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Research Article

Organic vineyard management in California

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Abstract

California grape production is a multi-billion dollar business, but only a small fraction of the productive acreage is farmed organically. One aspect of organic management is the pest control strategies, which rely heavily on biological and cultural controls, as well as approved pesticides. To determine what factors might restrict adoption of organic farming practices, we describe the current status and future needs for three primary arthropod pests: leafhoppers, mealybugs and mites. Two key factors – grape commodity and location – can impact pest and natural enemy abundance, and are discussed with respect to their influence on pest control strategies. Trends in pesticide use are presented as an indication of future direction in vineyard pest management.

Keywords: organic farming: vineyards: pest control: biological control: cultural control: sustainability

1. Introduction

Testimonials from farm managers, pest control advisors, 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. Organic management systems

There is not a universal definition of organic vineyard management, but generally it implies minimal use of synthetically produced fertilizers, pesticides, and growth regulators [7]. Soil fertility relies on composts of animal manure and/or green manure and rock phosphate, 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%) [5]. 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 registered acreage and sales [64]. 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 [70]; 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 [64]. 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 [62] 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.

1.2. Sustainable management systems

Sustainable agriculture integrates three main goals – environmental health, economic profitability, and social and economic equity [79]. 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* [73]. There are now 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.

1.3. IPM systems

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 [68]. 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 [59]. 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 [41]. This also increased the growers' reliance on timed pesticide sprays rather than an IPM systems approach.

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. The data are categorized by total 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 [64])

Rank	Commodity	Organic Sales ($)	% of Total Organic Sales	% of Total Commodity Sales
1.	Grapes—all	26,768,000	10.3	1.0
	Wine	14,557,000	5.5	0.8
	Raisin	4,072,000	1.6	1.0
	Table	8,139,000	3.1	1.9
2.	Lettuce	21,945,000	8.5	1.6
3.	Carrots	14,268,000	5.5	3.3
4.	Strawberries	12,525,000	4.8	1.5
5.	Tomato	10,126,000	3.9	1.3

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. [5]. 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, poultry and products), with organic fruits and nuts representing 1.4% of the state total.

Organic grapes led all other commodities in sales (Table 1, after Klonsky [64]) 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 (Fig. 1). 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 (Fig. 2).

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 [64]. 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

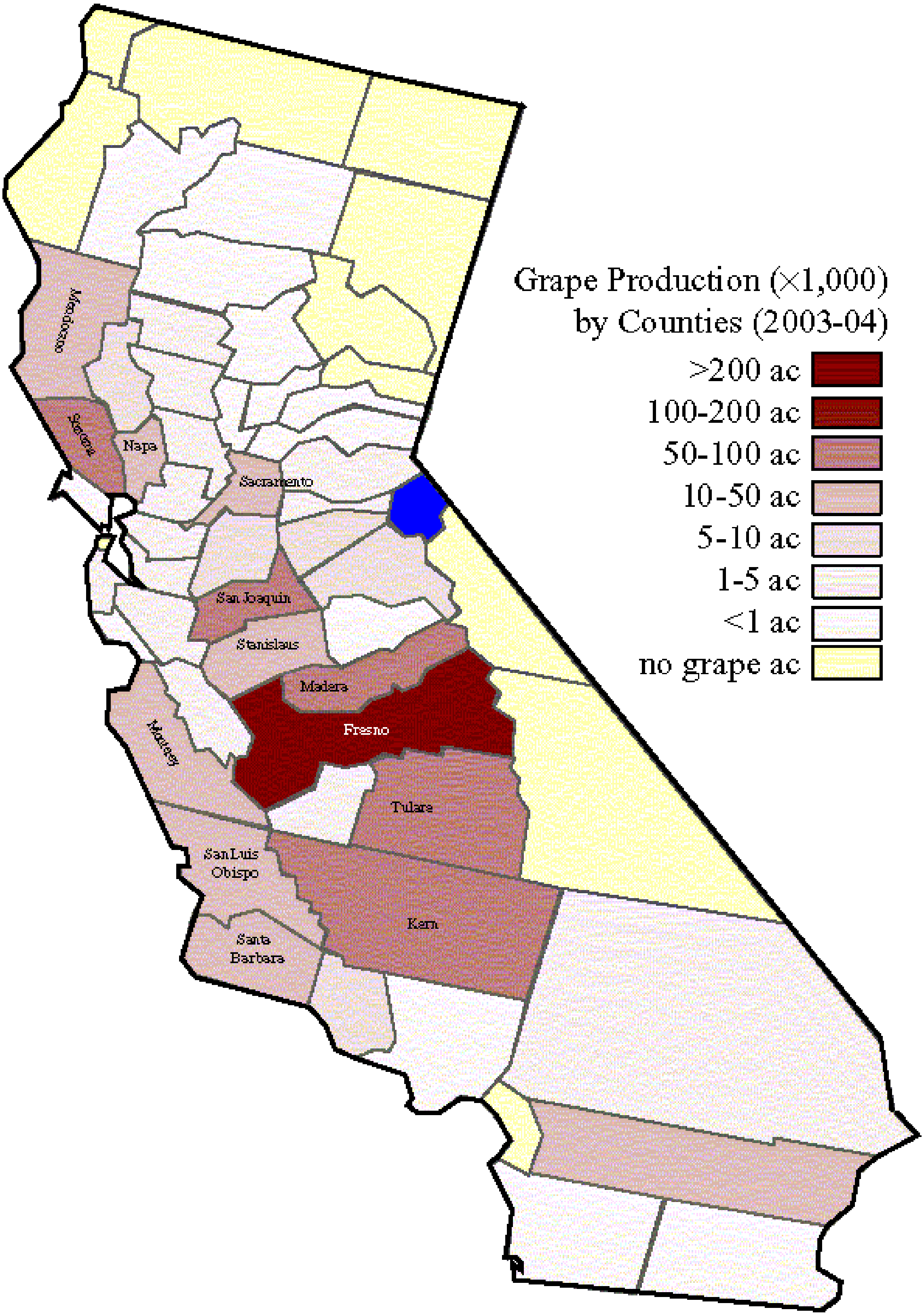

Figure 1. California grape acreage by county for the 2002 season

Joaquin Valley income was split evenly between fruit and vegetable crops and another 23% was from field crops [64]. 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

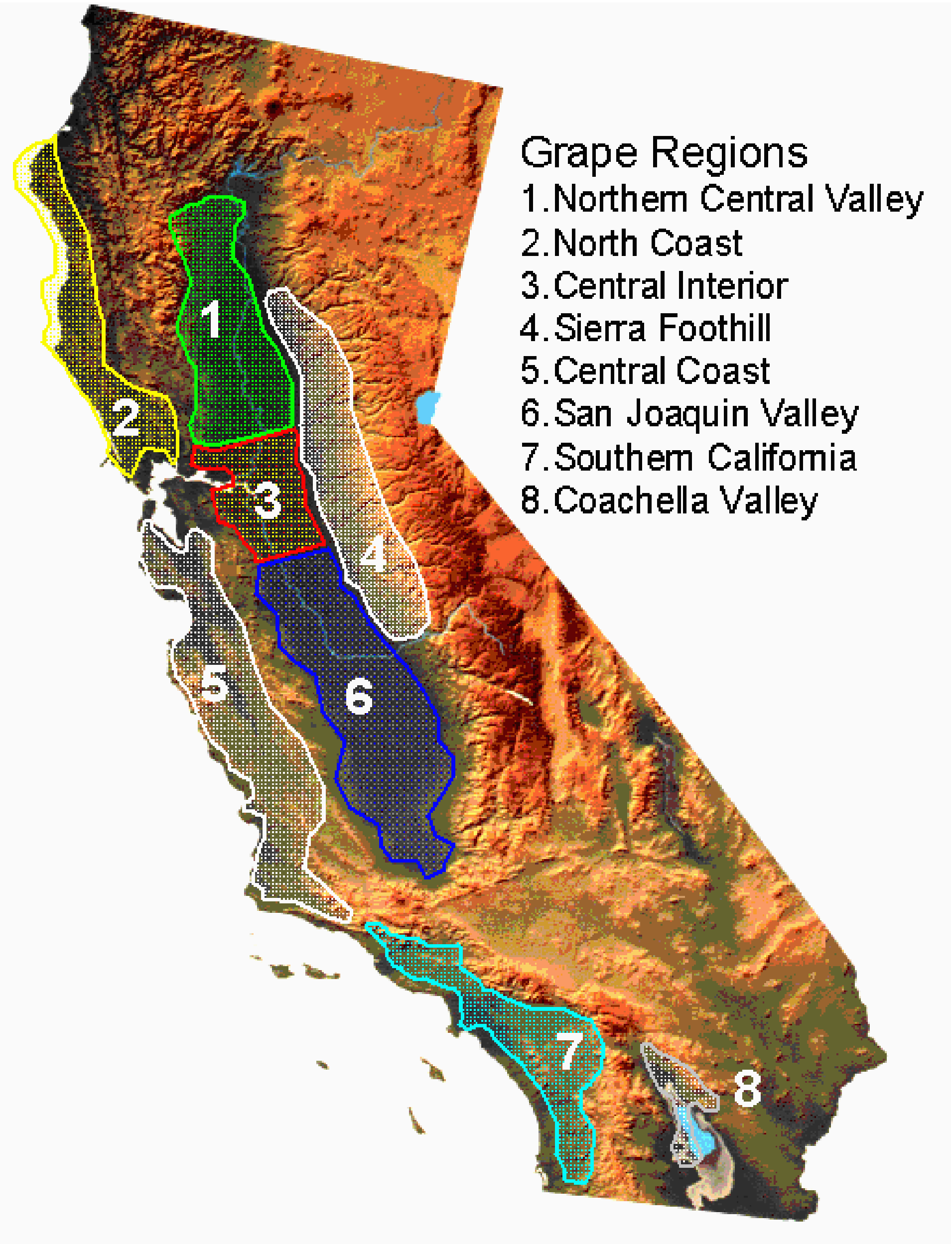

Figure 2. California grape growing regions, with borders for each region approximated.

Sonoma. Along with regional differences, there are also different levels of acceptable economic injury thresholds – for the same pest – among wine, table, and 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.

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, moths and mites. There are excellent summaries of the available scientific literature for vineyard biological control programs [39], vineyard pest management [41], and vineyard cover cropping [57], 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.

3.1. Leafhoppers

3.1.1. Leafhopper species and damage

Two leafhopper species are of primary concern: the western grape leafhopper, *Erythroneura elegantula* Osborn, and variegated leafhopper, *Erythroneura variabilis* Beamer [20, 95, 96]. 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 [81]. At present, VLH is commonly found in the Coachella Valley and San Joaquin Valley, and in isolated North Coast and Central Interior regions.

Leafhopper nymphs and adults cause direct damage to grape leaves as they feed, puncturing individual leaf cells and reducing the leaf's photosynthetic capacity [20, 95, 96]. 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 cause indirect damage by flying into the eyes, ears, noses, and mouths of workers [95]. 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) [95, 96]. Vine condition also impacts leafhopper density and direct damage, with well-watered vines (e.g., table grapes) able to support higher leafhopper population densities with less direct damage than water-stressed vines (e.g., raisin or wine grapes) [21]. 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 a problem for wine, raisin, and juice grape quality.

3.1.2. Leafhopper biological controls

Leafhopper natural enemies are present in all vineyards. There are, however, critical differences in their abundance and effectiveness. For this reason, the extent of biological controls varies considerably.

Parasitoids. Mymarid egg parasitoids, *Anagrus* species, are the most important natural enemies and are present in all leafhopper-infested vineyards. These tiny parasitoids typically control WGLH, with egg parasitism levels often reaching >90% mid-way through the growing season [20, 96]. In contrast, VLH egg parasitism rarely exceeds 40% until after harvest. One reason for this difference may be the location of leafhopper eggs [80]. WGLH eggs are closer to the leaf surface and are more exposed, while VLH eggs are placed deeper in the leaf tissue where they may be more protected from *Anagrus* species [95, 96].

To improve VLH biological control, egg parasitoids were imported from Mexico and the southwestern U.S.A. in a classical biological control program [50]. The collected and released *Anagrus* were initially treated as separate biotypes [76, 77]. A thorough taxonomic analysis later found that these parasitoids, which were formerly clumped as *Anagrus epos* Girault, were a complex of different species that included *A. epos*, *A. erythroneurae* Triapitsyn & Chiappini, *A. tretiakovae* Triapitsyn, and *A. daanei* Triapitsyn [87]. 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.

Predators. All of the predators found feeding on leafhoppers are, for the most part, generalist predators. Spiders form the most abundant and diverse group, with >50 spider species identified in vineyard collections [13, 16]. Common spiders include large nocturnal hunters (*Cheiracanthium* spp. and a *Trachelas* species), often found in grape bunches in summer; medium sized, day-active hunters, such as jumping spiders (*Metaphidippus* spp.) and the lynx spider (*Oxyopes* spp.); and "sit-and-wait" web building spiders such as the small, but very common, cobweb weavers (*Theridion* spp.) found on the leaves. Other leafhopper predators found include the whirligig mite, *Anystis agilis* (Banks) and green lacewings [95, 96]. Five different green lacewing species have been collected in vineyards [22]. The most common are *Chrysoperla carnea* (Stephens) and *C. comanche* Banks. Brown lacewings (*Hemerobius* spp.) are commonly found in coastal vineyards. While spiders are often quite visible and abundant, lacewing larvae are more difficult to find and far lower in density – typically <1 larva per 1,000 leaves. Their low larval abundance relative to the number of lacewing eggs found suggest either the larvae leave the vine, fall prey to other predators or cannibalism, or have high natural mortality.

While all of these generalist predators have been associated with leafhopper biological control, as well as the control of other vineyard pest species, there is no clear description of which species are most important or how many predators are needed. For example, *Metaphidippus vitis* (Cockerell) was a common spider found on leafhopper-infested vines, but in a laboratory trial this spider would starve rather than feed on leafhoppers (Costello and Daane, unpublished data).

Augmentation. Laboratory studies have shown that a lacewing larva can kill >250 large leafhopper nymphs (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 [22]. 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 [17]. Commercial producers and researchers are currently investigating improved release methods, including the release of adult lacewings.

Cover cropping. Cover crops are popularly associated with the attraction of natural enemies and lower pest densities [4]. Maintenance of a season-long cover crop in vineyards has been shown to reduce late-season leafhopper densities, on average by about 20% [15, 17, 20]. 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 [71].

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 [95, 96]. Therefore, *Anagrus* must find alternate leafhopper host species that overwinter in the egg stage in order to survive in each region. Doutt and Nakata [30, 31] 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) [63, 92, 87].

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 [90, 95]. In the 1990s, French prune tree refuges were similarly planted to increase prune leafhopper abundance [69]. Corbett and Rosenheim [11], 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 of prune leafhoppers. The refuge works in the wrong direction – resulting in nearly complete control of the prune leafhopper from *Anagrus* coming from the vine! With no prune leafhoppers, the refuge has no impact.

3.1.3. Leafhopper cultural controls

Vine vigor. Trichilo et al. [86] 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 [21]. 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 [97]. 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 [14, 17]. Given these results, we suggest that cover cropping can be an important tool for vineyard management, but cover crop species selections should be 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 immigrating 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 [65]. 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 grapes to reduce humidity and increase airflow and temperature; the result is lowered powdery mildew incidence [91]. 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.

3.1.4. Future needs 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 chlorinated hydrocarbons, organophosphate, 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.* [2] showed that horticultural mineral oils, applied prior to bloom, suppressed both WGLH and VLH populations. Another problem is the inconsistency reported with different formulations of botanical materials. This also needs 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 [20]. 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.

3.2. Mealybugs

3.2.1. Mealybug species and damage

Mealybug species. 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-Tozzetti), and vine mealybug, *Planococcus ficus* Signoret [47]. 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 is 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 only in newly infested, isolated vineyards.

Damage and Economic Thresholds. All of the vineyard mealybugs can feed on the vine's trunk, canes, leaves, or fruit [42]. Additionally, the vine mealybug can feed on vine roots [48]. 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 [49].

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 mealybugs 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 [45, 46]. For this reason, grape clusters on cultivars that are harvested earlier in the growing season, such as Perlette, have a shorter period of exposure than clusters on cultivars, such as Flame Seedless, that are harvested later in the season.

3.2.2. Mealybug biological controls

Parasitoids. The grape mealybug is considered native to North America and has the largest and most effective complex of associated parasitoid species. Clausen [9] reported >80% parasitism of grape mealybugs collected in San Joaquin Valley vineyards; the most common parasitoids were *Zarhopalus corvinus* (Girault), *Anagyrus yuccae* (Coquillett), *Acerophagus notativentris* (Girault), *Pseudleptomastix 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 [23]. It is not known whether changes in vineyard cultural practices, 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).

Prior to 1993, there were no effective parasitoid species of the obscure mealybug found in California. For this reason, the encyrtids *Pseudaphycus flavidulus* (Brèthes) 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 [25]. However, foraging Argentine ants, *Linepithema humile* (Mayr), diminished the success of these natural enemies [25]. 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 [27], 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 peregrinus* (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 [72]. In fact, before any newly imported material was released, *A. pseudococci* parasitism levels in the San Joaquin Valley could reach 80% of the exposed mealybugs near harvest-time [26]. However, it was hoped that the newly imported material, reared from vine mealybug, might have biological characteristics better suited to vine mealybug or the California vineyard environment. Currently, *A. pseudococci* is the only parasitoid species recovered from vine mealybug in any significant numbers, but the action of this parasitoid alone does not provide adeqaute control [26].

Predators. 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.

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 [23]. In pear, *C. carnea* was reported to suppress the grape mealybug populations [28, 29] 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 [42]. Charles [8] 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.

Augmentation. Experimental studies found that releases of *P. angelicus* and *A. pseudococci* suppressed the grape and vine mealybugs, respectively [27]. However, at this time there are no commercial insectaries producing these parasitoids.

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 [24]. On pear trees, Doutt and Hagen [28] 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.

3.2.3. Mealybug cultural controls

Cluster thinning. Most mealybugs overwinter under the bark [42, 26]. 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 arms tend to have higher mealybug infestation levels [45, 82]. 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. 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 crown and this often results in higher infestation levels.

3.2.4. Future needs for 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. 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 not 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 [45]. However, visual sampling of vineyard mealybugs, especially at low densities, is labor intensive [46]. The use of sex pheromone-baited traps, for the winged adult male mealybugs, offers a more effective sampling tool. Grimes and Cone [51] 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 [67, 88]. 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 [27]. 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 [25, 75]. 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 [25, 66, 84]. This work will be a crucial development for the implementation of mealybug biological control.

Mealybugs as vectors. While laboratory studies have shown that mealybugs can transmit these viruses, there is no information on the natural infectivity level of mealybugs collected in the field, or their transmission efficiency.

3.3. Mites

3.3.1. Mite species and damage

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 [43, 89]. 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 "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 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.

3.3.2. Mite biological controls

Predaceous mites. The most important natural enemy of spider mites is the phytoseiid *Galendromus* (=*Metaseiulus*) *occidentalis* (Nesbitt) [43]. 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 [43, 39]. However, their contribution to natural control in vineyards should not be discounted.

Augmentation. Predaceous mites can be easily reared at high quality and large densities, which is a primary component of a successful augmentation program [24]. They have been used successfully in vineyards and other crops to control spider mites [39]. 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 [39]. 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 [38]. The impact of release timing may be associated with a required late-season diapause induction for successful overwintering of the predaceous mites [58].

Food for predators. One possible method to support pollen-feeding tydeids is through pollen applications or planting cover crops [37]. 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 [36, 37]. Karban et al. [60] and Hanna et al. [54] 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 [12].

3.3.3. Mite cultural controls

Dust control. Along with dry conditions, there has long been an association between mite outbreaks and dusty roads [43]. It is a common cultural practice to oil roads and require crews to drive slowly in order to reduce dusty conditions. We have observed there is fewer adherences to this practice in San Joaquin Valley vineyards where dusty conditions often can not 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 [43, 55]. 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 [85, Costello pers. comm.]. For example, the influence of water stress on the two-spotted spider mite may be negative or nonlinear [34, 35].

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 [39]. Furthermore, English-Loeb et al. [33] 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 [56]; 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 [6]. For example, Duso [32] reported that *Amblyseius aberrans* Oudemans (*Kampimodromus aberrans*) 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 (*Anthoseius caudiglans*) 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 [61]. However, Flaherty and Wilson [39] 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 [53, 54, 93, 94]. The impact of grape cultivar on either predaceous or phytophagous mites remains open for debate.

3.3.4. Future needs for 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 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 their presence 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 clearly demonstrated the effectiveness of this program [39]. It would appear that most vineyard managers choose 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 know when and what to release [68]. 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.

To improve pest control decisions, such as augmentation, binomial sampling techniques using early-season ratios of predator: spider mites have been developed [39]. However, practical use of this technique needs better adoption by vineyard 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.

4. The future of organic vineyard management

4.1. Pesticide trends

Pesticide use reports for California vineyards show changes in pesticide materials used. Here, we group pesticide materials by category as follows: organophosphates (acephate, azinphos-methyl, chlorpyrifos, diazinon, dimethoate, disulfoton, fenamiphos, malathion, methidathion, parathion-methyl, mevinphos, naled, parathion, phorate, phosmet); carbamates (carbaryl, carbofuran, formetanate 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, kryocide); 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. 3A), primarily a result of lower raisin grape acreage. 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. 3B). 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

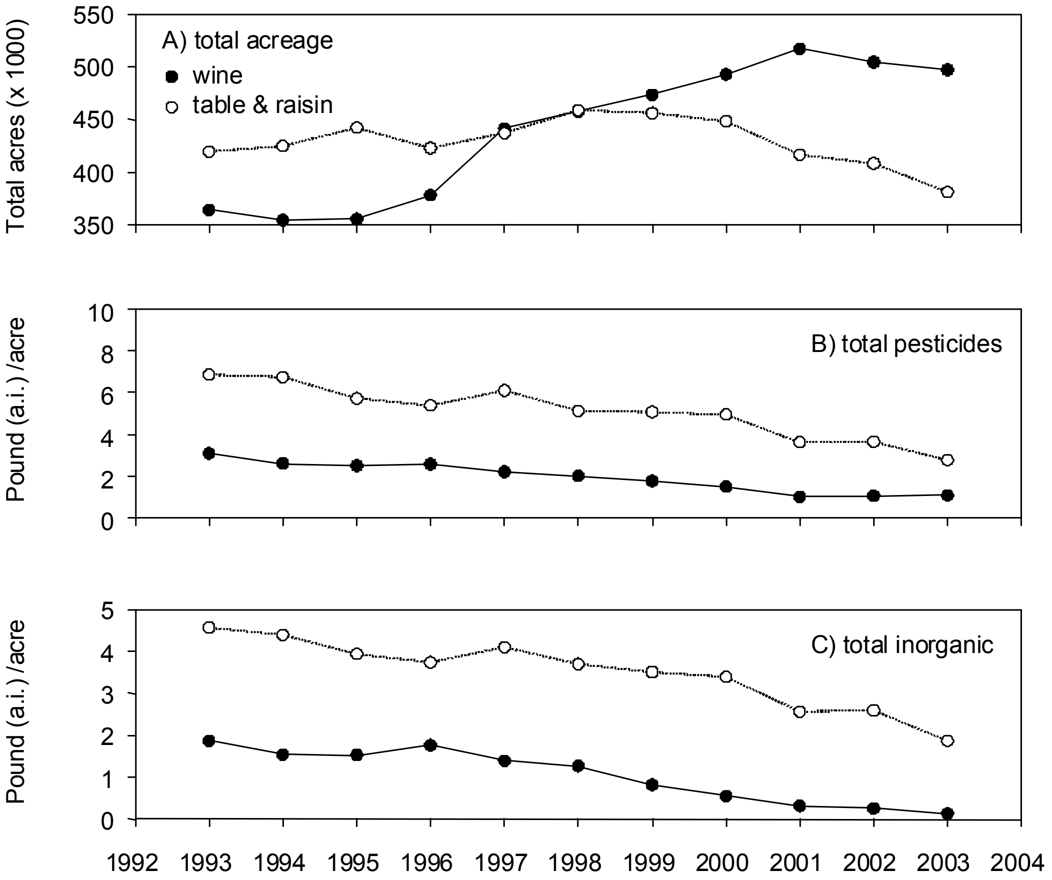

Figure 3. California pesticide use reports for 1993 to 2003 for A) total grape acreage, B) total insecticide and miticide applied, and C) inorganic insecticides (mostly Cryolite). Data are separated for wine grapes and the combination of table and raisin grapes. On graphs B and C, data are total pounds active ingredient applied per total grape acreage.

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. 3C). More important is the downward trend of pesticide material applied in all grape commodities (Fig. 3B). The general reduction in "pounds per acre" may also result from more toxic material that requires less product (in weight). 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 the chlorinated hydrocarbons (CHC) (Fig. 4A), organophosphates (OP) (Fig. 4B), and carbamates (Fig. 4C), and a fourth group would be the miticides (Fig. 4D. These materials are most often applied to control leafhoppers, mealybugs, or mites. 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 declined over the 10 year period, some materials are still commonly used for leafhoppers and mealybugs – chlorpyrifos, dimethoate, disulfoton, 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. 5A). 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. 5B). 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. 5C), botanical (Fig. 5C), 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 [45]. For this reason, some of the pesticide treatments initially used for mealybugs included fumigation with

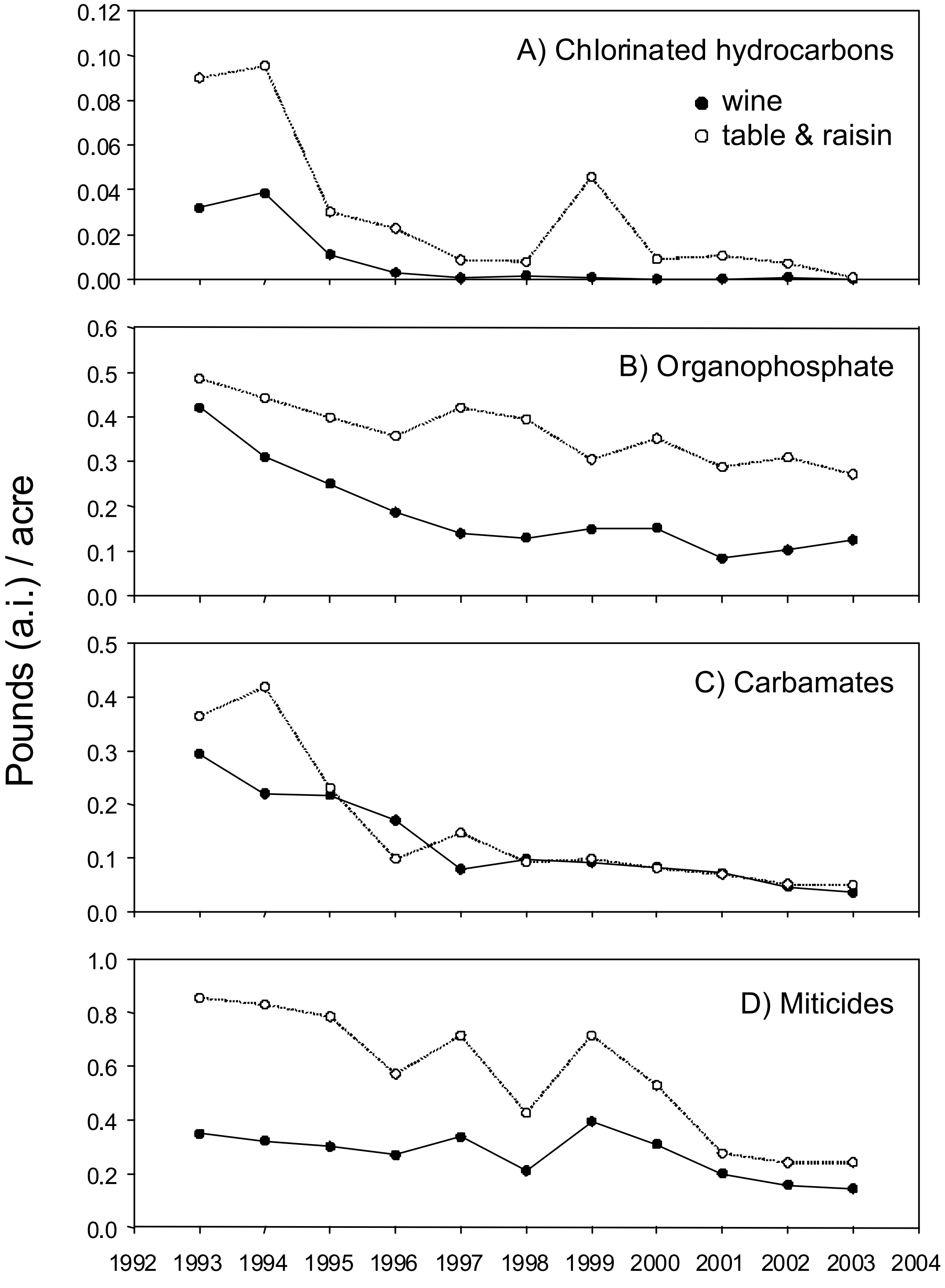

Figure 4. California pesticide use reports for 1993 to 2003 for applied materials grouped as A) chlorinated hydrocarbons, B) organophosphates, C) carbamates, and D) miticides. Data are separated for wine grapes and the combination of table and raisin grapes. On each graph data are total pounds active ingredient applied per total grape acreage.

potassium cyanide and sodium cyanide. From the 1950-80s, highly toxic organophosphates and chlorinated hydrocarbon pesticides were used for mealybug control [44, 82]. Eventually, it became evident that these pesticides disrupted biological controls [40] 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 [27]. Chlorpyrifos, imidacloprid, and buprofezin can have non-target impacts, and there is still a need for pesticide-

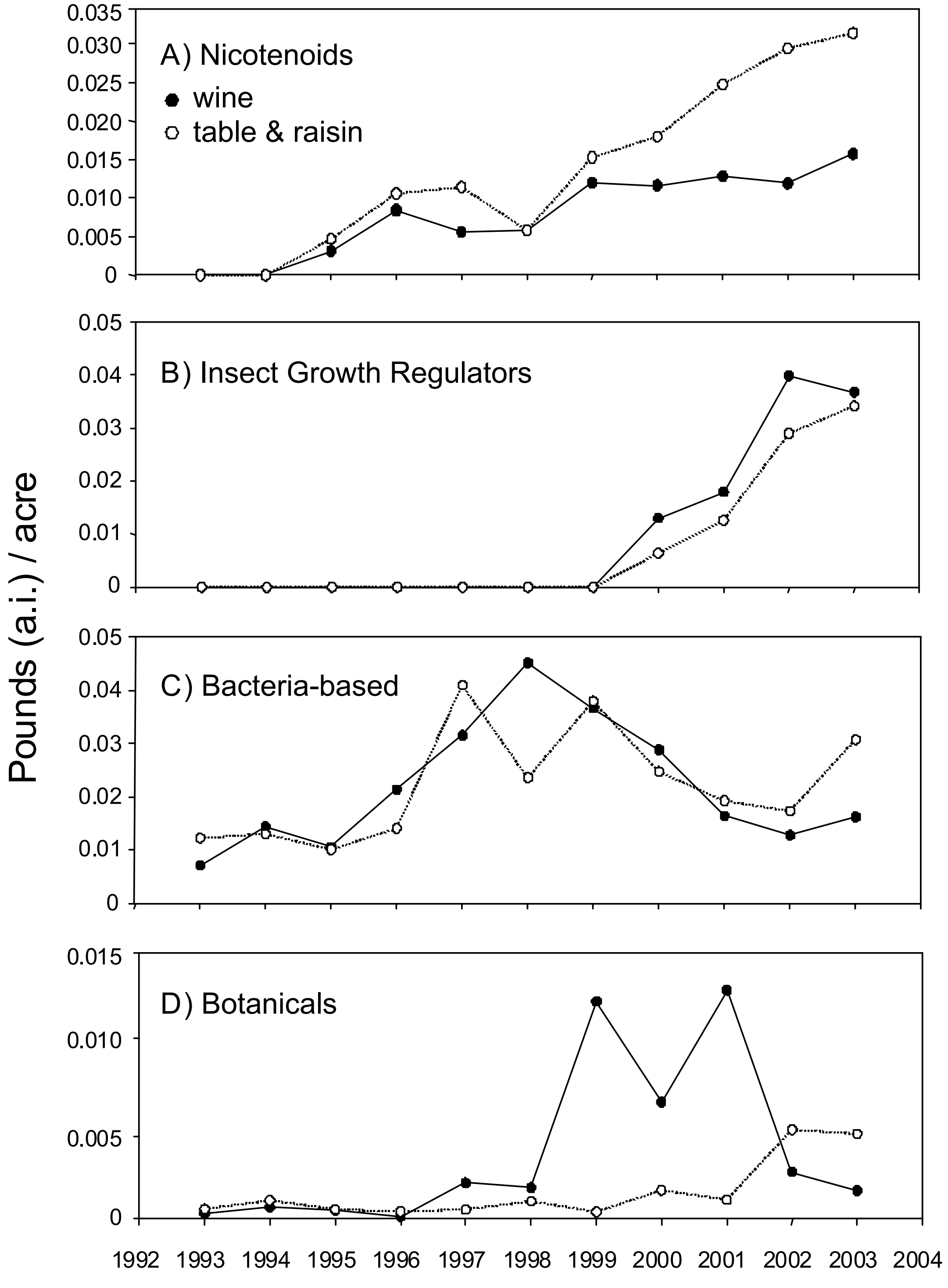

Figure 5. California pesticide use reports for 1993 to 2003 for applied materials grouped as A) nicotenoids, B) insect growth regulators, C) bacterial-based, and D) botanicals. Data are separated for wine grapes and the combination of table and raisin grapes. On each graph data are total pounds active ingredient applied per total grape acreage.

based tools for mealybug control in organically-managed vineyards.

4.2. 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* Walshingham, the grape leaffolder, *Desmia funeralis* (Hübner), and the western grapeleaf skeletonizer, *Harrisina brillians* Barnes and McDunnough (*Harrisina metallica*) [61]. 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. One of the more sustainable control options is the stomach poison sodium aluminum fluoride, which comes in a synthetic (kryocide) or organically-approved (cryolite) form. 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 [10, 52]. Only the braconid *Apanteles harrisinae* Muesebeck and the tachinid *Ametadoria misella* (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 [83] and this association of insect and pathogenic biological control agents 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 coagulata* (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) [78]. GWSS may not be a more "efficient" vector of Xf than the California sharpshooters [1], but it is certainly a more important vector [3]. The arrival of GWSS has dramatically changed the epidemiology of PD in California, as clearly demonstrated in the Temecula Valley (Riverside County) [74]. If and when it establishes in other grape regions will not make organic farming impossible, but it will make IPM efforts more complicated and control cost higher.

4.3. 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 better 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 key grape growing Cooperative Extension County offices. 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 (America Vineyard Foundation), table (California Table Grape Commission), and raisin (California Raisin Marketing Board) grapes support various extension activities, typically in a symposium format. Additionally, supporting groups, such as the California Association of Winegrape Growers (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. 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 [65]. Other successful on-farm demonstration projects have been joint efforts with University personnel and Community Alliance with Family Farmers (http://www.caff.org), the California 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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