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THE EVOLUTION OF BIOLOGICALLY-BASED INTEGRATED PEST MANAGEMENT IN CALIFORNIA CITRUS: HISTORY AND PERSPECTIVE.

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Abstract. Pest management of citrus arthropods in California may be divided into three broadly overlapping and regionally divergent historical eras: the fumigation era, the pesticide era, and the biologically-based integrated pest management era. During the fumigation era, hydrogen cyanic acid was relied on heavily for pest control and concurrently, classical biological control was established as a pest control discipline on citrus after imported natural enemies controlled cottony cushion scale and saved the fledgling citrus industry in California from collapse. The outstanding success of chemical control during the pesticide era in the late 1940s shifted research away from studies dealing with basic pest taxonomy, biology, ecology, and biological control. The biologically-based integrated pest management era began on citrus in California in the 1970s and continues to the present day. Biologically-based citrus IPM originated in coastal and interior southern California and spread to portions of the southern California desert and San Joaquin Valley (SJV) growing regions. Continued adoption of biologically-based citrus pest management in the SJV, however, is threatened by new pesticides that disrupt biological control and the introduction of new pest species that must be integrated into an evolving pest management system.

Citrus production in California occurs in four major climatic growing regions (Luck et al., 1986; Flint et al., 1991). These include coastal-intermediate southern California, interior southern California, the southern California desert valleys, and the San Joaquin Valley (SJV) (Figure 1). Historically, the southern California growing regions dominated in acreage but over the past 30 years, urban pressures including rising

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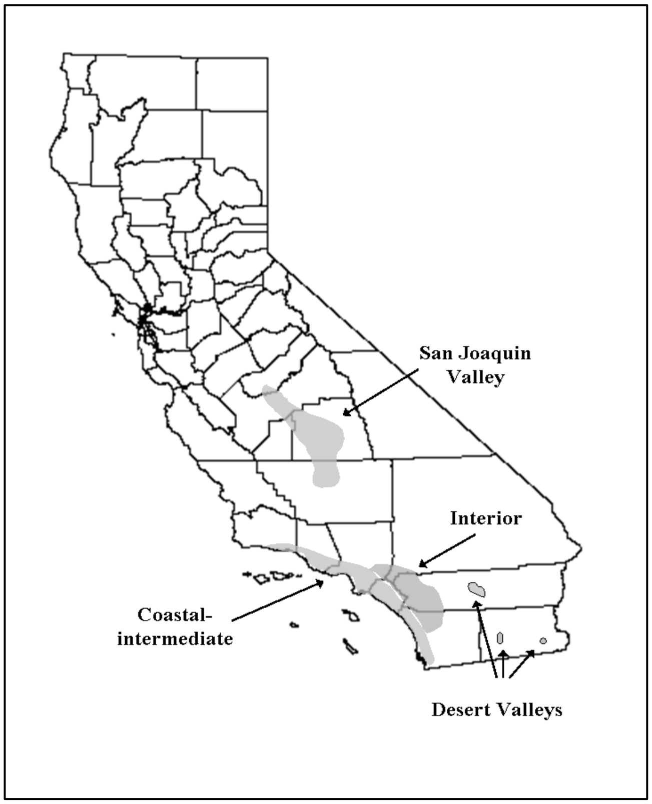

Fig. 1. Major growing regions for citrus in California.

land values and water costs have led to a shift in acreage. Currently, close to 70% of the state's citrus acreage is located in the SJV. Each of the climatic regions has somewhat differing key pest problems, levels of endemic biological control, and levels of adoption of biologically-based citrus IPM practices (see e.g., Tables I and II in Luck et al., 1986; for pest species by region, see Table 2 by selecting "California Citrus" at http://pestdata.ncsu.edu/cropprofiles/CP_form.cfm).

The Fumigation Era. The history of citrus arthropod pest management in California may be divided into three major eras, each of them broadly overlapping in time and showing regional differences. The first of these, prior to the introduction of DDT insecticide in 1946, might be called the "fumigation era." During this period, beginning with the introduction of hydrogen cyanic acid (HCN) in 1886 in California, all non-fumigant pesticides available (Paris green, lead and calcium arsenate, oil, sulfur, lime sulfur, nicotine, rotenone, pyrethrum, etc.) had limited efficacy by modern standards (Perkins, 1982; Carman, 1989). At peak use on citrus in California (1930-1940), as much as 6 million pounds of liquid HCN was used in a single season (Carman, 1989). This era was also characterized by numerous examples of rather high quality observational research focused on various aspects of pest taxonomy, basic biology, and ecology of citrus pests. In addition, classical biological control solved a number of pest outbreaks caused by the introduction of exotic citrus pests into California from various regions of the world. The science and philosophy of classical biological control originated with the outstanding control of cottony cushion scale achieved following the introduction of the vedalia beetle (Photo 1) and the *Cryptochaetum* fly into southern California citrus groves in 1888 (Doutt, 1958; Quezada and DeBach, 1973; Clausen, 1978). This led to the establishment of strong research units emphasizing biological control of pests of citrus and other crops at both Berkeley and Riverside within the University of California system.

Photo 1. Vedalia beetle adult, eggs, and larva feeding on cottony cushion scale.

The Pesticide Era. The second era in the history of citrus pest management in California, ranging from perhaps 1946 to the mid 1970s, might be called the "pesticide era" following the introduction of DDT and other organochlorines, and later, organophosphate and carbamate insecticides. DDT was experimentally tested on citrus against California red scale, *Aonidiella aurantii* (Maskell), in 1943, was released for commercial use in the U.S. in 1945, and was first used commercially on California citrus in 1946 (Perkins, 1982; Morse and Brawner, 1986). Throughout the U.S., the unprecedented level of control achieved with DDT on a wide range of pest species initiated, in retrospect, a shift of entomological research from a focus on basic pest biology to an emphasis on various aspects of chemical control. As an index of this shift, the percentage of research papers published in the *Journal of Economic Entomology* on the general biology of insect pests and their biological control dropped from 33% in 1937 to 17% in 1947, while the percentage devoted to the testing of insecticides rose from 59% to 76% (Jones, 1973; Perkins, 1982). More so than with other commodities, however, research on basic pest biology and especially biological control continued on citrus in California during the pesticide era, due in large part to the presence and citrus focus of an independent Department of Biological Control at the University of California, Riverside/Berkeley.

Although we use the date of the introduction of DDT on citrus in California in 1946 as the start of the pesticide era, DDT use on citrus in the state had a limited lifespan. One of its main uses was for control of citrus thrips, *Scirtothrips citri* (Moulton), but resistance to DDT appeared in this species in 1949, resulting in reduced use in the following years (Ewart et al., 1952; Carman, 1989). The philosophical bias in favor of chemical control of citrus pests maintained its momentum in California, however, with the commercial introduction of parathion in 1949, dieldrin in 1953, and malathion in 1954 (Morse and Brawner, 1986). Since that time, a number of other organophosphate and later, carbamate insecticides, were introduced and relied upon by growers.

Biologically-based IPM. The third era which we might call the "biologically-based integrated pest management era" has a less discrete beginning on citrus in California and continues to evolve to the present day. Here we operationally define the biologically-based IPM approach as the combined use of selective chemical, biological, and cultural controls, including regular monitoring of pest and natural enemy species, augmentative release of biological control agents such as *Aphytis melinus* DeBach (Photo 2) for control of California red scale, and use of economic thresholds which limit pesticide applications to an as-needed basis. The choice of selective pesticides and the timing and method of their application is made so as to minimally interfere with endemic and augmentatively released natural enemies.

Photo 2. *Aphytis melinus* wasps parasitizing California red scale.

Origins of Biologically-Based Citrus IPM in California. A major tenet of biologically-based citrus IPM is a recognition of the importance of maintaining endemic (i.e. natural) biological control through minimal use of broad-spectrum pesticides, minimization of dust caused by vehicular traffic, and suppression of ant species which interfere with natural enemies. In California, this appreciation for biological control was stimulated in southern California, in part, by classical biological control successes on citrus. Following the example of cottony cushion scale, as new citrus pest species were introduced into the state, foreign exploration programs were initiated with the aim of introducing effective natural enemies of these pests. Many of these programs were initially unsuccessful, but eventually led to control of the target or other non-target pests through the accumulation of a complex of natural enemy species or the introduction of a key natural enemy. In southern California, 13 exotic pests have been controlled biologically (Clausen, 1978;

Luck et al., 1986). Successes include the complete control of citricola scale, *Coccus pseudomagnoliarum* (Kuwana) in southern California, presumably due to natural enemies introduced to control black scale, *Saissettia oleae* (Bernard) (Clausen, 1978; Bernal et al., 2001). Other classical biological control successes include control of purple scale, *Lepidosaphes beckii* (Newman); Comstock mealybug, *Pseudococcus comstocki* (Kuwana); citrophilus mealybug, *P. calceolariae* (Maskell); longtailed mealybug, *P. longispinus* (Targioni-Tozzetti); citrus mealybug, *Leptomastidae abnormalis* (Girault); Japanese bayberry whitefly, *Parabemesia myricae* (Kuwana); citrus whitefly, *Dialeurodes citri* (Ashmead); and cloudy-winged whitefly, *D. citrifolii* (Morgan) (Luck et al., 1986; Flint et al., 1991). Many other arthropod pests of citrus in California are partially controlled in one or more of the growing regions in California by introduced or endemic natural enemies.

In addition to classical biological control, the practice of augmentatively releasing biological control agents has a long and successful history in California citrus. The Fillmore Citrus Protective District (FCPD) was established in 1922 in coastal southern California, mainly as a grower cooperative to assist with fumigation of California red scale (Graebner et al., 1984). In 1926, citrophilus mealybug, first introduced into the state in 1913, became a serious problem for FCPD growers and led to the construction of an insectary for rearing and annual release of the mealybug destroyer, *Cryptolaemus montrouzieri* Mulsant. In 1937, the FCPD insectary began rearing and releasing *Metaphycus helvolus* Compere (Photo 3) for black scale control, and in 1960, *A. melinus* rearing began for control of California red scale in grower-member groves. Unfortunately, a declining Valencia orange market and conversion of groves to other uses resulted in closure of the FCPD and its insectary in 2003.

During the pesticide era, growers and pest control advisors in coastal and interior citrus growing regions of southern California, often working in cooperation with researchers from the Citrus Experiment Station (CES) at Riverside,

Photo 3. *Metaphycus helvolus* parasitizing a soft scale.

experimented with and implemented reduced pesticide input pest management programs. Many of these programs were coupled with release of newly imported natural enemies or with insectary reared natural enemies. Southern California growers started relying heavily on biological control after the mid 1960s once the introduced parasitoid *A. melinus* started suppressing California red scale below levels of economic concern (DeBach and Sundby, 1963). Many growers in coastal areas started using twice annual (spring and fall) oil sprays to maintain key pest species such as California red scale, citrus bud mite, and others below economic levels, and were thus able to avoid the use of other pesticides. By the mid 1970s, several progressive pest control advisors in coastal and interior southern California had developed a biologically-based citrus IPM program which emphasized pest monitoring, selective pesticide use, and augmentative releases of insectary-reared *A. melinus* for California red scale control.

Development of a Biologically-Based IPM Program for San Joaquin Valley Citrus. During the latter period of the pesticide era, citrus production in the SJV relied heavily on broad-spectrum pesticide use. Despite repeated attempts by pest control advisors and CES scientists to introduce various facets of biologically-based citrus IPM into the SJV (e.g., Riehl et al., 1980), growers showed limited interest in reducing broad-spectrum pesticide use, and in the context of these treatments and the extremes of summer and winter temperatures, natural enemy effectiveness was limited. In the mid 1980s, a group of CES scientists, Cooperative Extension advisors, and pest control advisors from both southern California and the SJV, with funding provided by the Citrus Research Board, UC Statewide IPM Program, California Energy Commission, and the USDA Office of International Cooperation and Development, developed and tested a biologically-based citrus IPM program at the Crown Butte Ranch in Tulare County using methodologies and concepts originally developed in southern California. After several years of research and evaluation, this IPM program was disseminated as a model that might be used on citrus throughout the SJV (Haney et al., 1992; Luck et al., 1997). The program consisted of specific, intensive monitoring methods, intervention thresholds, and selective insecticide recommendations for each of the major arthropod pests found on SJV citrus at that time. Key among these were use of sabadilla (Veratran D), a botanically derived insecticide mixed with sugar or molasses as an attractant for citrus thrips control, various formulations of *Bacillus thuringiensis* (Bt) for "orangeworm" control, narrow range oil for citrus red mite, low rates of chlorpyrifos (Lorsban) for katydid and citricola scale, and management of California red scale through augmentative releases of 50,000-100,000 insectary-reared *A. melinus* parasitoids per acre per year. The *Aphytis* were released every two weeks beginning mid-February and ending mid-November each year, to total 20 releases of 2,500-5,000 wasps per acre annually. Low rates of chlorpyrifos were used to reduce California red scale levels prior to initiating the *A. melinus* releases. This program was shown to result in reduced pesticide use and similar, if not higher, fruit quality and economic returns compared with the conventional broad-spectrum pesticide-based program (Haney et al., 1992, 1994).

Several earlier research advances were key to development of the SJV biologically-based citrus IPM program. Atkins and Elmer (1981) and Flint et al. (1991) proposed economic thresholds and sampling methods for the lepidopterous pests on citrus which are collectively referred to as "orangeworms." Bellows et al. (1985, 1995), Morse and Bellows (1986), Morse et al. (1987), and Bellows and Morse (1988, 1993) determined the toxicity and persistence of commonly used pesticides to important citrus natural enemies, thus facilitating the choice of selective materials that could be used in the program. Hare et al. (1990, 1992) documented that the citrus red mite, *Panonychus citri* (McGregor), economic thresholds used in southern California were too low for application in the SJV, and that SJV populations seldom resulted in reduced yield. Moreno and Luck (1992) documented the efficacy of augmentative releases of *A. melinus* against California red scale in southern California, setting the stage for augmentative release strategies in the SJV. Finally, Walker et al. (1996), working with FMC Corp., adapted technology from South Africa and Israel and showed that a high-pressure post-harvest washer was effective in removing California red scale from fruit, thus allowing the economic threshold of this key pest to be elevated.

Although research efforts were critical, the biologically-based IPM program would not have been adopted in the SJV without extension education (Photo 4) and the dedication

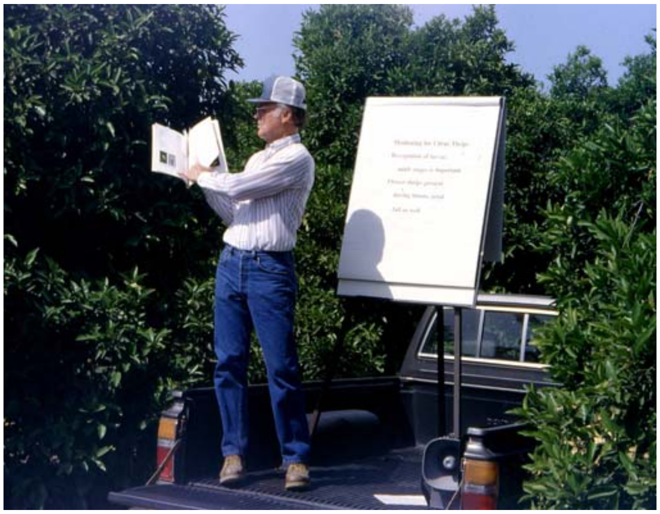
Photo 4. Tulare County UCCE Farm Advisor Neil O'Connell conducting a field day training on citrus IPM.

of many progressive citrus growers and pest control advisors. A number of grower meetings were held at the Crown Butte ranch in the late 1980s to present and discuss progress in development of the IPM program (Photo 5). Throughout the 1990s, yearly workshops were held to teach pest control advisors how to recognize

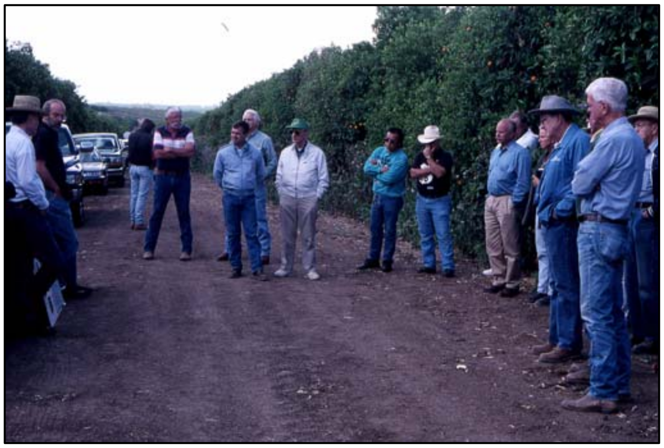

Photo 5. UCR Entomologist Dr. Robert Luck (second from left) teaching growers and PCAs about biologically-based IPM

the life stages of California red scale, their parasitoids, and how to determine if biological control was successful (Forster et al. 1995). Field days and video tapes on citrus thrips and orangeworm monitoring were produced. In addition, yearly roundtable discussions were jointly sponsored by the University of California Cooperative Extension and the Association of Applied IPM Ecologists. In these discussions, pest control advisors shared information about pest pressures, monitoring methods, control tactics, and the level of success of biological control they had achieved. Data on pest densities, natural enemy levels, degree-days, and the consequences of various pest management strategies were posted on a citrus entomology web site at the Kearney Agricultural Center. Organizations such as Paramount Citrus took a lead role in studying and transferring high-pressure post-harvest washer technology from South Africa to SJV packing-houses. All of this activity helped to increase grower adoption of biologically-based IPM methods.

Adoption of the biologically-based citrus IPM program in the SJV was initially slow, but was accelerated by the development of pesticide resistance in two key pest species. Citrus thrips has a history of developing resistance to broad-spectrum pesticides used extensively for its control, and following the appearance of dimethoate resistance in 1980, formetanate resistance in 1986, and cyfluthrin resistance in 1996 (Morse and Brawner, 1986; Immaraju et al. 1989; Khan and Morse 1998), growers became increasingly motivated to use a biologically-based approach in managing this pest. Of greater impact, however, was the appearance of California red scale resistance to organophosphate and carbamate insecticides in the SJV in 1990 (Grafton-Cardwell and Vehrs, 1995; Grafton-Cardwell et al., 2001). Because no new chemical options were available to growers with pesticide resistant California red scale, and because multiple applications of organophosphates and carbamates were so costly (ca. $160/acre per treatment), grower adoption of the biologically-based citrus IPM program accelerated in the early 1990s and reached a peak in 1997, with participation by perhaps 30% of SJV growers.

Impediments to Adoption of Biologically-Based Citrus IPM in the San Joaquin Valley. In 1998, because of increasing problems with California red scale resistance, the insect growth regulators pyriproxyfen (Esteem or Knack) and buprofezin (Applaud) were made available to SJV citrus growers through a Section 18 Emergency registration. The Section 18 was renewed for the 1999 field season and Esteem was fully registered in California in 2000. Buprofezin attained full registration in 2002. Pyriproxyfen was quite effective against California red scale, but unfortunately, was extremely disruptive to coccinellid predators such as the vedalia beetle (critical to cottony cushion scale control) and *Rhizobius (Lindorus) lophanthae* (Blaisd.), an important predator of California red scale (Mendel et al., 1994; Hattingh and Tate, 1995, 1997; Hattingh, 1996; Grafton-Cardwell, 1999; Grafton-Cardwell and Gu 2003). In South Africa, pyriproxyfen use led to mealybug flare-ups in untreated groves located near groves where it was used (the pesticide was sufficiently active to suppress mealybugs in treated groves but coccinellid predators which normally maintained mealybugs below economic levels were suppressed regionally). Similarly, in California, dramatic cottony cushion scale flare-ups were observed starting in early 1999 (Grafton-Cardwell, 2003) in biologically-based citrus IPM blocks near groves using pyriproxyfen (the material is also somewhat active against cottony cushion scale). In both South Africa and California, it is ironic that it was the growers not using pyriproxyfen who suffered flare-ups of secondary pests that are normally under excellent biological control. Unfortunately for California growers, malathion, methidathion (Supracide), and carbaryl (Sevin) are the only effective insecticides available for cottony cushion scale control and these materials are highly toxic to natural enemies needed for control of other pests such as *A. melinus*.

Based on experience from Israel and South Africa, California researchers were aware of the potential for secondary pest upsets if pyriproxyfen was used on California citrus. In May 1996, at the 7th International Citrus Congress in Sun City, South Africa, a number of citrus growers and researchers listened to an impassioned talk by V. Hattingh and B. A. Tate describing upsets of mealybugs and cottony cushion scale which resulted from pyriproxyfen treatments in South Africa. Subsequently, six meetings of growers, pest control advisors, and researchers were held in 1997 at various sites in the SJV to discuss the likely benefits and detriments of requesting the Section 18 use of pyriproxyfen. Despite concerns raised about possible secondary pest upsets, the consensus at those meetings was that this material was needed to deal with increasing populations of California red scale and the escalating use of organophosphate insecticides. In retrospect, our view is that the availability of this very effective red scale control material has dramatically lessened interest in adopting the biologically-based IPM program for SJV citrus. In addition, there is a perception that use of biological control is riskier and more difficult to employ, compared with a traditional chemical control program. For the present, many growers will continue to rely on pyriproxyfen for California red scale control, but we expect resistance to develop to this material. When this happens, more SJV growers will likely return to biologically-based citrus IPM, unless a new chemical option for red scale control becomes available.

At about the same time that pyriproxyfen and buprofezin were registered for California red scale control, spinosad was registered for citrus thrips control. These three insecticides showed greater safety for natural enemies (other than coccinellids), because they affected specific pest groups and these products had greatly improved worker safety. Growers rapidly switched from organophosphate and carbamate insecticides to pyriproxyfen for California red scale and spinosad for citrus thrips. However, use of these pesticides created a problem because the greater selectivity allowed several secondary pests to become primary pests. There was a problem, however, with greater selectivity allowing several secondary pests to become primary pests. Citricola scale and forktailed bush katydid are quite susceptible to organophosphates. They were easily suppressed by treatments for citrus thrips and California red scale during the “pesticide era”. The insect growth regulators used for red scale are not very effective against citricola scale because it only has one generation per year and molts infrequently. The spinosad treatments for citrus thrips have short residual periods of activity and thus are not effective in years with a prolonged hatch of katydid or for the larger instars. With the reduction in organophosphate and carbamate use, these insects have become chronic pests. Initially, growers managed increases in citricola scale with low rates of chlorpyrifos (Lorsban). Many natural enemies of citrus pests have developed tolerance to low rates of organophosphates, especially chlorpyrifos, due to years of exposure, and thus, these treatments are now considered fairly compatible with IPM if they occur relatively infrequently (e.g., once a year). However, as citricola scale has increased in numbers and become a common pest of citrus, lower rates of chlorpyrifos often fail to suppress it below economic levels for more than a single year. Hence, higher rates of organophosphates are now being used in an effort to control this pest, and natural enemies are less able to tolerate these treatments. Growers are currently alternating insect growth regulator treatments (pyriproxyfen and buprofezin) for California red scale with an organophosphate insecticide for citricola scale from year to year, or are tank-mixing these two types of insecticides to reduce application costs. For katydids, growers are tank-mixing low rates of pyrethroids or organophosphates with the spring spinosad treatment for citrus thrips control. As a result, an escalation in the use of broad-spectrum insecticides is underway.

A second problem for growers using biologically-based citrus IPM in the SJV is the introduction of new (exotic) pest species (Table 1). The rate of new introductions appears to be increasing because of greater movement of people and plant material between states and countries. When exotic pests enter a new region, they are often not accompanied by the full complement of natural enemies present in their native range. Thus, chemical control is often needed to maintain damage below economic thresholds until the full natural enemy complex is introduced and provides adequate control. One of the more disruptive exotic pests to enter California recently is the glassy-winged sharpshooter (GWSS), *Homalodisca coagulata* (Say). GWSS lives on citrus, as well as many other hosts, and vectors various strains of the bacterium *Xylella fastidiosa* that cause Pierce's Disease (PD) in grapes, almond leaf scorch, alfalfa dwarf, oleander leaf scorch, and several other diseases such as citrus variegated chlorosis and phony peach disease that are not yet present in California. There is currently no cure for PD, which causes the death of susceptible varieties of grape within 1-3 years. Because this pest is so destructive to the grape industry, citrus growers are asked to control GWSS in their plantings to reduce the potential movement of *Xylella* into nearby grapes. Currently, GWSS generally infests the southernmost region of the SJV and most of southern California. A difficulty for the biologically-based citrus IPM program is that GWSS is not sensitive to selective insecticides such as abamectin (AgriMek), sabadilla (Veratran D), spinosad (Success), or oil. The nonselective insecticides, such as the pyrethroids cyfluthrin (Baythroid) or fenpropathrin (Danitol), and the neonicotinoids imidacloprid (Admire) or acetamiprid (Assail), which are the insecticides of choice for GWSS, can potentially cause secondary pest outbreaks of California red scale, mites, thrips, and cottony cushion scale. Moreover, because many citrus packinghouses are located in non-infested areas, additional late season, broad-spectrum insecticides (especially the carbamate, methomyl [Lannate], or acetamiprid), may be applied to SJV groves if growers want to ship fruit to non-infested areas.

Other arthropod pests have also entered the state recently and many of them require insecticide treatments, at least initially. The red imported fire ant (RIFA), *Solenopsis invicta* Buren, was found in February 1997 in Kern County and eradication has been attempted. Since then, it has also shown up in large areas of southern California. At present it is unclear whether RIFA populations will be eradicated in the SJV, but it is possible that this pest may eventually become established and spread into citrus groves there. The citrus leafminer, *Phyllocnistis citrella* Stainton, was discovered in Imperial County in southernmost California in January 2000, spread to Riverside Co. in 2002, is now found throughout much of

Table 1. Exotic pests recently invading California citrus

Common name	Scientific name	Damage	Detection in California
Glassy-winged sharpshooter	*Homalodisca coagulata*	Vector of Pierce's Disease in neighboring grapes Reduced fruit production in citrus exposed to extremely high densities	Mid 1990s
Red imported fire ant	*Solenopsis invicta*	Damage to young plantings of citrus Human health hazard	1997
Citrus peelminer (Mexican strain)	*Marmara gulosa*	Reduction in pack-out due to mining of the rind of susceptible varieties	1998
Citrus leafminer	*Phyllocnistis citrella*	Attacks new foliage, can reduce growth of plants in nurseries and new plantings	2000
Diaprepes Root Weevil	*Diaprepes abbreviatus*	Larvae attack the root system of citrus trees	2005

California. Fortunately, the potential for biological control of this pest on bearing citrus is good. The citrus peelminer, *Marmara gulosa* Guillan & Davis is well-established in California, but has changed its habits, possibly due to recent introduction of a new biotype from Mexico, and is now causing extensive fruit damage to susceptible citrus varieties such as pummelos, grapefruit, and various navel oranges (especially Fukumoto, Atwood, and TI). Diaprepes root weevil, *Diaprepes abbreviatus* (L.), was discovered in southern California in 2005, and the larval stages are known to be a threat to the root systems of citrus and other crops. Broad spectrum foliar and systemic insecticides are utilized in the eradication program for this pest. In general, as new pests establish, their suppression will need to be integrated into the biologically-based citrus IPM program. Unfortunately, citrus growers often will need to manage them chemically until non-chemical options are developed.

CONCLUSIONS

Successful Biologically-Based IPM and Impediments to Success:

1. The success of the program depends on intensive sampling of pest and natural enemy populations, in order to maximize the effectiveness of soft pesticides and natural enemy populations.
2. Developing the required level of knowledge and training needed to successfully conduct biologically-based IPM for a crop system as complex as citrus takes years of experience and input from knowledgeable pest control advisors and supportive growers.
3. The biologically-based citrus IPM program is both sustainable and dynamic, due to changes in pesticide registrations, pest complexes, and the introduction of exotic species. Research, extension, and management programs have to be equally dynamic to respond to those changes.

For the near future, further implementation of the biologically-based citrus IPM program in the SJV faces an uphill battle, because chemical pest control appears to many to be a simpler pest management solution. However, experience with citrus has shown that at best, this approach is short-lived and is more costly in the long run.

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