on other crops in other regions, but no other parasitoids are known from pome fruit in California.

The arboreal spider *Cheiracanthium mildei* (Aranea: Clubionidae) destroyed 65% of leafroller larvae on pear and apple trees in small cage tests, while *Cheiracanthium inclusum* was responsible for a 35% reduction of leafroller larvae. However, in large cage tests, predation by *C. mildei* was less impressive, with predation of larvae ranging from 12 to 29%. In these trials, *C. mildei* was also found to feed upon leafroller egg masses (Miliczky and Calkins 2002). Other predators of obliquebanded leafroller larvae include: green lacewings, ants, minute pirate bugs, assassin bugs, and *Phytocoris* (Daane *et al.* 2001).

Studies investigating nucleopolyhedrovirus have resulted in leafroller mortalities between 58 to 75% (Smirnoff and Burke 1970, Lucarotti and Morin 1997, Pronier *et al.* 2002).

4.2.2. Classical biological control

No parasitoids or predators have been imported and released for the control of obliquebanded leafroller in the western United States. However, in Washington state, *Colpoclypeus florus* (Hym.: Eulophidae), originally imported to and released in Canada against the strawberry and redbanded leafrollers in the 1960's (Williamson 1966, Hikichi 1971), was found to be responsible for 66% and 75% parasitism of leafrollers in two unsprayed apple orchards (Brunner 1996).

4.2.3. Augmentative biological control

Releases of *Trichogramma minutum* (Hym.: Trichogrammatidae) in blueberries resulted in 47.9% parasitism of an obliquebanded leafroller egg mass in areas adjacent to the release point. However, 20 rows from the release point parasitism declined to 0%. The authors suggest that use of *T. minutum* as a biological control agent is limited, as the wasps are unable to parasitize 50% of an egg mass (McGregor *et al.* 2000). However, field trials suggest that *Trichogramma platneri* (Hym.: Trichogrammatidae) parasitizes more eggs per egg mass than *T. minutum* (Lawson *et al.* 1997). Inundative releases of *C. florus* against leafroller in Washington have resulted in high parasitism rates, but overall results have been inconsistent (Brunner 1992). As a polyembryonic species, one egg of *M. iridescens* can development into 20 to 30 adults (Krugner *et al.* 2005), making it a viable and attractive species for use in augmentative

biological control efforts. Krugner *et al.* (2005) discuss the biology of the species, as well as rearing methods capable of producing large numbers of parasitoids.

Sprays of *Bacillus thuringiensis* subsp. *kurstaki* have proved to be consistent and effective against leafrollers. Additionally, *B. thuringiensis* sprays are most effective when applied early in the spring against first generation larvae (Zanobini 1999). *B. thuringiensis* has been found to cause a mean mortality of 79.2% in fourth instar obliquebanded leafroller larvae. In contrast, the same study found mean mortalities of 37.9% and 48.8% for second and third instar larvae respectively, suggesting that the older instar is more susceptible to the bacteria (Cossentine *et al.* 2003). Pszczolkowski *et al.* (2004) found that the addition of a feeding stimulant to *B. thuringiensis* formulations increased the mortality rate of obliquebanded leafroller.

4.2.4. Conservation biological control

No specific cases of natural enemy conservation have been attempted for obliquebanded leafroller, but as for codling moth, natural enemy activity in pome fruit orchards can be enhanced through reduced use of broad spectrum insecticides.

4.3. Obliquebanded Leafroller Cultural Control

There are no known cultural controls for obliquebanded leafroller.

5. Pear Psylla: *Cacopsylla pyricola* (Hem.: Psyllidae)

5.1 Species and Damage

Introduced from Europe, pear psylla is an exotic pest on pears in California (Beers *et al.* 1993, Anon 1999). While pear psylla is found on other hosts, they are only able to complete their life cycle on pear (Beers *et al.* 1993).

Pear psylla overwinters as an adult under tree bark or under debris on the ground. Mating occurs in January and early February, with oviposition starting at bud swell and continuing for two to three weeks after petal fall (Anon 1999). At first, eggs are laid around buds or on twigs. After buds open, eggs are laid on the main veins and petioles of leaves or on the sepals and stems of blossoms (Beers *et al.* 1993). A single overwintering female can lay up to 500 eggs. Pear psylla has five nymphal stages, with all stages, as well as the adult, feeding on plant tissue. The first four nymphal stages are light colored and encased in honeydew, while the fifth nymphal stage, called the hardshell, has no honeydew casing (Anon 1999). The adults have a winter form and a summer form, with the winter form being larger and darker (Beers *et al.* 1993, Elkins *et al.* 2002). In California, pear psylla has five generations per year that overlap considerably after the first generation (Anon 1999).

5.1.1. Damage

Psylla nymphs produce honeydew that drips on leaves and fruit, providing a medium for fungal growth. When this occurs on the pear it results in russets on the skin that lead to a quality downgrading of the fruit (Anon 1999). Westigard *et al.* (1981) found that D'anjou pears are about five times more susceptible to pear psylla nymph damage than Bosc pears. Additionally, feeding nymphs inject a toxic substance into the leaves. When pear psylla densities are high this can cause psylla shock, resulting in dropped fruit, defoliation and stunted tree growth (Beers *et al.* 1993). Through feeding, pear psylla also transmit pear decline disease (Anon 1999). Pear decline damages the phloem, cutting off the flow of synthesized nutrients to the roots. The diseased tree then enters slow decline or quick decline, dependent upon the root

stock (Beers *et al.* 1993, Anon 1999). Infected trees with either *Pyrus pyrifolia* or *P. ussuriensis* root stock will enter quick decline; however, these root stocks are no longer used in California (Anon 1999).

5.1.2. Treatment thresholds

The UC IPM website states that dormant oil sprays should be used to keep the overwintering population at or below one pear psylla per 100 beat tray samples. At least one dormant spray is needed if there are two adults per 20 beat samples. If there are more than 50 adults per 50 beat samples, two dormant spray applications are needed. From green tip to tight cluster, treatment is necessary if 2 out of 100 fruit spurs contain eggs. If pear psylla are found on more than 1 out of 20 top shoots during the summer or more than 5 out of 20 top shoots during harvest and post-harvest, treatment is needed (Elkins *et al.* 2002).

5.2. Pear Psylla Biological Control

5.2.1. Current activity of parasitoids, predators and pathogens

The parasitoid *Trechnites insidiosus* (Hym.: Encyrtidae) attacks pear psylla in California (Anon 1999). While high estimates of parasitism by *T. insidiosus* have been reported (Nickel *et al.* 1965, Westigard *et al.* 1968, Burts 1970), it is generally believed that predators are more important in regulating populations of pear psylla than parasitoids (Unruh *et al.* 1995).

Pear psylla has many predators in California, and along with dormant and foliar oil treatments, are often able to keep pear psylla below economic levels. Predators of pear psylla found in pear orchards include: *Orius tristicolor* and *Anthocoris antevolens* (Het.: Anthocoridae); *Chrysoperla carnea* and *Chrysopa nigricornis* (Neur.: Chrysopidae); *Hemerobius* spp. (Neur.: Hemerobiidae); ladybird beetles; predaceous mirids; spiders (Anon 1999). These predators are part of the general predator complex and most feed on psylla eggs and nymphs, though spiders feed on adults (Beers *et al.* 1993). In Washington, higher pear psylla populations were found on trees that excluded the ant *Formica neoclara* (Hym.: Formicidae). However, this was not consistent over the entire study period (Paulson and Akre 1992a). Estimating the impact different predators have on pest suppression can be challenging, as evidence is often consumed. In order to eliminate some of the uncertainty that can arise, Agusti *et al.* (2003) have identified two molecular markers that can detect pear psylla during predator gut analysis.

5.2.2. Classical biological control

Pear psylla has been the target pest for a number of parasitoid introductions and releases. *Prionomitus mitratus* (Hym.: Encyrtidae), *Trechnites psyllae* and *Trechnites* sp. (Hym.: Chalcidoidea) were released in California, as well as in Oregon and Washington, from 1965 to 1990. However, while some recoveries were made, no long term establishment is recorded (Unruh *et al.* 1995).

During the same period that parasitoids were being released for psylla control, considerable numbers of predators were released as well. The generalist predators imported and released into California were: *Harmonia dimidiata, Harmonia conformis, Oenopia conglobata*, and *Diomus pumilio* (Col.: Coccinellidae). At the same time other predators were introduced to Washington and Oregon, though *Anthocoris nemoralis* (Het.: Anthocoridae) was the only predator that became established (Unruh *et al.* 1995) and has since expanded its geographic range south into California (Horton *et al.* 2004) Additionally, *A. nemoralis* has been found to preferentially lay eggs on leaves that contain *C. pyri* eggs (Sigsgaard 2005).

As a foliage feeder, rather than a fruit feeder, pear psylla is a good candidate for myco-insecticidal control; however, its effectiveness is limited to areas that experience high humidity and moderate

temperatures. Fungicide use also restricts the usefulness of entomopathogenic fungi for pest control in pears (Puterka 1999). *Beauveria bassiana, Paecilomyces fumosoroseus* and *Verticillium lecanii* were found to be more effective at reducing pear psylla populations than *Metarhizium anisopliae* or *M. flavoviride* (Puterka *et al.* 1994).

5.2.3. Augmentative biological control

Field experiments in Washington pear orchards suggest that introductions of the ant *F. neoclara* are able to reduce psylla populations (Paulson and Akre 1992b).

5.2.4. Conservation biological control

Over a two-year period in Oregon, organophosphates applied for codling moth reduced the natural enemy population by 90%, leading to higher pear psylla populations in orchards using organophosphates than in orchards relying on mating disruption for codling moth control. Furthermore, in orchards using organophosphates against codling moth, damage to pears due to psylla honeydew was 9.7%, compared to 1.5% in orchards using pheromones for codling moth control (Westigard and Moffitt 1984).

Spring emergence studies in Washington State suggest that the important pear psylla predators *Deraeocoris brevis* (Hem.: Miridae)*, Hemerobius ovalis, O. tristicolor* and *Anthocoris* spp. are active in orchards early in the season, with peak emergence occurring during February and March, when early-season insecticide sprays could have a damaging effect on populations (Horton 2004). Horton and Lewis (2000) also indicate that non-orchard sources of *Anthocoris* spp. and *D. brevis* could be improved by plantings of alternate host trees as windbreaks or hedge rows in orchards.

5.3. Pear Psylla Cultural Control

There are no known cultural controls for pear psylla.

6. Leafminer *Phyllonorycter* spp. (Lep.: Gracillariidae)

6.1. Species and Damage

The tentiform leafminer is native to California and can become a pest in apple orchards statewide (Anon 1999). Other economically important hosts are pear, cherry and prune (Beers *et al.* 1993, Anon 1999). Prior to 1980, leafminers received little recognition as a pest species of apple. This changed in 1980 when a severe outbreak occurred in Washington, which was thought to be caused by an introduction or selection of an insecticide resistant leafminer strain. Today, tentiform leafminer is considered an economic pest species of apple in California, Oregon, Washington, British Columbia and Utah (Barrett *et al.* 1995). It is unclear how many species are represented in the Pacific Northwest apple growing regions. Cossentine and Jensen (1992) state that *Phyllonorycter mespilella* is found in western North America, though it had previously been misidentified as *Phyllonorycter elmaella*. Varela and Welter (1992) identify the leafminer found in California apple orchards as *Phyllonorycter* nr. sp. *elmaella*.

Leafminers overwinter as pupae, concealed in mines bored into leaves that later fall to the orchard floor. In California, adults start to emerge in late February. In apples, females begin to lay eggs from tight cluster through petal fall (Anon 1999). Single eggs are laid on the underside of leaves (Barrett *et al.* 1995) and as soon as the eggs hatches the larvae mine into leaf tissue. There are five larval stages. The first three stages are referred to as the sap-feeding stage, during which the larvae feed on the mesophyll of the leaf (Anon 1999). The last two larval stages, collectively referred to as the tissue-feeding stage, feed on the upper part on the leaf. During the tissue feeding stage, leafminers string silk threads horizontally across

the mines, pulling the sides of the mines closer together and giving the mine an overall tent-like appearance (Beers *et al.* 1993). Larvae pupate in a cocoon located inside of a mine, though the pupae cut through the leaf surface so that they protrude from the leaf prior to emergence (Anon 1999). Depending on the location, leafminers have four to five generations a year (Varela and Welter 1992).

6.1.1. Damage

As foliage feeders, leafminers do not directly damage the fruit, but heavy infestation or concurrent mite infestation can cause stunting and discoloration of fruit, as well as defoliation (Anon 1999, Caprile *et al.* 2002). Heavy infestations can destroy 60% of leaf tissue (Caprile *et al.* 2002). Fruit may also become sunburned, as severely damaged foliage offers no protection (Beers *et al.* 1993, Anon 1999, Anon 2005b).

6.1.2. Treatment thresholds

The treatment threshold for tentiform leafminer is dependant upon the parasitism rate of the previous generation. Treatment of the first generation of leafminer is generally not needed, but the rate of parasitism is calculated for use later in the season. Treatment of the second generation is recommended if the average number of mines exceeds five or if two or more mines are present per leaf and parasitism of the first generation was under 10%. However, if parasitism of the first generation was greater than 10%, treatment should be delayed until the current generation reaches the tissue-feeding stage and the parasitism rate of the second generation can be calculated. Treatment is recommended against the third generation if the mean number of mines per leaf exceeds five and the parasitism rate of the second generation was below 30%. Treatment of the fourth generation is not necessary unless there are low levels of parasitism or the average number of sap-feeding mines per leaf surpasses five (Caprile *et al.* 2002).

6.2. Leafminer Biological Control

6.2.1. Current activity of parasitoids, predators and pathogens

The most important parasitoids of the leafminer in California are *Pnigalio flavipes* and *Sympiesis marylandensis* (Hym.: Eulophidae) (Anon 1999), accounting for 48% and 36% of parasitoids collected respectively in one study (Varela and Welter 1992). Other parasitoids collected from leafminers in California apple orchards include: *Sympiesis bimaculatipennis, Sympiesis sericeicornis, Sympiesis stigmata, Zagrammosoma centrolineatum, Zagrammosoma mirum, Zagrammosoma nigrolineatum* (Hym.: Eulophidae); *Pholetesor ornigis* (Hym.: Braconidae).

Parasitism in California apple orchards fluctuates between leafminer generations and trends in parasitism vary between orchards (Varela and Welter 1992). In the Pacific Northwest, *P. flavipes* can cause 90% mortality of a leafminer generation (Beers *et al.* 1993). In contrast, the highest mortality reported in California apple orchards due to parasitism was 77% (Varela and Welter 1992). While preferring to lay eggs on tissue-feeding larvae, *P. flavipes* favors sap-feeding larvae when host feeding (Barrett *et al.* 1995).

Predators include generalists such as lacewings and spiders. However, predators are thought to be less important than parasitoids in controlling leafminer populations (Anon 1999).

6.2.2. Classical biological control

There is no record of classical biological attempts against tentiform leafminer in the United States.

6.2.3. Augmentative biological control

There is no record of augmentative releases of natural enemies for the control of tentiform leafminer.

6.2.4. Conservation biological control

P. flavipes is capable of keeping leafminer populations below economically damaging levels. It is when the natural biological control provided by *P. flavipes* is disrupted by broad-spectrum insecticide use, usually for codling moth control, that leafminers become pests (Caprile *et al.* 2002). Thus selective use of non-disruptive insecticides in pome fruit can conserve parasitoid control of this pest.

7. Webspinning spider mites (Acari: Tetranychidae)
European red mite: *Panonychus ulmi*
Pacific spider mite: *Tetranychus pacificus*
Twospotted spider mite: *T. urticae*
McDaniel spider mite: *T. mcdanieli*

7.1. Species and Damage

The spider mite complex associated with apple and pear orchards in California includes the European red mite, Pacific spider mite, twospotted spider mite and the McDaniel spider mite. The mite complex species composition differs between hosts, as well as geographically. European red mite can be a major pest in all northern California pear and apple orchards. Twospotted spider mite, while occurring in all areas of California, is prevalent in areas with hot summers and where other host crops, such as strawberries, occur (Anon 1999). Twospotted spider mites are not usually culpable for mite problems in apples, while in pears they, along with the McDaniel spider mites, are the dominant pest mite species (Beers *et al.* 1993). Preferring cool summer temperatures, the McDaniel spider mite is less prevalent in California than in the Pacific Northwest, occurring only in orchards at higher elevations in California (Beers *et al.* 1993, Anon 1999). Pacific spider mite is an important mite species in the San Joaquin Valley and southern California mountain orchards (Anon 1999).

The three *Tetranychus* species differ from the European red mite, as they overwinter as adult females, while *P. ulmi* overwinters as an egg (Beers *et al.* 1993, Anon 1999). Overwintering *P. ulmi* eggs are laid on tree bark, opposed to the rest of the year when they are laid on either side of a leaf. Female Pacific, twospotted and McDaniel spider mites overwinter under bark scales, on the orchard floor under debris or on ground cover plants. Twospotted and McDaniel spider mites lay eggs on the undersides of leaves, while Pacific spider mites will lay eggs on either side. However, if high populations occur, all three species will lay eggs on both sides of the leaves (Anon 1999). *P. ulmi* has anywhere from 5 to 10 overlapping generations a year depending on conditions (Anon 1999). The *Tetranychus* species have between 8 to 15 generations a growing season, which overlap after the first generation (Beers *et al.* 1993, Anon 1999). Twospotted and Pacific mites reproduce more rapidly in dry and hot conditions, while McDaniel mites thrive in cooler conditions, accounting for their limited distribution in California (Anon 1999). All four mite species go through three immature stages before becoming adults (Beers *et al.* 1993, Anon 1999).

7.1.1. Damage

Damage caused by the Tetranychidae found in California pome fruit is similar for all species. Generally, apples and Asian pears are more tolerant to mite damage than European pear varieties (Beers *et al.* 1993). The spider mites feed by sucking out the contents of leaves. In apples, feeding on leaves will cause fruit to discolor and turn a bronze color. In pears, feeding can also lead to bronzing; however, leaf burn or transpiration may also occur (Beers *et al.* 1993, Anon 1999). High mite populations can cause defoliation

in both crops, though it is more likely to occur in pear. When defoliation occurs in pear, fall bloom can occur causing fruit size to be negatively affected the following year (Anon 1999). High mite populations on both apple and pear can cause adverse effects on fruit development during the current growing season, as well as the following growing season (Caprile *et al.* 2002, Elkins *et al.* 2002).

7.1.2. Treatment thresholds

As the susceptibility differs between hosts, apples and pears have different treatment thresholds. In apples, if more that 10% of spurs are found to have European red mite eggs during the winter, then a pre-bloom oil spray is recommended. During the growing season, treatment decisions in apples are made based on the total webspinning spider mite population. In July and August, or earlier if high populations of mites are evident, treatment is needed when there is a mean mite density of 10 mites per leaf and if there is less than one predatory mite per 10 spider mites (Caprile *et al.* 2002).

As pears are more susceptible to spider mites than apples, monitoring and treatment guidelines are more complex. Dormant oil sprays are recommended for all pear orchards independent of the European red mite overwintering population. During the winter, if European red mite eggs are found on 10% of the spurs, then close monitoring of this mite is recommended throughout the season. However, if a dormant oil spray is not applied, close monitoring of European red mite throughout the season should be done if 3% or more of the spurs contain eggs. From finger bud to petal fall, oil should be applied if more than 10% of fruit clusters are infested. However, oil plus miticide is recommended if more than 20% of fruit clusters are infested (Elkins *et al.* 2002).

The IPM websites lists thresholds using total mite counts (all stages of European red mite and nymphs and adults of other spider mites) for Bartlett and Bosc pears at different points during the growing season. At turn down pear stage, oil applications are recommended if 1 to 50 mites per 100 leaves are present. During fruit development, greater than 50 mites per 100 leaves warrant treatment with oil plus miticide. After harvest, in early districts, oil treatments are necessary if 50 to 100 mites are found per 100 leaves and there is less than one predaceous mite found for every 10 spider mites (Elkins *et al.* 2002).

7.2. Webspinning spider mites Biological Control

7.2.1. Current activity of parasitoids, predators and pathogens

The major predator of spider mites is the western predatory mite *Galendromus* (=*Metaseiulus, Typhlodromus*) *occidentalis* (Acari: Phytoseiidae). While *G. occidentalis* is abundant in inland orchards in California, it is not common in coastal orchards (Anon 1999). In laboratory assays using twospotted spider mite, one strain of *G. occidentalis* displayed a preference for eggs, while three other strains showed no prey stage preference (Blackwood *et al.* 2001). However, western predatory mite is unable to break through the egg shell of the European red mite (Anon 1999).

Other predators of spider mites include: *Chrysopa* spp. (Neur.: Chrysopidae); *Hemerobius* spp. (Neur.: Hemerobiidae); *Orius tristicolor* (Hem.: Anthocoridae); *Zetzellia mali* (Acari: Stigmaeidae); *Stethorus picipes* (Col.: Coccinellidae); *Scolothrips sexmaculatus* (Thy.: Thripidae) (Anon 1999). Intraguild predation and competition between predator species can disrupt natural control of spider mites. Negative associations have been found for *G. occidentalis* and *Z. mali* (Slone and Croft 2001). Croft and MacRae (1992b) demonstrated that *Z. mali* can check establishment of *G. occidentalis* in apple orchards and Hardman *et al.* (2000) propose that *Z. mali* might not be an effective spider mite predator. Furthermore, Croft and Luh (2004) suggest that *G. occidentalis* may be displaced by increasing populations of generalist predators when crop areas switch to less disruptive management practices. *Typhlodromus pyri* (Acari: Phytoseiidae), a widespread predator of spider mites, is able to kill over 100 *T. urticae* per day

(Zemek 2005). *T. pyri* also has be observed feeding on nymphs of *Z. mali*, while *Z. mali* feed on eggs of *T. pyri* (Macrae and Croft 1996). Predation on *T. urticae* eggs by *T. pyri* was found to decrease in the presence of apple powdery mildew, though the author suggests, in the long term, the presence of apple powdery mildew as an alternative food source might be beneficial to the success of *T. pyri* (Zemek 2005). However, spider mite densities have also been found to be greater on apple leaves infected with powdery mildew than on healthy leaves (Reding *et al.* 2001).

7.2.2. Classical biological control

In California almond orchards, *Stethorus histrio* (= *S. nigripes*) (Col.: Coccinellidae) was released for control of European red mite (Hoy and Smith 1982), but never became established (Hoy 1995).

7.2.3. Augmentative biological control

Mixed releases of *G. occidentalis* and *T. pyri* provided better control of European red mite and twospotted spider mite in apple than releases of either species alone (Croft and Macrae 1992a). While releases of permethrin and organophosphate resistant *G. occidentalis* in pear and apple orchards have led to successful establishment and overwintering, success is contingent on the availability of prey throughout the season. (Hoy *et al.* 1983). Releases of carbaryl and organophosphate resistant *G. occidentalis* in California almond orchards provided significant control over *T. urticae* and *T. pacificus*. Additionally, resistant *G. occidentalis* were found in orchards two years after release (Hoy 1982).

7.2.4. Conservation biological control

Predatory mites can be disrupted by use of insecticides, miticides and some fungicides. Judicious use of pesticides can prevent the loss of predatory mite control in pome fruit orchards.

7.3. Webspinning spider mites Cultural Control

Twospotted spider mites often feed on weeds in the cover crop of an orchard, moving onto trees when weeds become unsuitable. This migratory behavior makes twospotted spider mite infestation more sporadic than that of other spider mites, as well as making infestations more likely later in the season after weeds have dried or been cut (Hoyt 1995). As some weeds are reproductive hosts of spider mites, large populations can build during the growing season, causing migrating populations to be too large for natural enemies to control. A number of common cover crops are hosts of twospotted spider mite (Boller *et al.* 1985, Flexner *et al.* 1991, Alston 1994, Hardman *et al.* 2005). However, perennial grassers are unsuitable hosts (Boller *et al.* 1985, Flexner *et al.* 1991, Alston 1994), suggesting that they would be a preferred cover crop in orchards. Horton (1998) found that spider mites were not found on broadleaf weeds that were frequently mowed; however, neither were beneficial species.

The predatory mite *T. pyri* prefers apple varieties with greater leaf pubescence (Roda *et al.* 2001). Additionally, pubescent apple leaves have been shown to trap more pollen and fungal spores, which can be used as an alternative food source for predators such as *T. pyri* (Roda *et al.* 2003). Alston (1994) found that a minimum of 50% total ground vegetation with less than 12% cover of reproductive hosts can provide the necessary predaceous mite densities to control spider mites.

Reding *et al.* (2001) suggest that spider mite outbreaks could be controlled by management of powdery mildew in apple orchards.

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Development of Biological Controls in Stone Fruit [2]

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1. Introduction

Biological control programs for insect pests in stone fruit provide instructive examples of improved strategies and tools for integrated pest management (IPM). Foremost among these improvements is the development of mating disruption and insecticide programs that are compatible with biological control agents. Because stone fruit orchards can harbor many different pest species, implementing a systems approach that uses complementary management practices is essential. Historically, insect control in stone fruit was based on broad-spectrum pesticides. Improvements in monitoring systems and in the basic understanding of pest biology allowed the implementation of effective IPM programs. At first, these still relied largely on synthetic pesticides for insect control. More recent advances in IPM have included the development of sustainable stone-fruit practices that emphasize biological and cultural controls and significantly reduce the use of organophosphate and carbamate materials (Bentley *et al.* 20001, 2000b, 2001). Here, we discuss the three key insect pests that have been the targets of most control efforts in California stone fruit: San Jose scale, oriental fruit moth, and peach twig borer. We highlight the interrelationships among the control strategies for these pest species, and how recent improvements in IPM methods and technologies have created an opening for a renewal of research into their biological control.

2. Stone Fruit Production in California

2.1. Cultivated Stone Fruit Species and Varieties: Overview

Peaches (*Prunus persica* (L.) Batsch), nectarines (*P. persica* var. *nectarina*), and plums (*P. salicina* Lindley and *P. domestica* L.) comprise the majority of commercial stone fruit. Among the many cultivated species of *Prunus*, these are most similar to each other in terms of growth requirements and management practices, and they tend to be afflicted by the same arthropod pests. *Prunus* species occur mainly in temperate regions. The commercial production of stone fruits is confined by climate, soils, and water availability to selected locations in the United States, Canada, Europe, China, and Japan, in the northern hemisphere, and to Chile, Argentina, South Africa, Australia, and New Zealand in the southern hemisphere. By limiting this review to California we are hardly limiting its scope. In the U.S., more than 30 states produce fresh-market peaches, but California is by far the single largest producer of peaches, nectarines, and plums in the world. Over 90% of US nectarine production is in California, and nearly 100% of prunes. More than 95% of plums for fresh consumption are grown in California, including those used for canning, freezing, and preserves. Within the state, the stone-fruit industry is concentrated in the southern San Joaquin valley, in Fresno, Tulare, and Kern counties, although peaches, plums, and nectarines grow well throughout California's Central Valley (the San Joaquin and Sacramento valleys) and in some coastal regions. The combined peach, plum, and nectarine industries take up about 90,000 acres in California, with average annual revenues of over $300 million.

[2]The material reported herein represents, in part, a draft manuscript intended for submission to a peer-reviewed journal and is not meant for duplication or citation.

Archaeological evidence indicates that peaches were probably the first fruit tree domesticated in China, around 4000 years ago. The earliest written record dates to 1000 B.C., when a Chinese book of poems and songs described the ripe fruit and pink blossoms. Peach cultivation had spread to Europe by 300-400 B.C. Trees were brought to Mexico from Spain in the sixteenth century and to California, by Spanish missionaries, in the eighteenth century. Less is known of the origins of nectarines. European references date to 1616, but it is undoubtedly centuries older. Some 42 plum species (*Prunus* subgenus *Prunophora*) exist, but of these only two species produce commercially useful fruit. The European plum (*P. domestica*) originated in the Caucasus about 2000 years ago. It was introduced to North America by early English settlers and to California by Spanish missionaries. Used mainly for drying, this species is the basis of California's prune industry. The Japanese plum (*P. salicina*), despite its name, was first cultivated in China several thousand years ago and brought to Japan relatively recently, in the sixteenth century. It was first brought to California from Japan in 1870 by John Kelsey, a nurseryman from Berkeley. Later, the horticulturist Luther Burbank imported 12 seeds from Japan, from which he developed new varieties that led to most of those currently cultivated for fresh consumption in California.

2.2. A multidisciplinary approach

Pest-management practices for stone fruit are closely tied to the production practices of each orchard, creating an inherent need for an integrated approach to orchard and pest management. The multidisciplinary nature of the problem is most obvious in the selection of which stone-fruit species or cultivars to plant, as they vary in the type and intensity of pest damage to which they are susceptible. Over 400 varieties of peaches, nectarines, and plums are commercially available, differing in fruit color, size, taste, and timing of harvest. California peaches, for example, are harvested from early May to September, with the timing depending mainly on the cultivar. Pests that feed on ripe fruit and reach peak abundance in the summer will be less of a problem for early-ripening varieties, but these varieties will be more vulnerable to other pests that appear during the cooler spring months.

Another example of the multidisciplinary approach to orchard management concerns soil fertility, one of the essential building blocks of sustainable systems. Growers are often encouraged to lower the input of synthetic nitrogen (N) fertilizers or to use compost or leguminous cover-crops to provide sufficient N needed for fruit production. Fertilization recommendations must take into account the effects of N fertilization rates not only on crop yield but also on fruit quality and pest levels (Daane *et al.* 1995). In nectarines, for example, excessive N fertilization lowers fruit quality, and is associated with increased vegetative growth that favors certain lepidopteran pests. Fertilization practices also have environmental consequences when the N that is not taken up by plants leaches through the soil and into ground water, an increasing concern in California. N fertilization rates may also have a direct influence on disease incidence or postharvest performance by altering fruit nutrient composition, or an indirect effect by influencing firmness, bruising susceptibility, and physiological disorders.

3. San Jose Scale - *Diaspidiotus perniciosus* (Hem.: Diaspididae)

3.1. San Jose Scale Species and Damage

3.1.1. Description of pest

San Jose scale (SJS), *Diaspidiotus* (= *Quadraspidiotus) perniciosus*) (Comstock) (Hemiptera: Diaspididae), was first identified in stone-fruit orchards in California in 1870, apparently arriving on peach trees shipped from China. By the 1890s, SJS was reported as a major economic pest of stone fruit throughout the USA. Its spread was facilitated by a broad climatic tolerance and wide host-range, as it feeds on stone fruit, pears, and apples, as well as many nut crops (Gentile and Summers 1958). During the

first half of the 20th century, however, it went into decline more or less spontaneously, a drop attributed largely to the activity of natural enemies. From the 1940s to the 1990s, SJS was characterized by sporadic eruptions followed by periods of relative scarcity. Control during that period was generally attributed to the use of in-season or dormant insecticides applied for moth pests. Paradoxically, outbreaks during the same period were attributed to the disruption of biological control by the same pesticides. Because or in spite of these chemical treatments, SJS was considered a minor pest in California until the 1990s, when it again became a persistent problem on stone fruit in the Central Valley. These recent economic losses stimulated renewed interest its biological controls (Badenes-Perez *et al.* 2002).

3.1.2. Damage

The degree of damage inflicted by SJS varies with density, tree condition, and species or cultivar. The scale feeds on twigs, older wood, shoots, and fruit. Heavy infestations can kill fruiting branches and even main limbs, retarding growth and sometimes cause permanent injury to the tree. Younger trees are most vulnerable, but older trees may be damaged when deep, longitudinal, gum-filled cracks form in heavily infested limbs. Most of the economic loss, though, occurs when SJS feeds on the fruit. Typically the damage is cosmetic, as the scales cause unsightly discoloration and blemishing. Nectarines are especially susceptible, as the crawlers readily settle on the hairless fruit and even small populations cause extensive damage.

3.2. San Jose Scale Biological Control

3.2.1. Current parasitoids, predators and pathogens

Parasitoids—particularly Hymenoptera in the family Aphelinidae—are the most important natural enemies of SJS. As the history of SJS in the USA suggests, they have the potential to significantly reduce SJS populations. Most of the SJS parasitoids were accidentally introduced, along with the scale pest. The importance of natural enemies for SJS suppression was reported as early as 1905. By about 1910, SJS was in decline across most of the USA, its decrease linked to the buildup of a fauna of parasitic Hymenoptera, including the aphelinids *Encarsia* (=*Prospaltella*) *perniciosi* (Tower) and several *Aphytis* species (Gulmahamad and DeBach 1978). Surveys conducted in California in the 1970s identified *Aphytis aonidiae* (Mercet) as the dominant parasitoid species, with *A. diaspidis* Howard also relatively common and *E. perniciosi* rare (Gulmahamad and DeBach 1978). More recent surveys, conducted in Central Valley stone-fruit orchards in 1999-2003, reveal a shift in the composition of the parasitoid fauna: *E. perniciosi* is now the most abundant species, with *A. vandenboschi* DeBach & Rosen second and *A. aonidiae* recovered in much lower numbers (Daane *et al.* 2003).

Though regularly recovered in California, these parasitoids do not consistently provide the necessary level of control, especially for cultivars that ripen late in the season. Although *E. perniciosi* often occurs in high numbers, it peaks in early spring, with a lesser peak in late fall. The early spring peak does not prevent the scales from increasing in density throughout the summer to economic-injury levels. The *Aphytis* species exhibit a different pattern, being relatively rare in the spring and reaching maximum abundance in the summer. Generally their populations build up too late to have any useful impact on SJS. One explanation for the decline of *E. perniciosi* in the summer months is that it is less tolerant than *Aphytis* species of summer heat (Daane and Sime, unpublished data). Several lines of evidence support this explanation. For one, *E. perniciosi* preferentially parasitizes scales in the cooler interior and lower parts of the canopy, while the *Aphytis* species occur evenly throughout the canopy. Laboratory experiments indicate that at higher temperatures adult *A. vandenboschi* live significantly longer than *E. perniciosi*, and that the upper temperature threshold for larval development is several degrees higher than that of *E. perniciosi*. These observations may also explain why San Jose scale is less of a problem in the cooler parts of the Central Valley.

The distinct seasonal pattern suggests that augmentative releases of the parasitoids could enhance biological control. In 2000, inoculative releases of *A. vandenboschi* and *E. perniciosi* were shown to increase parasitism levels over those in untreated controls (Daane *et al.* 2003). Although *E. perniciosi* produced higher parasitism rates in the cages than did *A. vandenboschi*, a significant finding of this study was that *A. vandenboschi* can inflict high mortality levels through host feeding. Augmentative release of *E. perniciosi* may not be effective in conditions of extreme summer heat.

3.2.2. Classical biological control

The more important SJS parasitoid species (*E. perniciosi A. aonidiae* and *A. vandenboschi*) were accidentally introduced into the USA, probably along with the scale. We are unaware of any recent systematic surveys of SJS parasitoids in Asia.

3.2.3. Augmentative biological control

Mass-releases of *E. perniciosi* and *A. vandenboschi* were tested in cage and open-field releases (Daane et al. 2004). Selected branches were then inoculated with ~500 SJS crawlers (from an insectary colony) in late spring or summer to match the natural SJS population. The inoculated branches were enclosed in large, self-supporting organdy cages. After the SJS reached an appropriate size, a pre-release count of the number of settled SJS and *E. perniciosi* or *A. vandenboschi* were then released into the cages at either 1:5 or 1:10 or 1:20 ratio of parasitoids to SJS. After 4-6 weeks, the cages were removed and SJS were counted and dissected to determine their development stage and condition (live, dead or parasitized). Results from *E. perniciosi* release show that 35.5% of 2nd instar SJS were parasitized, while only 20% of 3rd instar SJS were parasitized. There was very little host feeding, as indicated by the number of dead SJS. Using a similar number of *A. vandenboschi*, there were no 1st instar female or male SJS were parasitized, 10% of 2nd instar SJS parasitized, and 42.5% of 3rd instar SJS parasitized. There was also considerable host feeding, with no live 1st instars found, 80% of the 2nd instars were dead, and 29% of 3rd instars were dead. These results are quite promising and what is needed for further development is the interest and involvement of a commercial insectary.

3.3. Cultural controls

There are few cultural controls, other than pruning heavily infested branches from the tree.

4. Peach Twig Borer, *Anarsia lineatella* (Lep.: Gelechiidae)

4.1. Peach Twig Borer Species and Damage

4.1.1. Description of pest

The peach twig borer (PTB), *Anarsia lineatella* Zeller (Gelechiidae), which presumably originated in eastern Asia, has been a problem in North America for over 100 years (Lovett 1923, Jones 1935). It was the most important pest of California peaches and nectarines until the oriental fruit moth arrived in the 1940s (Summers 1966). Jones (1935) and Bailey (1948) provided the first extensive descriptions of PTB life history.

4.1.2. Damage

Larvae feed in growing shoots and in the fruit. Feeding-site selection depends on time of year, timing of fruit maturity, and population density. PTB overwinters in the larval stage, in small chambers

(hibernacula) bored into thin bark or cracks in the tree (Price and Summers 1961). Around blossom time, the larvae move up the branches to feed on shoots and flower buds. Subsequent development depends on temperature and tree condition, with three or four generations per year in California. The fruit become attractive as they ripen. Besides causing obvious cosmetic damage in fruit, the feeding activity of the larvae creates infection sites for brown rot. Damaged fruit are culled at harvest, and high infestation levels can result in rejection of the entire crop.

4.2. Peach Twig Borer Biological Control

4.2.1. Current parasitoids, predators and pathogens

A variety of insect predators occur in stone-fruit orchards. Generalist predators commonly found in California orchards include ants (Formicidae), convergent lady beetles (*Hippodamia convergens* Guérin-Méneville (Coccinellidae)), green lacewings (*Chrysoperla carnea* Stephens, *Chrysoperla comanche* Banks, *Chrysopa nigricornis* Burmeister (Chrysopidae)), minute pirate bugs (*Orius* spp. (Anthocoridae)), and salticid spiders (*Metaphidippus vitis* (Cockerell) and *Thiodina* sp.) (Dlott *et al.* 1994, Daane and Dlott 1998). Presumably all of these can attack small PTB larvae, which are exposed to predators whenever they move between feeding sites (a larva requires more than one vegetative shoot to complete its development) (Daane and Dlott 1998). The native gray field ant (*Formica aerata* Francoeur) is the most common and most effective predator of PTB larvae in the San Joaquin Valley. It attacks all larval instars and significantly lowers both shoot damage and fruit infestation levels, though not necessarily below economic levels (Daane and Dlott 1998).

4.2.1. Classical biological control

About 30 natural enemies of PTB have been identified worldwide. None, however, is known to provide effective control. One parasitoid, *Habrobracon lineatellae* Fischer (Hymenoptera: Braconidae) has been imported to and released in California (Laing and Caltagirone 1969), and several endemic and accidentally introduced parasitoids are also present, but their performance is highly variable (Daane *et al.* 1993).

In general, parasitism rates of PTB in California tend to be higher and parasitoid species composition more diverse in the Sacramento Valley than further south. Total parasitism rates of <1%, due mainly to *Paralitomastix pyralidis* (Ashmead) (Hymenoptera: Encyrtidae) and *Macrocentrus ancylivorus* Rowher (Hymenoptera: Braconidae), are typical in the San Joaquin Valley. Although *M. ancylivorus* is primarily a parasitoid of oriental fruit moth, it is also the parasitoid most commonly recovered from PTB in the San Joaquin Valley, though it has not been found to parasitize more than 0.5% of PTB collected over the entire season. In contrast, in northern California, *P. pyralidis* parasitizes over 90% of PTB fifth instars and pupae, and another chalcid wasp, *Euderus cushmani* Crawford (Eulophidae), up to 12% of overwintering larvae. It is not clear whether insecticide use patterns, host condition, orchard cultivar, or climate factors are responsible for the regional differences. The highest parasitism rates are found in organic orchards that have not received dormant organophosphate sprays for several years, which suggest that disruption of parasitoids by insecticides is part of the problem (Daane *et al.* 1993).

4.2.3. Augmentative biological control

There are no published accounts on the effectiveness of augmentative biological control for the peach twig borer, although stone fruit growers in California often release Trichogramma for peach twig borer control.

4.2.4. Conservation biological control

There are no published accounts of conservation biological control, such as cover cropping, for parasitoids of the peach twig borer. As discussed in the "Apple and Pear" chapter, an important area of conservation biological control is the selection and use of pesticides that are compatible with biological control agents in the ecosystem.

5.2.5. Pathogens

As detailed below, the use of *Bacillus thuringiensis* to control PTB helped move sustainable stone fruit forward (Barnett *et al.* 1993). To date, however, there have been no studies showing significant mortality of key stone fruit pests resulting from pathogens resident in the orchard.

4.3. Peach Twig Borer Cultural Control

The timing of harvest is a critical determinant of levels of fruit infestation by PTB. Orchards harvested mid- to late season often require additional pheromone or insecticide treatments, and these strategies tend to lose effectiveness as the season progresses.

Early recommendations included removal of suckers to reduce the number feeding sites and destroying fallen fruit and prunings (Bailey 1948). Later studies indicated that new growing shoots, rather than suckers, are preferred host sites for PTB when fruit are not available (Daane *et al.* 1995). Patterns of fruit damage within trees and within the orchard can inform cultural controls as well. Weakley *et al.* (1990) showed that fruit damage in the tops of trees is greater than fruit damage in the lower half of the tree canopy, and that fruit damage at harvest was greater than fruit damage at sampling dates up to four weeks earlier. Furthermore, levels of fruit damage in trees located at the orchard border are greater than in trees in the center of the orchard.

In general, high levels of PTB damage occur in trees with excessive growth of new foliage, and such shoot growth is in turn correlated with high nitrogen (N) fertilization. Studies conducted in a San Joaquin Valley nectarine orchard have confirmed a positive relationship between N fertilization and fruit infestation (Daane *et al.* 1995). In these experiments, plot size was small and the moths could easily fly between treatments. Three explanations for the relationship were proposed. First, fruit in the higher N treatments required more time to reach maturity, increasing the period of vulnerability to pests and thus the likelihood that eggs would be laid directly on the ripening fruit (hard, green fruit are less suitable). Second, more eggs were deposited on both shoots and fruit subject to the higher N treatments, perhaps as a result of such trees producing greater amounts of attractive compounds. Third, there was a positive relationship between the number of new shoots and N fertilization levels, and new shoots provided a better habitat for moth larvae than older vegetative growth. These results suggest that lowered N fertilization regimes, which minimize vegetative growth, can reduce moth density in several ways. Fruit would be less susceptible both as a consequence of lowered attractiveness to ovipositing moths and of a smaller time window of vulnerability. The moth larvae would have fewer feeding sites available, which would increase the time they spend moving between feeding sites and thus increase their exposure to natural enemies.

The significant contribution of gray ants to PTB mortality suggests that enhancing their numbers would provide an effective complement to regulation of N levels. Unfortunately, the ants are difficult to manipulate and their population densities do not correlate with any particular cultural practice (Daane and Dlott 1998). The possibility of altering gray ant densities has been tested by monitoring ant populations in San Joaquin valley orchard blocks subject to different management practices. Cover crops or resident vegetation can provide alternative food sources in the form of alternate prey, seeds, or nectar, but clean-cultivated systems are just as suitable. The surprising finding was the lack of any clear relationship

between orchard floor management practices and ant numbers. Only the presence of southern fire ants (*Solenopsis xyloni* McCook) has a significant effect on gray ant populations. The southern fire ant is rarely observed foraging on the shoot terminals and is not an important PTB predator; rather, it is almost always considered a pest in orchards. Both species nest in the soil, forage on the ground cover or in trees, and often aggregate around abundant food sources. Defensive behaviors and aggression between foragers appear to result in spatial separation of gray ant and fire ant colonies, and the fire ant tends to out-compete the gray ant. Because the gray ant and fire ant compete for territory, any cultural practice that diminishes one species may allow the other species to increase in numbers. A better understanding of orchard floor management strategies that might simultaneously encourage gray ant populations while reducing the abundance of fire ants is needed. Cover cropping and disking are possibilities, as the fire ants prefer dry, undisturbed soils.

Gray ants occasionally tend homopteran insects to obtain carbohydrates, and thus there are potentially situations in which it is a pest. Shorey *et al.* (1993) reported that gray ants tend several aphid species in plum trees, for example, and thus may disrupt their biological control. However, aphid and soft scale outbreaks are rare in peaches and nectarines, and the gray ants can be considered to play an entirely beneficial role in these crops.

5. Oriental Fruit Moth, *Grapholita molesta* (Busck), (Lep.: Tortricidae)

5.1. Oriental Fruit Moth Species and Damage

5.1.1. Description of pest

The oriental fruit moth (OFM), *Grapholita molesta* (Busck) (Tortricidae), is currently the principal lepidopteran pest in California stone fruit. It was introduced into eastern North America around 1913, probably on infested nursery stock from Japan (Peterson and Haeussler 1926), and quickly spread throughout North America on infested fruit and nursery trees (Brunson 1946). During the 1920s and 1930s, OFM was reported in most stone-fruit regions east of the Mississippi (Stearns 1921, Guyton 1924, Peterson and Haeussler 1926, Snapp and Swingle 1929, Cagle 1930, Eddy *et al.* 1930, Garman 1930, Neiswander and Stearns 1930, Wingo 1941, McCampbell and Newton 1944). During this period of rapid agricultural expansion in North America, OFM was also accidentally introduced from the USA into Europe (Allen 1932). It arrived relatively late to California. It was first reported in 1942 in southern California (Orange County) and for the next 10 years its populations remained relatively low (Summers 1966). Then, in the 1950s, OFM outbreaks and damage were reported in several parts of the Central Valley. During this period, OFM replaced PTB as the most serious insect pest in stone fruit and became the principal target of insecticide treatments.

5.1.2. Damage

OFM can be found on almond, apple, apricot, cherry, nectarine, pear, plum, and quince, but it is mainly a pest of peach (Summers 1966). Like those of PTB, the larvae of OFM damage shoots and fruit. The preferred feeding site varies with time of year and cultivar, which affect the timing of fruit maturity, and with OFM population density. Most damage in the spring is to the shoots, as the larvae bore into and kill the growing tips. Younger trees are the most affected at this stage, as the death of the terminals can deform the trees. As the season progresses, maturing fruit soften and become susceptible to later generations. The larvae of OFM (like PTB) bore into the fruit and older larvae tend to feed near the pit. Besides causing the obvious cosmetic damage, the feeding activity of even small larvae creates infection sites for brown rot. Before the development of effective insecticide treatments, fruit infestation rates from 50 to 100% were reported.

The seasonal phenology of OFM was documented in detail as the moth moved into new regions (Peterson and Haeussler 1926, Eddy and Nettles 1931). Mature larvae or pre-pupae overwinter in the cracks and crevices of the tree's trunk and scaffolding. Development resumes in February or March, when pupation takes place. In most cultivars, the adults emerge near bloom. There are five or six generations per year in California, which allows populations to grow quickly when good feeding sites are available. The phenology of OFM and its tendency to feed deep in growing shoots or fruit pose problems for biological control agents. Parasitoids that attack eggs or early instars must contend with a long period, from October to April, when these stages may not be found. The deep feeding sites protect larvae from predators and from parasitoids that need to contact the host for oviposition.

5.2. Oriental Fruit Moth Biological Control

5.2.1. Current parasitoids, predators and pathogens

5.2.2. Classical biological control

A major biological control campaign of the early 1900s targeted OFM in eastern North America, motivated in part by the lack of effective insecticides at the time (Eddy and Nettles 1931). The work was largely organized by the Bureau of Entomology and Plant Quarantine, United States Department of Agriculture, and directed from the station at Moorestown, New Jersey (Allen *et al.* 1940). The project was considered to be quite promising as early studies of OFM in the field had identified numerous endemic natural enemies (Peterson and Haeussler 1926, Allen *et al.* 1940). In addition, surveys conducted in the 1920s in Japan and Korea found a rich fauna of parasitoid species that were not present in North America (Allen 1932, Haeussler 1940).

From 1929 to 1935, approximately 30 imported parasitoids (primarily from Europe, Australia, Japan, and Korea) and 10 endemics were released in the USA, some after mass-rearing in insectaries and some simply collected in the field and released in smaller numbers. By 1940, some 390,000 ichneumonids and 1,100,000 trichogrammatids had been released, spread over 20 states from Georgia to Connecticut (Allen *et al.* 1940). Despite considerable efforts, surveys conducted in the 1930s indicated that only one of the imported species, *Eriborus molestae* (Uchida) (Hymenoptera: Ichneumonidae) established, and this species has since become extremely rare.

Ultimately it was not the imported Asian or European species but rather the natural enemies' resident to North America that had the greater effect on OFM. Some of the earliest reports of OFM establishment and dispersal in North America noted that it was parasitized by numerous endemic Hymenoptera, primarily *Macrocentrus* sp. (Braconidae) and *Trichogramma minutum* Riley (Trichogrammatidae) (Garman 1917, Stearns 1921). Later studies of OFM population dynamics and parasitoid surveys confirmed that a rich fauna of resident parasitoid species was associated with OFM in North America (summarized in Table 1), and in some cases substantial levels of suppression were observed. In most of these early surveys only a few parasitoid species were predominant. For example, McConnell (1932) reared 25 species of egg, larval, and pupal parasitoids in Maryland, but most of the individuals were either *Macrocentrus ancylivorus* or *Glypta rufiscutellaris* Cresson (Ichneumonidae). Butler (1933, 1935) reared 17 parasitoid species and found that 55% of OFM in Tennessee peach orchards were parasitized, mainly by *M. delicatus* Cresson. Driggers (1941) found that *M. ancylivorus* parasitized 46-100% of the second brood in 74 of 86 New Jersey orchards surveyed from 1938-1940, while *G. rufiscutellaris* was the dominant parasitoid in the remaining 12 orchards. In Virginia, 10 different parasitoid species were recovered, but only *M. ancylivorus* and *G. rufiscutellaris* were at high enough levels to be important (Bobb 1939). Stearns and Amos (1941), summarizing a 10-year study of OFM parasitism in Delaware, reported an average parasitism rate of 62%, with *M. ancylivorus* comprising 92.8% of the parasitoids collected.

Egg parasitoids are missed in most parasitism surveys because usually only larvae are collected. Of those surveys that accounted for egg parasitism, *Trichogramma* species parasitized up to 60% of the late-season eggs in New Jersey (Peterson and Haeussler 1926) 50% in South Carolina (Eddy and Nettles 1931), and 95% of eggs in Arkansas (Wylie 1966).

There exist regional exceptions to the pattern of dominance by the parasitoid species mentioned above, as well as variations through the season. For example, *M. ancylivorus* tends to be the dominant species in warmer regions (Peterson and Haeussler 1926, Driggers 1930, 1941, Daane *et al.* 1993), but *G. rufiscutellaris* has been reported as more abundant in the cooler peach-growing regions of the northeastern USA (Driggers 1941), and *M. delicatus* was found to be the dominant species (95.5% of parasitoids reared) in Tennessee (Butler 1933, 1935). In California and other parts of the USA, *M. ancylivorus* and *Trichogramma* species are currently the dominant OFM parasitoids (Wylie 1966, Pinto *et al.* 2002). For both, levels of parasitism tend to be low during the first one or two OFM generations and increase as the season progresses. Late-season OFM parasitism rates in the San Joaquin Valley can reach 60-95% (Daane *et al.* 1999). Similarly, Stearns and Amos (1941) found that in Delaware parasitism levels of *M. ancylivorus* were lower in the first generation (29.1%) than in the third generation (76.3%).

A key limitation for *M. ancylivorus* in some regions is the availability of suitable overwintering hosts (Eddy and Nettles 1931). OFM overwinter in the fifth instar or pre-pupa, and the younger instars that are preferred by *M. ancylivorus* for oviposition are unavailable in September when a large number of adult *M. ancylivorus* emerge during the last OFM generation in California (Summers 1966). Common alternate hosts for *M. ancylivorus* in the northeastern USA and Canada are two tortricids, the ragweed borer, *Epiblema strenuana* (Walker) and the strawberry leafroller, *Ancylis comptana* (Fröhlich) (Haden 1935). In California, overwintering hosts include sunflower moth and PTB (Daane *et al.* 1993). Studies are currently underway to determine the advantages gained by planting sunflowers near stone fruit orchards in order to provide habitat for the sunflower moth (Bentley *et al.* 2006).

The failure of imported parasitoids led researchers to focus attention on the two most abundant resident species, *T. minutum* and *M. ancylivorus*, for redistribution to regions where parasitism rates were low. Initially, *M. ancylivorus* was reared mainly from field collections of the strawberry leaf roller or from OFM collected on excised peach twigs, both very labor-intensive methods. As OFM spread to the western states, particularly Colorado, Oregon, and California, investigations of rearing methods were conducted for state-managed mass-production and inoculation projects. After mass-culturing techniques were developed in the 1930s (Garman and Brigham 1935), millions of *M. ancylivorus* were reared and released in different state programs (Daniel 1936, Allen *et al.* 1940, Driggers 1941). After the war, researchers in California refined *M. ancylivorus* rearing methods, converting Army buildings into insectaries and forming what eventually became the International Center for Biological Control (University of California, Berkeley). Early findings on *M. ancylivorus* releases in California suggested that the parasitoid provided some control (Daniel 1936). These conclusions proved premature, however, for after millions of *M. ancylivorus* were released it was found to have little effect on OFM populations in California, and it appeared to have difficulty even establishing in most areas.

5.2.3. Augmentative biological control

Augmentative release of *Trichogramma* has become an established tool for sustainable management of various lepidopteran pests. Some of the initial work with this species targeted OFM in the northeastern USA (Allen and Warren 1932). Peterson (1930) noting that resident *T. minutum* parasitized eggs of OFM, conducted initial studies of the parasitoid's life history, developed rearing methods, and performed early field trials using mass-cultivated *T. minutum*. While these early efforts showed some promise, researchers concluded that the reductions in fruit infestation were not economically significant. The trials

were conducted using release rates of 55,000 *T. minutum* eggs per acre per season, which is far lower than rates used today. Although *Trichogramma* is often released today for both OFM and PTB control, especially in organic or sustainably managed orchards, we could find no recent reports of the impact of these releases on OFM in stone fruit.

5.2.4. Conservation biological control

Recent studies have investigated the use of sunflower planting, near stone fruit orchards, to increase the number of the sunflower moth and provide an overwintering refuge for *M. ancylivorus* (Bentley *et al*. 2006). To date, there is no commercial use of this practice.

5.3. Cultural controls

Most of the cultural controls described for PTB are also applicable to control of OFM. The timing of harvest is a critical determinant of levels of fruit injury (Peterson and Haeussler 1926) For example, Summers (1966) suggested that canning (cling) peaches are more vulnerable because they are harvested later in the season and when fully ripe. The importance of cultivar and plant vigor with respect to OFM population density was also noted early (Frost 1930). As discussed for PTB, N fertilization rates also affect the susceptibility of orchards to attack by OFM (Daane *et al.* 1995). In general, high levels of both OFM and PTB damage are found in trees with excessive growth of new foliage, and this shoot growth is in turn correlated with high nitrogen fertilization.

6. Development of Modern Stone Fruit IPM Systems

6.1. Historical Patterns of Insecticide Use.

Before the arrival of OFM in the 1940s, SJS and PTB were the two major pests in California stone fruit. Broad-spectrum insecticides that targeted both pest species were used from the start, typically applications of lime sulfur during the dormant season and lead arsenate and/or nicotine sulfate during the growing season. Early modern insecticides included dinitro-o-cyclohexylphenol and oil for SJS (Dutton 1936). An excellent discussion of these pioneering insecticide materials is provided by Howard *et al.* (1943). Until the 1980s, biological controls and insecticide sprays for stone-fruit pests were not compatible.

Few effective materials were available to control OFM when it first appeared in the eastern USA. Eggs could be killed with nicotine sulfate (Peterson and Haeussler 1926), and neonate larvae were killed or repelled by various grades and concentrations of oil emulsion (Frost 1932). Older, burrowing larvae, however, were difficult to target. In-season sprays of pyrethrum soap emulsion, Bordeaux mixture, or lead arsenate, and dustings of sodium fluorosilicate and hydrated lime were used with mixed success (Eyer 1927, Stearns and Neiswander 1930, Frost 1932, Wylie 1966). The arrival of OFM in California coincided with the advent of chlorinated hydrocarbon and organophosphate insecticides.

In California and elsewhere, researchers showed that these broad-spectrum, long-residual materials were effective, although their disruptive effects on beneficial insects and the environment were initially not well understood. Parathion, DDT, benzene hexachoride, and related compounds were shown early on to control the immature stages of OFM (Rings and Weaver 1948, Cochran 1949, Driggers and Merrill 1949, Hamilton 1949, Laplante 1949, Driggers 1950, Brunson 1952, Wylie 1966). Usually, two to six applications per season were made, though it is unclear from the literature whether multiple applications were necessary because of insecticide resistance or because of the necessity of treating three pest species with different phenologies. In-season insecticide applications directed at OFM also kept PTB under control, while dormant-season applications controlled both PTB and SJS. During the 1970s, synthetic

carbamates and organophosphates, typically applied multiple times during the growing season, were the usual control option, along with an oil and organophosphate combination during the dormant season (Rice *et al.* 1972, Downing and Logan 1977, Rice *et al.* 1979). However, as studies began to show a positive correlation between organophosphate use and residue load in surface water, the movement to reduce their use began to grow (Zhang *et al.* 2005).

6.2. Monitoring to Improve Insecticide Applications.

Initial progress in stone-fruit IPM combined knowledge of pest biology with improved monitoring tools. The resulting improvements in the efficiency of each insecticide application led to the reduction of the number of applications. The key research finding was the identification and production of synthetic sex pheromones, as there had previously been few reliable tools with which to determine pest density and flight periods (Cardé and Minks 1995). Early sampling methods for moths consisted mainly of liquid bait traps (Frost 1927, Yetter 1930), which can provide reliable information on flight activity (Phillips and Proctor 1970) but are clumsy to use in the field. Similarly, SJS crawlers can be monitored by double-sided sticky tape (Daane et al. 2002, Bentley et al. 2000a, 2000b), but the tape works only on the part of the branch on which it is placed, is often compromised by weather and aerial debris, and is time-consuming and awkward to use. The use of sex pheromones as a monitoring tool provided a fast and easy sampling method for the three key pest species.

Female sex pheromones were known to be important part of OFM mating behavior (George 1965). After the components of the pheromone were identified (Roelofs *et al.* 1969), researchers assessed the male moth's response to individual pheromone components (Carde *et al.* 1975, Baker and Carde 1979, Carde *et al.* 1979), blends (Baker *et al.* 1981), and concentrations (Baker and Roelofs 1981, Kuenen and Baker 1982). The effects of pheromone concentration and quantity, dispenser age, and trap placement on OFM monitoring are still being evaluated and refined (Kovanci *et al.* 2006).

The PTB sex pheromone was identified in the 1970s (Roelofs *et al.* 1975). Initially, the performance of PTB pheromone in the field was often poor. Reanalysis of the blends and the identification of behavioral antagonists in some synthetic pheromone preparations (Millar and Rice 1992, 1996) led to the improvement of commercial formulations and field performance. Use of the sex pheromone for monitoring was also improved through studies investigating the optimal component ratios and concentrations of the pheromone and the effect of aging on the attractiveness of the pheromone in rubber septa (Hathaway 1981, Hathaway *et al.* 1985, Kehat *et al.* 1994).

Rice (1975) demonstrated the responses of male SJS to female sex pheromone. The pheromone components were subsequently identified and synthesized. The winged males are easily sampled in pheromone traps (Jorgenson *et al.* 1981, Rice and Jones 1982). Careful tracking of seasonal phenology has improved the timing of insecticide applications. Further refinements have included analysis of SJS response to pheromone load (Zalom *et al.* 1992).

With improved monitoring techniques, researchers have been able to create development-rate models and determine degree-days for OFM and PTB flight and egg-laying periods (Zalom *et al.* 1992) and SJS crawler emergence. Improved spray schedules were especially important for timing in-season insecticide applications for multiple pests (Rice *et al.* 1979). Among various refinements of these applications, Brunner and Rice (1984) modeled PTB development in Washington and California using on male flight data, and Rice *et al.* (1984) used degree-days to determine optimal spray timing for OFM. Rice and Jones (1988) showed that post-bloom insecticide sprays for PTB and SJS could be timed to PTB larval and SJS crawler emergence using precise day-degree (DD) accumulations after male moth or scale collections in pheromone traps.

6.3. Movement towards sustainable products.

The beginning of widespread sustainable practices in stone-fruit is marked by the initiation of mating disruption for OFM, which was implemented in California on a large scale in the 1980s, followed by the use of mating disruption and novel insecticides for PTB. Mating disruption for OFM has been used throughout the world, with reports of partial or complete OFM control in Australia (Vickers *et al.* 1985), Europe, South Africa, and Canada (Free *et al.* 1994, Fraser and Trimble 2001).

Successful implementation of mating disruption for OFM did not, of course, protect the orchard from PTB, as broad-spectrum insecticides had done (Weakley *et al.* 1990). The decrease in spraying for OFM that followed successful implementation of mating disruption often led to a resurgence of PTB infestations. This situation presented a quandary in that the resumption of in-season insecticide spraying for PTB would negate the environmental and economic benefits of OFM mating disruption. Starting in the 1980s, therefore, there was renewed interest in developing sustainable PTB controls. Initial efforts included the use of pheromone-baited traps to trap and kill male PTB (Hathaway *et al.* 1985). Mating disruption for PTB has been not been as successful as OFM mating disruption, though some trials have been successful. Kyparissoudas (1989) compared infestations levels in Greek peach orchards treated with combined mating disruption of OFM and PTB, standard insecticide, applications, and an untreated control. Here, results were similar in the mating disruption and insecticide treatments (1-3% fruit damage) and lower than in the unsprayed control orchards (14-23%). Several trials combining PTB and OFM mating disruption in Italy have also showed promise (Molinari and Cravedi 1990, 1992). On the other hand, some studies found that while combined mating disruption for both PTB and OFM, in the absence of insecticides, provided some reduction in fruit infestation compared with untreated controls, the level of suppression was not sufficient (Nicollo *et al.* 1990).

Recent improvements to mating disruption programs include the use of wax and aqueous paraffin emulsions as controlled-release carriers for sex pheromones (Atterholt *et al.* 1999). Stelinski *et al.* (2005) documented effective OFM mating disruption using high densities of wax-drop pheromone dispensers. However, comparative studies have found that sprayable formulations of OFM sex pheromone do not provide as high a level of control as the traditional hand-applied dispensers (Trimble *et al.* 2004, Kovanci *et al.* 2005a). Technologies and strategies for sprayable pheromones are currently being investigated and improved (Waldstein and Gut 2003, Kovanci *et al.* 2004, Waldstein and Gut 2004, Kovanci *et al.* 2005b, Waldstein 2005).

In summary, OFM mating disruption typically provides adequate control, especially for early-season fruit cultivars (i.e., those ripening before the third OFM generation). Control is less consistent for mating disruption with PTB. Insecticides that are compatible with a mating disruption program thus continue to be necessary. Trimble *et al.* (2001) combined mating disruption and insecticides in Ontario, using chlorpyrifos to control first-generation larvae and mating disruption for the second and third generations. Suppression of OFM in this study was similar to that attained in a conventional program that used insecticides for each OFM generation; reductions of PTB and SJS were noted as well. However, materials other than organophosphates are needed for a sustainable approach (Mills and Daane 2005).

One of the most significant advancements in insecticide technology was the use of *Bacillus thuringiensis* to control PTB (Barnett *et al.* 1993). PTB larvae are frequently found in exposed positions, as they require numerous shoots to complete larval development (Daane and Dlott 1998). As the larvae move from shoot to shoot, or, at the beginning of the season, from the hibernacula to the canopy, they are vulnerable to *B. thuringiensis* applications. Later in the season, however, when the larvae bore deeply into fruit or the more mature shoots, they have less need to move between feeding sites. The effectiveness of *B. thuringiensis* is also diminished by its short residual period during the warm summer months. Its use is thus limited mainly to the early-ripening cultivars harvested from May to mid-June. Recent developments

in *B. thuringiensis* use include the use of ultra-low volume spray techniques (Roltsch *et al.* 1995). The ULV application of *B. thuringiensis* by aircraft shows promise as an alternative to conventional chemical insecticides in controlling PTB, although to date this method has not lowered pest densities as consistently as conventional sprays.

Currently, PTB is most commonly controlled by a dormant application of esfenvalerate (Asana®) or a spring application of spinosad (Success®). Other materials are currently being tested, including novel, target-specific controls that have not been widely adopted. For example, PTB populations in hibernacula on almond trees can be reduced by a *Steinernema carpocapsae* strain and a cold tolerant *Heterorhabditis* species (Agudelo-Silva *et al.* 1995). While not likely to be employed as a sole control, such approaches may contribute to sustainable management programs.

San Jose scale has typically been controlled by dormant oil combined with an organophosphate, or spring and summer applications of organophosphates. The more sustainable programs use carefully timed oil sprays, often without insecticidal materials, as it has been demonstrated that the oil alone, applied in winter, provide some control of SJS (Rice *et al.* 1972). The recent development of higher-grade oils offers promise for additional spring and summer suppression of SJS (Bentley *et al.* 2000a, 2000b).

6.4. Increased activity of natural enemies.

Recent reductions in the use of broad-spectrum, long-residual pesticides provide opportunities for a larger role of biological control in stone-fruit pest management. In particular, the implementation of mating disruption and the concomitant reduction in insecticides directed at OFM and PTB mean that natural enemies are expected to make a greater contribution to control. Viggiani (1996) suggested that one side effect of the use of mating disruption was a decrease in the number and density of non-target pest species, presumably due to the enhancement of natural enemies. Atanassov *et al.* (2002) implemented a program to reduce organophosphate and carbamate insecticide use and mitigate their associated risks in New Jersey peach production. Mating disruption was integrated with ground-cover management practices to reduce OFM and key hemipteran pests (e.g., tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois) and stink bugs, *Euschistus servus* (Say), *E. tristiginus* (Say), *Acrosternum hilare* (Say)). The reduced-insecticide program provided a level of pest control equal to or better than conventional peach pest management programs. At the same time, higher levels of OFM parasitism were observed (Atanassov *et al.* 2003).

In California, one consequence of the success of insecticides and, more recently, mating-disruption programs has been that, since the 1940s, little effort has been directed at biological control research. Yet many natural enemies are known worldwide, most of which have not been imported into or tested in the U.S. In addition to parasitoids discovered during the early 20th century, discussed above, recent investigations have provided more updated information on the status of natural enemies overseas. For example, in Bulgarian peach orchards, 25 parasitoid species belonging to 9 families (hymenopteran or Dipteran species) were reared from OFM and PTB, with the average season-long parasitism rate during the three-year project reaching 32% for OFM and 37% for PTB (Dimova 1987). Trandafirescu (2004), surveying insect pests and their natural enemies in apple and peach orchards in Romania, found that SJS was controlled by two coccinellid beetles, *Chilocorus renipustulatus* Scriba and *C. bipustulatus* L., and two species of parasitic wasps, *Aphytis diaspidis* (Howard) and *Encarsia perniciosi* (both Aphelinidae). PTB and OFM were controlled by fourteen species of primary parasitoids and four species of secondary parasitoids.

Such findings suggest that classical biological ought to be reconsidered as a component of stone-fruit IPM. In addition, in the last half-century, there have been important improvements in importation and quarantine methodology, parasitoid taxonomy, and access to areas in which these pests are native. Early

OFM parasitoid importation programs focused on Europe, Japan, Australia, and Korea (Allen 1932, Allen *et al.* 1940). However, Australia first recorded OFM around 1909, and Europe after the first world war. Although the likely origin of stone fruit and associated pests is in temperate eastern Asia, China was not investigated as a source for natural enemies. Furthermore, of 65 parasitoid species reared from OFM in Japan and Korea in the course of early foreign exploration, only 17 reached the U.S. (Allen *et al.* 1940). A major limitation was the time required for shipment. Material collected in Asia and Australia was typically sent by ship to San Francisco, California, and then by air to Moorestown, New Jersey, with a total transit time of about two weeks; or, alternatively, was sent entirely by ship, through the Panama Canal, to New York, which took over a month. Once they arrived in the U.S., methods for rearing parasitoids were limited, as artificial diets had not yet been developed. The moth larvae were reared either in apples or in peach shoots that were trimmed, placed in water, and infested with OFM eggs. Because fruit and suitable twigs are only seasonally available and decompose quickly, many parasitoid cultures were lost or could not be maintained in large numbers.

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Biological Control of Insects and Mites in Almonds: Constraints and Opportunities

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1. Introduction

Almond ecosystems represent an excellent template for implementing biological control for many different reasons. Some of the structural advantages for this commodity include:

a. the large almond acreage of ca. 550,000 acres allows for development of a strong research community-industry partnership through a marketing order instrument;
b. the perennial nature of the crop fosters a long-term mind set towards management;
c. the perennial nature of the crop also allows for long-term investments and minimizes short-term gains that might prove disruptive of subsequent programs;
d. the Almond Board (as a proxy for the industry) has demonstrated a long-term commitment to research and a willingness to form partnerships to develop management programs in terms of their political, economic, environmental, and social sustainability (Pest Management Alliance).

Some biological advantages include a relatively small set of insects that are economically important as well as a diverse set of non-disruptive strategies already in place for the key pest, the navel orangeworm. Similarly, the key pests already have effective, yet somewhat time consuming, monitoring systems, realistic decision making thresholds, and for at least two sets of the key pest are either indirect feeders (spider mites), or indirect feeders for a portion of their lives (peach twig borer), or with a subset of the population feeding on less critical portions of the plant or damage to the hull is non-economic (e.g., San Jose scale on limbs).

The advent of some newer pesticide chemistries (e.g., insect growth regulators, bacterial by-products) have also provide opportunities for greater integration of biological control and more conventional practices, but these are not unique to almonds. However, many insecticides reported as selective are in fact relatively harsh on some natural enemies. Almond growers though, have been willing to look for alternatives as demonstrated by their recent shift from organophosphates to the softer alternative, *Bacillus thuringiensis,* for management of peach twig borer. Here we review current management status of five economically important pests -- 1) the navel orangeworm, 2) peach twig borer, 3) San Jose scale 4) Pacific spider mite and 5) the twospotted mite. We discuss their biological control potential and potential barriers to incorporating more biological control in California almond pest management programs.

2. Navel Orangeworm, *Amyelois transitella*

2.1. Species and Damage

2.1.1. Description of pest

The navel orangeworm *Amyelois transitella* (Lepidoptera: Pyralidae) is a key pest of almonds, pistachios, and figs in California. Damage from this pest is caused by the larvae, which feed directly on nuts or

drying fruit. Eggs are typically laid on mummy nuts in the trees or new crop nuts and hatch within 4 to 23 days, depending on temperature. Eggs are not laid on new crop nuts until initiation of hull split. The larvae cannot bore into closed nuts, and therefore must find nuts or fruit that have "splits," cracks, or cuts through which they can gain entrance.

Elements of the life history of this pest lend themselves to effective management using non-insecticidal alternatives. Specifically, the navel orangeworm overwinters as larvae within "mummy nuts," i.e., nuts that have adhered to the tree after harvest. . The mummy nuts remain on the tree and serve as effective overwintering sites until the emergence of the moth later during the following spring. As outlined below, efforts to either minimize the occurrence of these nuts immediately after harvest or during the winter have proven key to the management of this pest.

The moth has two significant flights during the growing season, typically referred to as a spring flight and a hull-split flight. Almonds vary in their susceptibility to infestation by navel orangeworm with nuts early in the spring being protected by a tightly sealed hull surrounding the shell casing. In mid-summer, the outer hull splits open along a naturally forming seam as part of the almond's maturation process. This open seam provides the navel orangeworm larvae the opportunity to enter the young nut. Traditionally, insecticide applications have been timed to coincide with peak flights and egg laying during the spring flight or during hull-split.

2.1.2. Damage

The navel orangeworm is one of the most important pests of almonds given the direct damage to the nutmeat by the developing larva. The feeding by larvae renders the nutmeat unmarketable and the copious amounts of frass or silk produced during their feeding also ruin the marketing of the crop.

More indirect, yet serious concerns for marketing and possible health effects result from secondary fungal infections that follow entry by the navel orangeworm as it pierces the external shell of the almond. Concerns about possible carcinogenic effects of some fungi, e.g., *Aspergillus flavus,* which may produce an aflatoxin, increase the need to preclude damage by this pest.

A recent change in the EU market with additional restrictions on aflatoxin contamination has made this issue more critical. Such a direct pest whose damage may result in secondary infections of the marketable portion of the crop would not be the typical target for biological control efforts. For that reasons, there is relatively conservative treatment thresholds (<2% nut infestation) to avoid significant economic losses.

Almond cultivars differ in terms of susceptibility to navel orangeworm. Almonds also require pollination across cultivars to ensure maximum yields, therefore, plantings of rows of different cultivars every 2-3 rows is the norm. The soft-shelled cultivars, e.g., Nonpareil, are very susceptible to navel orangeworm damage due to easier entry by the larvae. Alternatively, hard-shelled cultivars (e.g., Missions) are less susceptible to damage by navel orangeworm as their harder shell provides greater protection to the nut meat. As such, not all cultivars require treatment at the same time during the growing season (Welter *et al.* 1987), but the interplanted nature of almond orchards have made the option of selective treatments to specific cultivars logistically quite difficult to implement.

2.1.3. Monitoring and treatment thresholds

Surveys of overwintering NOW populations during the winter are necessary to assess the risk of damage the following spring. Mummy almonds are relatively easy to collect to determine the percent infestation and number of larvae per mummy. Similarly, estimates of the number of mummies per tree provide an

excellent correlate to damage for the following year. Sanitation practices (removal of the overwintering nuts) typically have a target threshold of <1 mummy per tree.

Monitoring of adult flights is done using the indirect measure of rates of egg laying, which can occur on mummy nuts, developing almonds, or on artificial traps that are placed into the orchard by pest control advisors or growers. Many moth species are typically monitored using pheromone baited traps, but the pheromone for navel orangeworm has proven relatively elusive. The pheromone blend developed for commercial use does not attract sufficient number of moths. However, the recent discovery of previously unidentified components of the navel orangeworm pheromone (Leal *et al.* 2005) may resolve this situation.

Monitoring of egg laying is done by placing commercially available traps baited with either pressed almond cake collected from cull almonds containing damaged and undamaged almonds or by a bran based lure mixed with molasses. The materials are replaced periodically on the trap and the exterior of the trap is checked for the presence of navel orangeworm eggs. As new eggs are found on the trap, they are counted and removed from the trap.

2.2. Navel Orangeworm Biological Control

2.2.1. Classical biological control

Two parasitoids have potential as biological control agents for navel orangeworm, *Copidosoma (Pentalitomastix) plethorica* and *Goniozus legneri*. *Copidosoma plethorica* is an egg-larval polyembryonic parasitoid imported in 1963 (Caltagirone *et al.* 1964) from Mexico and S. Texas, whereas *G. legneri* was imported from Uruguay and central Argentina (Gordh 1982). However, *C. plethorica* did not present a significant enough mortality agent for management considerations [edit]. Initial efforts suggested that *G. legneri* was capable of providing useful mortality of navel orangeworm, but the results were variable (Legner 1983a, b, Legner and Gordh 1992).

2.2.2. Augmentative biological control

Interests in *G. legneri* were and are strong enough for the parasitoid to be produced by commercial insectaries. Field tests of inoculative releases of the parasitoid have met with mixed success.

Within UC/IPM funded research, Daane demonstrated mixed results as well with additional parasitism from these releases ranging from 0-45%. However, more careful examination of the release strategies from gelatin capsules demonstrated that >80% mortality resulted from generalist predators in the field consisting of 3 ant species *Formica aerata, Solenopsis xyloni and Solenopsis sp*. While dispersal from release points was shown to be relatively robust both within the tree canopy and up to 12 trees from the release site, the results were still limited in their predictability.

Surprisingly, 8% of the growers surveyed (see Zalom *et al.* http://www.ipm.ucdavis.edu/IPMPROJECT/almondpcas.html) indicated that releases of *G. legneri* were made within the past year despite the mixed record of this program. Similarly, 3% of the growers followed the practice of holding of infested nuts during the winter as reservoirs of *Goniozus* with little direct data to support the practice.

Another area for possible continued exploration has been the use of Steinernematid nematodes for control of navel orangeworm. The most recent work has focused on a post-harvest application to control NOW in fallen pistachios on the orchard floor. *Steinernema carpocapsae and S. feltiae* increased mortality up to 72% when conditions were favorable for nematode survival (Agudelosilva *et al.* 1995, Siegel *et al.* 2004).

However, the use of nematodes has proven logistically difficult in the past due to their needs for moisture to survive and move effectively. The commercial feasibility of this approach has yet to be established.

2.2.3. Conservation biological control

Conserve *G. legneri*, which overwinters in the orchard, by leaving additional mummy nuts as habitat for the parasitoid has not been shown to be effective program. This was especially problematic given that the mummy nuts also serve as reservoirs for the navel orangeworm. Thus, this practice is not currently recommended. This parasitoid may have limited potential because of its tendency to tend (or guard) its egg brood also may limit the utility to orchards with low to moderate populations (Daane and Yokota 2005).

Reduction of insecticide sprays early in the season is probably a key element in the conservation of natural enemies. A very promising trend towards reduced insecticide use was supported by the low percentage sprays for navel orangeworm during the spring ("May sprays") at 22% compared to 78% in 1986, whereas only 59% of the growers reported using a hull-split spray compared to 82% in 1986. This has been a relatively dramatic shift from management trends in the 1980s.

2.3. Navel Orangeworm Mating Disruption /Semiochemicals

Management of navel orangeworm has been pursued along multiple avenues including use of plant volatiles as potential disruptants (Curtis and Clark 1979, Van Steenwyk and Barnett 1987, Phelan *et al.* 1991). The hope was that the use of attractants derived from almonds or from infested almonds would serve as a powerful disruptant of host location, yet no commercial product is available to date for control. However, the pressed almond bait used in monitoring is an indirect benefit from this area of research.

A newer product called Stealth, which is a soy-based product applied to almonds to reduce egg laying resulted in trials with 90% reductions in navel orangeworm, but grower results have been more mixed (http://www.lookercomm.com/AlmondPMA/Work%20Plan/Year%20Five/update_of_the_pest_management_ev.htm).

Pheromone mating disruption using the sex pheromone of navel orangeworm was attempted in 1979-1981 (Landolt *et al.* 1981, Curtis *et al.* 1985) on both small and large scales with some success. Mating success was reduced significantly and damage was reduced from 12-34% in the treated acres compared to a control. However, this approach languished as the pheromone proved to be only relatively less attractive at ca. 10% of a virgin female. A pioneering effort in the mid-90s (Shorey and Gerber 1996) demonstrated that low numbers of pheromone emitters ("puffers") could provide very strong trap suppression using few applicators per acre. This led to a commercially based product that was implemented widely in parts of the Central Valley, however, this program is currently under review and the methodologies are still being developed and improved. Similar efforts in figs to disrupt navel orangeworm look promising but this approach has yet to be commercially accepted (Burks and Brandl 2004). The discovery of another component in the navel orangeworm pheromone blend that improves lure attractiveness to the male navel orangeworm provides hope that this approach may prove more useful as it has for other lepidopterous pests in other tree crops (Leal *et al.* 2005).

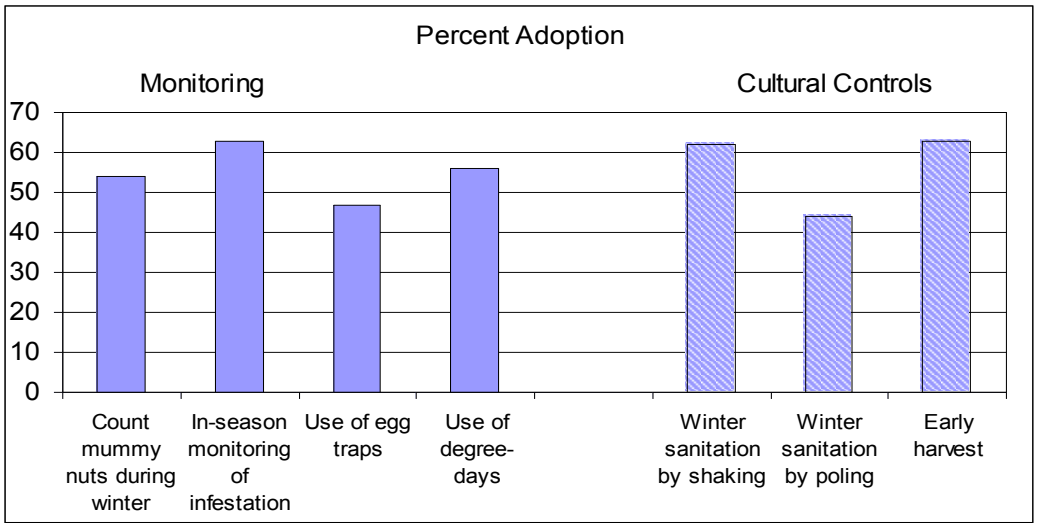
2.3. Navel Orangeworm Cultural Controls

The most effective non-insecticidal management option for control of navel orangeworm is orchard sanitation, the removal of mummy almonds either post-harvest or during the winter period. In essence, it is the direct physical elimination of the larva from the orchard as potential sources of infestation. The mummies are removed from the tree and dropped to the ground either during the shaking process, with

poles following harvest, or by birds during the winter. Some mummy nuts that are left undisturbed on the ground will continue to serve as overwintering sites for the navel orangeworm, especially on the row berms that are above the water line of the orchard. Therefore, dropped mummies should be blown or swept to the center of the rows. Moist conditions provided by most cover crops of the orchard floor will add significantly to the mortality of larvae on the orchard floor. However, many orchards remain clean cultivated year-round. Therefore, the physical crushing of the mummy nuts with a flail mower has proven most effective. The flail mower has a series of metal paddles that are turned mechanically at high speeds which both cut the existing plant material and crush any nuts remaining on the ground.

Orchard sanitation was first shown to be effective in 1983 (Curtis *et al.* 1983) as a means to control navel orangeworm, but more definitive thresholds based on the relationships between damage and mummy loads per orchard followed later (Zalom *et al.* 1984a). Currently, no more than 2 mummy nut per tree by Feb 1 is recommended to minimize damage the following year. Similarly, destruction of the mummy nuts on the orchard floor should be finished by March 1 before the initiation of the spring flight.

A corollary approach is the early harvest of the almonds because of increasing infestation levels in the almonds from the summer flight. Early harvest of the crop is commercially beneficial in 1) reducing the current year's damage and 2) reducing the rates of infestation in the mummy nuts which in turn reduces damage the following year. Harvest is often followed immediately by work crews using long aluminum poles to remove almonds that remain attached to the trees after mechanical shaking has been completed. Similarly, crews can be brought into the orchard during the winter to remove excessive numbers of mummy nuts.



A recent survey of almond grower practices by Zalom *et al.* (2005) revealed that many of these practices have been widely adopted: monitoring of navel orangeworm by growers or their PCAs in 2000 was implemented in 83% of the almond orchards, including monitoring of mummy nuts or hull-split nuts (63%), winter sanitation (62%), or removal of winter nuts (44%), early harvest 63%).

3. San Jose Scale - *Diaspidiotus perniciosus* **(Hem.: Diaspididae)**

3.1. Species and Damage

3.1.1. Description of pest

San Jose Scale (SJS), *Diaspidiotus* (formerly *Quadraspidiotus*) *perniciosus* (Comstock) continues to be one the more important indirect pests of almonds, with almond branch dieback and tree death a possibility under severe and continuous infestations. San Jose scale was first discovered in California and America in 1870, presumably from imported plant material from China (Gulmahamad and Debach 1978). Arriving without its complement of natural enemies, the SJS spread quickly as a serious pest throughout California by the mid 1890s. However, regular monitoring combined with effective dormant control programs typically is effective at controlling this pest below economically damaging levels.

San Jose scale undergoes a series of changes in form over its lifetime that dramatically affects its mobility and potential damage. Females lie under a self-secreted waxy protective cap and give birth to living young that soon emerge from this scale covering. The first stage, or instar, has functional legs which allow it to disperse to new areas on the branch in search of suitable feeding sites. This crawler stage is both a time of vulnerability for control practices as well as a stage that can be easily monitored (see section below). After finding a suitable site, the crawler stage will insert its mouthparts into the plant tissue to start feeding. The crawler subsequently loses its legs, eyes, and antennae, and starts to secrete the external scale covering. Subsequent to the final molt, males emerge from the scale covering with functional wings. Males are highly responsive to a sex pheromone produced by the female adult scale. Thus, male flight activity can be monitored with commercially available pheromone traps. Typically, 4-5 generations are produced each year as determined by both degree-day models and peaks in flight curves produced by pheromone trapping data.

3.1.2. Damage

Direct infestation of some fruit, e.g., pears, results in the direct cullage, but no direct economic damage of the nutmeat occurs in almonds because the hull is removed. Damage is more typical in older, larger trees, where damage is both more difficult to spot and adequate spray coverage is more difficult. San Jose scale sucks plant juices from tissues beneath the bark of younger wood which may result in bark cracking in several infestations. Loss of tree vigor, growth, and productivity are the most common form of damage, whereas limb or tree death can occur if infestations are not treated for several years. Older, larger trees are more susceptible to damage as monitoring and adequate spray coverage is more difficult.

3.1.3. Monitoring and treatment thresholds

Biologically based pest control systems are typically more risky than chemical programs and thus require robust monitoring protocols. Monitoring programs need to be both highly predictive and easy if growers or their pest management consultants are to be willing to use them to determine risk. Without an ability to understand their risk, growers are sometimes “forced” or are more willing to use less risky practices, e.g., pesticide applications, if immediate control is the sole objective.

Monitoring of San Jose scale with female sex pheromone was used as early as 1974 (Rice 1974) in plum orchards, whereas the synthesis of the pheromone started as early as 1979 (Anderson *et al.* 1979, Gieselmann *et al.* 1979). Development of field monitoring of San Jose scale with natural and synthetic versions of the pheromone continued throughout the early 1980s (Rice and Hoyt 1980, Hoyt *et al.* 1983). Similar to most pheromone based monitoring, direct correlations between pheromone trap counts and infestation or even population levels has proven difficult.

Monitoring of scale crawlers in the spring can be accomplished by placement of double-sided sticky tape surrounding branches as the crawlers move throughout the canopy after eclosion from the egg (Gentile and Summers 1958, Reissig *et al.* 1985). The ability to detect movement of one of the target instars during the growing season was used to time insecticide applications. Monitoring of spur infestations during the dormant season has proven more predictive than during the growing season. Recently, update

threshold guidelines have been developed for decision making during the dormant season, the most effective and common treatment period for control of SJS.

Treatment guidelines take advantage of the fact that parasitized SJS can be determined by the presence of a parasitoid exit hole in the cover of the scale. UC/IPM guidelines (http://www.ipm.ucdavis.edu/PMG/r3300811.html) suggest management decisions based on the percentage of infested spurs should consider parasitoid activity (only live scales should be counted). However, guidelines for parasitoid levels are vaguely provided as follows: "It is also important to note how many scales are parasitized. A parasitized scale can be distinguished from a live scale by a small hole in the top of the scale covering. Parasitized European fruit lecanium scales turn black. If a large number of scales have been parasitized, minimize the use of insecticides during the growing season and only use those that are not harmful to parasites so that naturally occurring populations will not be destroyed". The lack of specific guidelines for predicting the future effects of the parasitoids obviously limits the grower's ability to rely on biological control agents.

Badenes-Perez *et al.* (2002) examined the relationship between capture rates in pheromone traps and double-sided sticky tape traps and concluded that "relative densities of SJS crawlers on sticky tape can be estimated using SJS male trap captures for first generation" with correlation coefficients ranging from 0.46-0.73. The level of correlation between pheromone trap captures and crawler densities varied between years, scale generations, and with the number of replicates. The percentage of the variation explained by the regressions thus ranged from 21.2% to 53.3%, which as the authors noted was not "very precise." Pheromone traps are much easier to use and service compared to the labor intensive sticky tapes -- many growers or their PCAs are reluctant to adopt this technique (Badenes-Perez *et al.* 2002). While the authors acknowledge the potential advantage of information from these pheromone traps, they also note that the lack of correlations between scale crawlers and pest damage as well as a need for trapping standards based on data (e.g., number of traps per acre). An earlier attempt by (Bentley *et al.* 1998) to correlate spring trap capture of males and number of crawlers was more positive with a significant linear relationship found (72% of the variation explained), despite only sampling 6 orchards.

From 1999-2003, researchers attempted to correlate pheromone trap captures of male SJS, number of crawlers on sticky tapes, and infestation levels on almond spurs (Zalom *et al.* 1999, Zalom *et al.* 2001a, Bentley *et al.* 2002, Zalom *et al.* 2002, 2003). Similar to the results of Badenes-Perez *et al.* (2002), general relationships were observed, but with much higher percentages of the variation explained.

From a more positive perspective, a significant relationship was found between number of infested spurs and damage suggesting that effective direct monitoring could be used to detect damaging populations. Less precise correlations between trap counts and number of crawlers on sticky tapes or between sticky tape and spur infestation make the use of pheromone traps as sole indicators of problem spots within an orchard more difficult.

Adoption of these practices varies by growers or PCA (http://www.ipm.ucdavis.edu/IPMPROJECT/almondinsects.html). Approximately 19% of surveyed growers used double-sided sticky tape for trapping San Jose scale males, 15% used pheromone traps, but 43% examined dormant spurs for scale infestation suggesting that the more labor intensive approaches were not being adopted or viewed as necessary. From the survey, 18% of the growers reported monitoring for scale parasites in sticky traps.

3.2. San Jose Scale Biological Control Agents

2.2.1. Classical biological control

San Jose scale possesses several important parasitoids that are capable of providing effective control (Daane *et al.* 2003). The three key parasitoids of SJS are *Aphytis aonidiae*, *A. vandenboschi*, and *Encarsia perniciosi* (formerly referred to as *Prospaltella perniciosi*). A variety of studies have assessed the potential for biological control of SJS under different management programs ranging from no pesticide treatments to conventional programs incorporating a variety of chemistries.

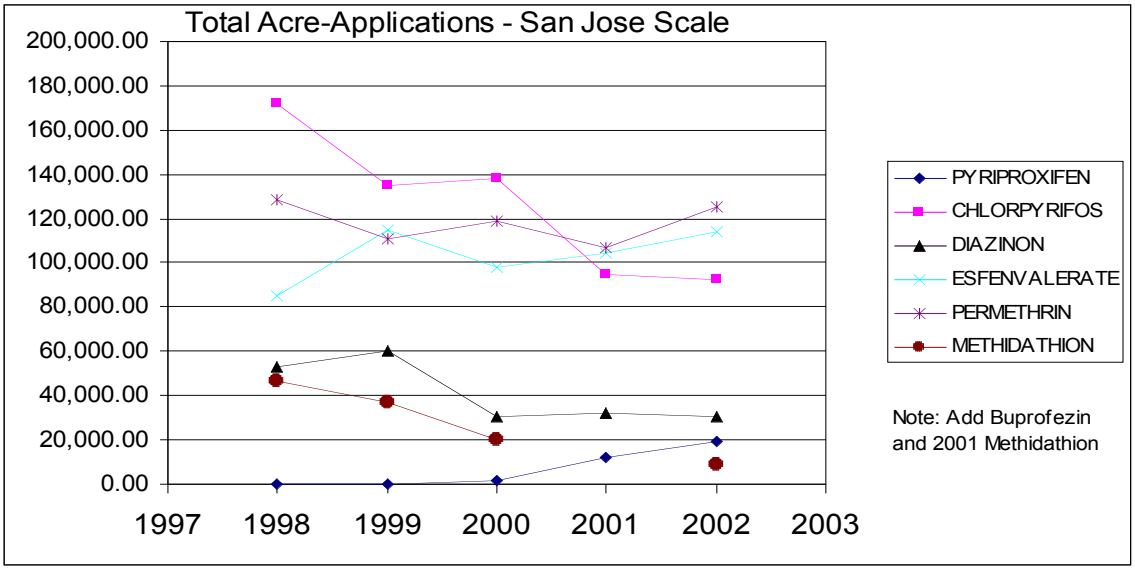
2.2.2. Augmentative biological control

More recently, efforts to explore augmentative programs for two parasitoids of SJS have been undertaken (Daane *et al.* 2003), as well as potential inoculative programs late in the summer or early fall in hopes of influencing parasitism the following year. Results of cage studies found that SJS populations could be reduced by releases of *A. vandenboschi*, however, there are currently no insectaries producing this parasitoid and the practice was not tested on a commercial scale (e.g., large plots, open field releases).

2.2.3. Conservation biological control

Traditionally, control of low to moderate infestations of SJS has been accomplished with dormant oil applications that may include an insecticide, often an organophosphate. Specific treatment thresholds based on the percentage of infested spurs exist (reference?), which helps to restrict insecticide applications to populations that merit treatment. However, detection of scale insects can sometimes be difficult given their distribution in the tops of almond trees and prophylactic treatments are often made.

Problems from runoff of organophosphates from orchards during the dormant period have made the practice less desirable. If the dormant application is not made and infestation levels appear high, then applications during the early part of the growing season may be warranted. Again, control of SJS is facilitated by the development of better monitoring approaches.



4. Peach Twig Borer: *Anarsia lineatella* (Lep.: Gelechiidae)

4.1. Species and Damage

4.1.1. Description of pest

See "Stone Fruit" Chapter for more information.

4.1.2. Damage

The peach twig borer is a direct pest of almonds -- larvae feed directly on the nut meat later in the growing season. Early season damage is restricted largely to the growing shoot tips as indicated by die-back of the young shoots. The moth can reach very high numbers quickly after emergence from an overwintering structure called the hibernaculum. The young larva emerges from the hibernaculum and enters the tip of a growing shoot and proceeds to bore or feed down the length of the shoot. These killed shoot tips are called strikes or flagging and can be used to monitor for the presence of peach twig borer early in the season. As the nuts mature, larvae will enter the husk and sometimes feed on the nutmeat. However, some of the larvae remain in the nutmeat if the shell has already hardened off.

4.1.3. Monitoring and treatment thresholds

During the 1980s, peach twig borer was controlled primarily by a dormant application of oil plus an organophosphate application that also targeted a variety of pest mite species. However, concerns about organophosphate insecticides being found in waterways after winter rains (Epstein *et al.* 2000, Epstein *et al.* 2001, Werner *et al.* 2002, Zhang *et al.* 2005) has promoted tremendous efforts to reduce the organophosphate input during the winter season. The ability to monitor for peach twig borer directly during the early spring, coupled with the low risk of any direct damage to the almond, was conducive to the potential elimination of this approach. By 2000, only 9% of the acreage was treated during the dormant period with an organophosphate (Zhang *et al.* 2005), whereas 57% of the total acreage received no dormant treatment of any kind for insects. However, the decline in OP use has been mirrored by an increase use of pyrethroid in some cases.

A secondary means to monitor peach twig borer are pheromone baited traps for adult peach twig borers. The moth is highly responsive to the lure and will quickly fill traps, making interpretation difficult. Adoption of monitoring tools has been fairly successful with 56% of the growers reporting that their advisors or they will monitor for emergence from the overwintering hibernaculum, 64% will sample blossom or shoot strikes in the spring, and 56% using pheromone traps. The high use of pheromone traps is partially explained by their ease of use, but their ability to predict female flight activity is relatively limited (Barnett and Hendricks 1992).

4.2. Peach Twig Borer Biological Control

4.2.1. Classical biological control

Peach twig borer has a large complex of natural enemies that collectively can provide significant mortality in some cases, but are often insufficient in their effects to provide commercially reliable control. The parasitoids include a series of commonly found chalcids, *Hyperteles lividus, Paralitomastix pyralidis* (=*varicornis*), or *Macrocentrus ancylivorus* (Daane *et al.* 1993) as well numerous other less abundant spp. *M. ancylivorus* is reported more commonly from the oriental fruit moth but has been reported for a variety of families (e.g., sunflower moth – a pyralid). However, parasitism levels were relatively low in treated and untreated orchards (0-3.85%) with one notation of parasitism as high as 12%. Thus, elimination of the conventional insecticides would not be expected to significantly increase parasitism to commercially acceptable levels, but any additional mortality provided by the parasitoids would act in concert with selective programs such as pheromone mating disruption outlined below. However, these levels of

parasitism were lower than previously reported in literature stemming from before the 1940s and the more broad scale use of insecticides.

The only controlled study of generalist predators and their effects on peach twig borer suggested that only the ant species, *Formica aerata*, had a significant effect on the peach twig borer survival in shoot tips (Dlott *et al.* 1994). However, complications with ants tending pest species or direct damage by other ant species to the almond nut meat may make this group of predators problematic (http://news.ucanr.org/newsstorymain.cfm?story=424).

4.2.2. Pheromone mating disruption

Pheromone mating disruption is a potential substitute to insecticides for control of peach twig borer using primarily hand-applied dispensers of the sex pheromone. Within large-scale farm implementation studies in peaches and nectarines, a mating disruption program proved effective, yet more expensive than existing insecticide programs (Pickel *et al.* 2002). Partial programs that relied on supplementation proved less expensive, but were still ca. $60 over the costs of a conventional program. The pheromone programs present a highly specific means to control peach twig borer without any disruption of natural enemies. However, reports of mixed success with this approach may be limiting its rates of adoption.

4.3. Pesticide use trends

During the growing season, there have been similar trends for reduced organophosphate usage, which have been offset by smaller increases in pyrethroids. One positive trend has been the increased use of *Bacillus thuringiensis* (3-6% of the total acreage in almonds) for control of peach twig borer. One disconnect between data sets are illustrated here in which the survey (http://www.ipm.ucdavis.edu/IPMPROJECT/ almondinsects.html) of growers would indicate a much stronger shift in recent years with 36% of growers reporting the use of Bt at bloom and 27% using it during other times of the growing season. Several explanations might include the pesticide use trends have a lag time for calculating use patterns and the differences in the reporting periods or perhaps the survey might have reached a more progressive constituency. Similarly, 62% of the growers reported using some type of insecticide during the dormant application, whereas Zhang *et al.* (2005) reported only 43% applying an insecticide during this period.

5. Web spinning spider mites – *Tetranychus pacificus* and *T. urticae*

5.1. Species and Damage

5.1.1. Description of pest

See “Grape” and “Apple and Pear” Chapters for more information.

5.1.2. Damage

Spider mites present both an opportunity and challenge for almond growers. The 2 most important species in almonds include the Pacific spider mite, *T. pacificus*, and the two spotted spider mite, *T. urticae*. The damage by spider mites is indirect through photosynthetic reductions in the leaves due to penetration of the leaf cells by the stylets of the spider mites. While the damage is easily diagnosed, the costs of this type of damage are more difficult to quantify. Long term studies have shown that even severe damage levels are delayed in their effects on almond yields until the next year (Barnes and Andrews 1978, Welter

et al. 1984, Youngman and Barnes 1986) and were typically less than 20% yield losses. However, there are strong interactions with water stress that make the relationship more difficult to predict.

Spider mites have very effective natural enemies exist that are capable of both effective regulation at commercially acceptable levels and are capable of arresting outbreak situations (Hoy *et al.* 1979). Spider mites have traditionally been the best example of pesticide outbreaks early in the 1970s and 80s with the widespread use of organophosphates and pyrethroids. Examination of the effects of pyrethroid residues on predatory mites shows significantly increased mortality up to 7 months after treatment, essentially covering much of the growing season. While resistance to pyrethroids in *G. occidentalis* has been reported (Welter et al. – unpublished data), the increased resistance was offset by decreased reproductive rates of the resistant strain (Zalom *et al.* 2001b).

The two tetranychid prey species developed insecticide resistance before their most effective predator, the predatory mite, *Galendromus (=Metaseiulus) occidentalis*, resulting in a dislinkage between predator and prey (Hoy *et al.* 1980, Roush and Hoy 1980, Roush *et al.* 1980, Hoy *et al.* 1988, Hoy and Conley 1989, Hoy and Ouyang 1989). As such, the classic secondary pest outbreak commonly occurs after insecticides targeting the navel orangeworm disrupt the effective biological control of spider mites by elimination of their key predator. Direct selection of colonies of the predatory mites for resistance to specific insecticides, e.g., carbaryl, proved effective and researchers suggested these strains could be mass-reared and released into almond orchards so as to establish higher baseline levels of resistance. However, there are currently no insectaries producing insecticide-resistant mite strains as resistant populations were commonly found in the orchard.

5.1.3. Monitoring and treatment thresholds

Monitoring of spider mites is relatively easy in terms of identifying hotspots within orchards that might require treatment. Traditionally, leaves are collected and brushed off within a machine onto glass discs for counting. Alternatively, many PCAs would make counts using a hand lens in the field. These techniques were fairly quantitative, but also were time consuming and laborious. Spider mite populations are also notoriously patchy in their distribution within an orchard such that monitoring throughout the entire orchard was necessary.

More recent advances in which the actual number of mites are not directly counted but estimated from presence/absence sampling schemes have made the monitoring effort much easier for growers and PCAs (Wilson *et al.* 1984, Zalom *et al.* 1984b). A fixed number of leaves are scored as either having mites or not having mites on them and then an average percent infestation is calculated. Based on the counts, additional sampling may be warranted or if levels are sufficiently high or low, no additional samples may be necessary. This strategy helps to limit the number of samples that are required to accurate assess risk from spider mite populations.

Monitoring of spider mites and their predators should be done concurrently. The ratio of spider mites to predacious mites is a key component of the decision to treat an orchard with acaricide. Decision making criteria for some of the predators effective at very high spider mite densities, the six spotted thrips or *Stethorus* beetles, has been less well developed. Targeting weekly searching along margins of orchards, within water stressed portions of the orchard, or in traditional hot spots often detects populations on the rise before problems arise. If insecticide treatments are required, their efficacy can be severely reduced if sufficient webbing occurs across the leaves thus preventing adequate spray coverage.

5.2. Spider Mite Biological Control

5.2.1. Biological control

The most important predator in the almond system for spider mites is the predatory mite, the western orchard predatory mite *Galendromus (=Metaseiulus) occidentalis*. This predatory mite has the reproductive potential to respond effective to outbreaking spider mite populations, but more importantly to provide effective regulation at low to moderate levels of spider mites.

5.2.2. Augmentative biological control

Some insectaries have tried to incorporate populations that have been selected for insecticide resistance, but maintaining uniform colonies has proven difficult.

Two other predators of importance are the six spotted thrips, *Scolothrips sexmaculatus*, and the spider mite destroyer, *Stethorus* spp. Both of these species are highly effective consumers of spider mites, but require high prey densities in order to survive or stay within an almond orchard. Thus, the presence of significant numbers of these predators is often found when spider mite populations have already reached damaging levels that should have warranted some type of suppression earlier in the season. While these predators are also available from commercial insectaries, no data on the efficacy of augmentative releases are available from peer reviewed sources.

As of 2000, sampling for spider mites was practiced by more than 50% of the surveyed growers (http://www.ipm.ucdavis.edu/IPMPROJECT/almondpcas.html) with 61% using presence absence sampling programs and 54% brushing leaves for making spider mite counts during the growing season. Monitoring for natural enemies, six spotted thrips or predatory mites, was reported by 70% of the growers. Eleven percent of the surveyed growers reported releasing predatory mites for control of spider mites, which is substantial given the acreage of almonds at >500,000 acres.

5.2.3. Conservation biological control

Similarly, use of low rates to preserve predatory mites has been adopted by 41% of the growers compared to only 24% using full labeled rates of acaricides during the growing season.

Pesticide resistance in the predatory mite has been selected in the laboratory (see above references) as well as under field conditions such that OP resistance is now the norm rather than the exception. However, some classes of insecticides such as the pyrethroids have proven more difficult to select and indirect effects on the efficacy or life histories of the predators have been noted (Welter *et al.* – unpublished data).

Almonds are relatively unique as a crop in that sub-label rates are recommended to readjust populations to more appropriate ratios of predator to prey if outbreaks are suspected. Rates as low as 1/8 to 1/10 or normal application rates are recommended in the UC Pest management guidelines http://www.ipm. ucdavis.edu/PMG/r3400211.html.

See “Grape” and “Apple and Pear” Chapters for more information.

5.3. Spider Mite Cultural Controls

The conventional wisdom among almond growers is that spider mite outbreaks are triggered by tree water stress and road dust. However, in the only replicated trial attempting to confirm these observations in almonds, no direct effects from dust or water stress were observable (Oi and Barnes 1989). In more controlled studies of water stress effects, leaf temperatures were higher and developmental rates increased by 11% on average which would be predicted to have a strong effect given the very short generation time

of this pest species (Oi *et al.* 1989). Despite the mixed results, grower personal observations are clearly dictating their decision making in that 89% of growers surveyed reported avoiding road dust (watering of roads or driving slower), and 79% reporting management of water regimes to manage spider mite outbreaks.

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