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California Agriculture

Beyond organophosphates

University of California | Division of Agriculture and Natural Resources | Research in Agricultural, Natural and Human Resources

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Environmental laws elicit evolution in pest management

The era of synthetic organic pesticides began in the 1940s and brought with it many benefits. The new pesticides enabled growers to produce abundant food and fiber, both economically and predictably. They enabled public health officials to control many serious insect-vectored diseases in the United States and throughout the world. However, the universal adoption of synthetic organic pesticides in the 1950s also brought risks. UC scientists soon noted adverse impacts from these broad-spectrum pesticides on natural biological control agents and developed the concept of "integrated control." In addition to their adverse effect on biological control agents, it soon became apparent that pests could develop resistance to the new pesticides. This resistance required that increased rates of pesticides be applied to achieve acceptable control, exacerbating the problem.

The publication of Rachel Carson's famous book, *Silent Spring*, in 1962, brought concerns about the environmental and health risks of pesticides to the forefront of public awareness, and began a national debate. The U.S. Department of Health, Education and Welfare established the Commission on Pesticides and Their Relationship to Environmental Health in 1969, chaired by UC Davis Chancellor Emil Mrak, to conduct the first assessment of pesticide risks. The Mrak Commission recommended the establishment of a governmental mechanism for assessing the environmental safety of pesticides.

In 1971, President Nixon created the Environmental Protection Agency (EPA) by executive order, transferring pesticide regulation from the U.S. Department of Agriculture (USDA) to the new agency. Congress soon mandated EPA's charge to evaluate risks and benefits of pesticides by passing the Federal Insecticide, Fungicide and Rodenticide Act of 1972. Lawmakers had now established a mechanism for careful evaluation of any pesticide's environmental and health risks, and for consideration of more environmentally benign pest-management alternatives. UC scientists, who were already leaders in the development of biological control, integrated pest management (IPM) and pesticide toxicology, became increasingly engaged in national programs to identify and develop alternative pest-management strategies to broad-spectrum pesticides. They formed alliances with their counterparts in federal and California agencies to develop and implement new pest-management systems and tactics, including both biological and chemical means to combat pests.

However, developing and implementing alternatives to organophosphate pesticides to meet the needs of California's highly diverse agriculture, as well as its urban areas and natural resources, has been and will continue to be a challenge because of decreasing public funding for research and extension.

UC and USDA scientists released a task force report in 1992 entitled *Beyond Pesticides: Biological Approaches to Pest Management in California* (UC DANR Pub. 21512). This report provided an overview of possible alternative control tactics without the use of broad-spectrum pesticides, and was produced with an appreciation for the mounting political pressures on these products because of safety concerns. Two controversial National Research Council reports, *Regulating Pesticides in Food: The Delaney Paradox* in 1987, and *Pesticides in the Diets of Infants and Children* in 1993, focused attention on dietary risk from pesticides and on the differential effects of pesticides on vulnerable groups in the population. These reports questioned how the EPA established pesticide tolerances, and were drivers for passage of the Food Quality Protection Act of 1996 (FQPA). The FQPA is the most important regulatory reform yet enacted. Many broad-spectrum pesticide products and uses have been lost and more are anticipated in the future.

The elimination of the uses of many broad-spectrum pesticides has resulted in the development and registration of a number of reduced-risk and environmentally benign pesticides and control strategies. These new pesticides are more pest-specific and less robust in their control and will require increased vigilance on the part of pest control advisers. The new products are often slower-acting, will control only related pest species, and are more expensive. In addition, resistance to these new materials can occur in populations of many important pest species. Effective reduced-risk pesticides have not been developed for a number of important pests. Thus, there could be substantial economic impacts on California agriculture from implementation of the FQPA.

To address these concerns, the California Department of Food and Agriculture supported a study to measure the economic impact on the 13 top-valued economic agricultural crops in California if all organophosphate insecticides were eliminated from use. The study, *The Economic Impact of Organophosphates in California Agriculture* (http://www.cdfa.ca.gov/publications.htm), showed that the elimination of broad-spectrum pesticides would increase the cost of production, and the amount of increase was crop-specific. This report was the stimulus for the publication of this special issue of *California Agriculture*, in which UC scientists discuss alternative control measures that they have developed over decades of research.

The importance of UC maintaining its capacity to respond to future regulatory issues, introductions of invasive species, vector-related public health issues and economic challenges faced by California citizens has never been greater. To meet these challenges, a new era of cooperation and integration between UC's Agricultural Experiment Station and Cooperation Extension must be implemented in the near future. This reorganization must be substantial and collegial, and foster the vertical integration of knowledge development and delivery. Through the closer integration of these two units, a leaner and more efficient organization will be positioned to lead California as it responds to the challenges ahead.

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News departments

Galen Rowell/Corbis

Under the Food Quality Protection Act of 1996, many uses of organophosphate insecticides and other broad-spectrum pesticides are being phased out, with important implications for California growers; UC scientists are exploring a range of alternatives. Shown on this home gardener's shelf are generations of pesticides, some of which have been banned or their uses curtailed.

Research articles

Beyond organophoshates

Clarification

The October-December 2004 cover of *California Agriculture* showed fishermen harvesting snow crab in Alaska, a dangerous crab fishery. This identification was omitted from the caption. *California Agriculture* regrets this error.

Letters

WHAT DO YOU THINK?

The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at calag@ucop.edu or 1111 Franklin St., 6th fl., Oakland, CA 94607. Include your full name and address. Letters may be edited for space and clarity.

"Crabbing" about Cal Ag cover

The October-December 2004 issue of *California Agriculture* is, as usual, very interesting and informative, particularly the Dungeness crab articles.

Your cover picture, however, does not depict Dungeness crab fishing. More likely the photo is of a snow crab boat — in Alaska or maybe even the Bering Sea! Nevertheless, it is a beautiful, dramatic photo. Just looking at it gives me a bit of motion sickness.

The scene is familiar to me. I did my Ph.D. research at the College of Fisheries and the Institute for Food Science at the University of Washington in Seattle. To carry out the study I spent many weeks at sea going from Puget Sound as far as the Gulf of Alaska. Most of my time was spent aboard a small research vessel converted from a trawler. (I almost had my legs cut off by a snapped winch cable that whipped across the deck.)

I have enjoyed reading *California Agriculture* over the years. The topics covered are broad and the articles are consistently well written and informative. Your publication is particularly important to me since I have retired and have become a fruit grower — still learning, growing great fruits, trying to make a buck or two and having a lot of fun.

John G. Chan
Hilo, Hawaii

Editor's response: Thank you for your interest in California Agriculture *— and for your correct observation regarding the October-December 2004 cover.*

We located this stock photo after searching for an illustration depicting the dangerous conditions at sea when the race for crab begins. However, the agency providing this photo had not documented the identity of the crab. We established its identity as snow crab and immediately corrected the omission on our Web site.

Donation to Amazon research institute

You will be pleased to learn that a shipment of 50 years of *California Agriculture* magazines (from 1954 to present) has been received by the Instituto Nacional de Pesquisas de Amazonia (INPA) in Manaus, Brazil. Several years ago, I met Dr. Rosalee Coelho Netto at a conference and decided to donate my personal library of phytopathology resources to the institute, which had very little reference literature in its library. I arranged to ship the *California Agriculture* magazines, as well as several decades of *Plant Disease, Phytopathology* and a small library of agricultural manuals. The crate arrived in good order at the Manaus port in April, but was held up at the docks by a worker strike until August. Finally, all matters were worked out and the shipment is now in the hands of the receiver library.

In a letter, Dr. Netto of INPA wrote: "The books and journals will be a wonderful and important resource for INPA students and researchers." The acting director of INPA, Edinaldo Nelson dos Santos Silva, added, "Your act enriched our library and will help to enlarge the knowledge of our students, professors, researchers and scholars of the Amazonia region."

Franklin Laemmlen
County Director & Farm Advisor
Santa Barbara County

Editor's response: We are gratified to learn of your donation, and impressed that your perseverance paid off. Because your collection ended in 2004, California Agriculture *has provided a free subscription to the institute's library (international subscribers normally pay $24 annually to defray postage and handling costs).*

Franklin Laemmlen, with his shipment of 5 decades of *California Agriculture* magazines and other research materials; Rosalee Coelho Netto receiving the shipment for the Instituto Nacional de Pesquisas de Amazonia in Manaus, Brazil.

Editor's note

We gratefully acknowledge the efforts of those who contributed to the publication of this special issue on alternatives to organophosphate insecticides: Robert A. Van Steenwyk, Cooperative Extension Entomologist at UC Berkeley, and Frank G. Zalom, Cooperative Extension Entomologist at UC Davis, who served as co-chairs; *California Agriculture* associate editor Timothy D. Paine, Professor and Entomologist at UC Riverside, who oversaw the peer review of manuscripts; and the California Department of Food and Agriculture, which partially funded this issue of the magazine.

New look for nameplate

With this issue, the *California Agriculture* nameplate on the front cover takes on a new look. While using the same typeface, we have slightly enlarged the print and placed it on one line, without italics. We believe this makes it visually stronger and clearer, while increasing flexibility in cover design.

A pipe discharges field runoff into Orestimba Creek near Modesto. Sediment from this creek was found to be toxic to shrimplike bottom-dwellers called amphipods, most likely because of high levels of pyrethroids.

Pyrethroids in Central Valley stream sediments toxic to bottom-dwellers

Recent evidence shows that pyrethroids, used increasingly as substitutes for organophosphate insecticides (see page 11), accumulate in creek sediments in some locations at levels toxic to freshwater bottom dwellers.

Except in the immediate vicinity of their application, pyrethroids have been considered safe for fish and other organisms that live in the water, but their effect on sediment-dwelling organisms has not been studied, says UC Berkeley biologist Donald Weston.

Weston and colleagues collected 71 sediment samples from rivers, creeks, sloughs and drainage ditches in the Central Valley and exposed amphipods and midge larvae to the sediments. These two organisms are used by the U.S. Environmental Protection Agency (EPA) as indicators of the health of freshwater sediment. Of the sediment samples, 20% killed amphipods at an elevated rate relative to controls and had concentrations of pyrethroids high enough to explain the deaths. The study appeared the journal *Environmental Science & Technology* in May (Vol. 38, No. 10).

"We have no data on the effects of the pyrethroids on resident species," Weston says. "Such effects are very difficult to show, although that is an area in which we are working. However, the test species we used are nationally recognized surrogates for resident aquatic life, and their mortality indicates effect on the resident organisms should be considered."

Pyrethroid use in California has risen due to increased regulation of organophosphates, which pose health threats to workers and cause toxic runoff. Agricultural pyrethroid use in California jumped 25% from 1999 to 2002, although, according to Weston, the increase is only half the picture since it does not take into account the fact that growers are gradually switching to pyrethroids with greater toxicity. About 500,000 pounds of pyrethroids were used in 2002 for nonagricultural uses such as structural and pest control, and landscape maintenance, while more than 250,000 pounds were applied to California farm fields on crops such as cotton, fruit and nut orchards, lettuce, alfalfa and rice.

Despite this increased use, environmental monitoring tends to focus on water sampling, under the assumption that sediment-bound chemicals like pyrethroids are unavailable. The current study shows that is likely to be untrue.

Weston advocates best management practices to reduce the aquatic impacts of pyrethroids. For instance, practices that reduce soil erosion would greatly reduce the offsite transport of pyrethroids. "In this case, the interests of environmentalists and farmers are the same," he says. — *Editors*

State announces new methyl bromide use rules; phase-out delayed

In late November 2004, the California Department of Pesticide Regulation (DPR) announced new regulations limiting the levels of methyl bromide that may remain in the air for several weeks, the first such subchronic "seasonal exposure" rules in the nation. The rules impose buffer zones and advance notification for field fumigations, as well as other restrictions (see page 41).

Methyl bromide — a toxic fumigant injected into the soil to kill insects, weeds and diseases — is used widely by American tomato and strawberry farmers, as well as in food processing and storage.

The new regulations give the DPR and county agricultural commissioners the authority to ensure that ambient air concentrations of methyl bromide do not exceed an average daily nonoccupational exposure of 9 parts per billion (ppb) in a calendar month. In 2001, DPR implemented regulations limiting short-term (24-hour) exposures to methyl bromide in the air to no more than 210 ppb. While maintaining that short-term standard, the seasonal (4-to-8-week) standard of 9 ppb addresses average daily exposures for children or other individuals deemed most sensitive.

DPR pesticide-use reports show that methyl bromide applications in California have fallen from more than 15 million pounds in 1999 to 6.5 million pounds in 2002. Factors contributing to the decline include DPR restrictions, research on less-toxic alternatives, and reductions mandated by the federal Clean Air Act and the Montreal Protocol, a global treaty regulating ozone-depleting substances that is gradually phasing out most uses of methyl bromide.

Also in late November, Montreal Protocol negotiators meeting in Prague extended the United States' "critical use" exemption for methyl bromide for 1 year, but said the country must cut its use in 2006. (The Bush administration had secured the exemption on the grounds that viable alternatives to methyl bromide are lacking.) The exemption amounts to a 2.5% increase in allowed usage for 2005, most of which will

◀ **On Nov. 2, voters in Marin County, *left*, approved a measure banning the planting of genetically modified crops. Similar measures in three other counties failed.**

go to California strawberry growers.

"The national adjustment announced for methyl bromide use does not affect California restrictions on the fumigant, which are the toughest in the nation," DPR spokesperson Glenn Brank says. "We do not expect any significant increases in use given DPR's limitations on methyl bromide."

For more information, go to: www.cdpr.ca.gov/docs/legbills/recntadop.htm (DPR) or *http://www.undp.org/seed/eap/montreal/ (Montreal Protocol)* — *Editors*

Three of four county anti-GMO measures fail

Measures on the November 2004 ballot to ban the growing of genetically engineered crops failed in three of four California counties, most notably Butte, a major rice-growing area that was seen as an important test case (see "California voters assess anti-GMO initiatives," October-December 2004, page 182). While opponents are claiming victory, supporters are downplaying the outcome as a short-term setback.

"It could go either way," says UC Cooperative Extension biotechnology specialist Peggy Lemaux. "It's too early to tell, we'll have to see what happens in the coming year."

Butte County's measure lost 61% to 39%, San Luis Obispo's lost 59% to 41%, and Humboldt's lost 72% to 28%. In contrast, Marin County's measure passed 61% to 39%, making it the third California county along with Mendocino and Trinity to ban genetically modified organisms (GMOs).

Mendocino County set a precedent in March 2004 by becoming the first county nationwide to pass an anti-GMO measure. However, this was seen as largely symbolic because, unlike Butte County, Mendocino County is not a major agricultural area. Furthermore, while the opponents of Mendocino County's measure were funded largely by the biotech industry, the opponents of Butte County's measure were funded largely by farming interests. "People in the county were deciding their own fate, not being influenced by industry outside the county," Lemaux says.

Anti-GMO supporters say they will try again in San Luis Obispo and Humboldt counties. According to published news reports, in Humboldt County supporters ended up opposing the November measure due to flaws in the wording. As in Mendocino County, the authors of Humboldt County's measure made the mistake of defining DNA as a protein. Moreover, the Humboldt measure could have been interpreted as violating both the state and federal constitutions by, for example, denying offenders the right to a jury trial, according to Humboldt County district attorney Paul Gallegos (in a Sept. 8, 2004, *Eureka Reporter* article).

Although the Humboldt County measure failed, one of the cities in this county has already jumped into the mix. On Nov. 17, 2004, Arcata's city council unanimously voted to adopt an anti-GMO ordinance, making it the only city in California with such a ban.

In addition, anti-GMO measures are in the works in 12 more counties in the state, according to an assessment on the UC DANR Statewide Biotechnology Workgroup Web site (based on information from the Organic Consumers Association Web site). They are Alameda, Lake, Napa, Nevada, Placer, Sacramento, San Francisco, Santa Barbara, Santa Cruz, Solano, Sonoma and Yolo. Of these, only Sonoma County is likely to have an anti-GMO measure on the ballot by spring 2005, and this will be a special election that has not yet been scheduled, says Ryan Zinn, national campaigns coordinator of the San Francisco-based Organic Consumers Association, which is spearheading the anti-GMO movement in California and elsewhere in the country.

"The overall strategy in California will likely not change, at least in the near term," Zinn says. "Down the road, we will likely set our sights on statewide legislation. But we are several years away."

In contrast, on Nov. 30, the Fresno County Board of Supervisors passed a resolution *supporting* the use of biotechnology in agriculture. Fresno is one of nine Central Valley counties where significant amounts of genetically engineered crops are grown, particularly cotton. The resolution was passed at the request of the Fresno County Farm Bureau and concludes with the statement: "The County of Fresno will make every effort to preserve the choice of using biotechnology in its county and encourage the establishment of a state or national biotechnology policy." — *Robin Meadows*

Food Quality Protection Act launches search for pest management alternatives

Robert A. Van Steenwyk
Frank G. Zalom

Insecticides have long been important tools for California farmers to combat agricultural pests. By 1995, organophosphate (OP) insecticides such as chlorpyrifos, azinphos-methyl, methamidophos, phosmet and diazinon accounted for an estimated 34% of worldwide insecticide sales, and they are widely credited with allowing large yield increases in commercial agriculture. The U.S. Food Quality Protection Act (FQPA), signed into law in 1996, established a new human health–based standard that "reasonable certainty of no harm will result from aggregate exposure to the pesticide chemical residue." When the FQPA was passed, 49 OP pesticides were registered for use in pest control in the United States; since then, many uses have been canceled and others are expected to be lost, with particular significance for California growers. A number of alternative pest-control products and strategies are available, with varying degrees of effectiveness and cost. Research and development of control measures to replace OP insecticides must be pursued to maintain an economically viable state agricultural industry.

In 1910, Bliss S. Brown, professor of botany and horticulture at the University Farm (later UC Davis), demonstrated a spray pump to a pomology class in Davis. Nearly a century later, UC scientists are researching alternatives to insecticides whose uses are being restricted under the Food Quality Protection Act.

Insecticides have long been important tools for California farmers to combat agricultural pests. However, the types of insecticide products have changed substantially over time in response to the availability of new chemicals, the development of pest resistance and regulations addressing environmental and health concerns. Prior to World War II, most insecticides used by farmers were inorganic products such as calcium arsenate, lead arsenate and sulfur, or botanical insecticides such as pyrethrum and nicotine. With the exception of sulfur and pyrethrum, various synthetic organic insecticides have replaced the inorganic and botanical insecticides.

In the turbulent years immediately preceding and during World War II, supplies of the botanical products became limited and an effort was made to identify, synthesize and manufacture replacement insecticides to protect military personnel from insect-borne diseases and crops from insect pests. Scientists in England and France identified the insecticidal properties of the precursors to organochlorine and cylclodiene insecticides in 1939. Because their acute mammalian toxicity was low and their spectrum of activity against insects was high, the organochlorine insecticides — which include products such as DDT, dieldrin and aldrin — were immediately useful in controlling insect vectors of diseases (especially typhus and malaria) during World War II. Following World War II, organochlorine and cyclodiene insecticides became widely used in agriculture.

Despite their effectiveness, the organochlorine and cylclodiene insecticides were persistent in the environment, and their effects on nontarget species resulted in outbreaks of a number of secondary pests or the rapid resurgence of the target pest through the suppression of beneficial insects (Stern et al. 1959). In addition, organochlorine and cylclodiene insecticides were widely implicated in adverse effects upon wildlife (Carson 1962). As a result, most of these products were eventually banned for use.

German scientists identified the insecticidal activity of organophosphorus compounds the 1930s, but their chemistry was primarily exploited for possible use as chemical warfare agents. After the war, the organophosphate (OP) compounds were developed as insecticides. The OP insecticides are acutely toxic to mammals, exhibit cholinesterase inhibition, have a broad spectrum of activity against insect pests and have relatively short environmental persistence. They are much less persistent in the environment than the chlorinated hydrocarbons. By 1995, OP insecticides accounted for an estimated 34% of worldwide insecticide sales (Casida and Quistad 1998). Some popular products include chlorpyrifos (Lorsban), azinphos-methyl (Guthion) and phosmet (Imidan). They are widely credited with allowing large yield increases in commercial agriculture.

In the late 1940s, methyl carbamates were developed as insecticides. The methyl carbamates exhibited cholinesterase-inhibition activity similar to that of the OP insecticides. Like

"Food quality" is a misnomer, since FQPA considers *all* potential pathways by which people may be exposed to pesticides.

the OP insecticides, they have a broad spectrum of activity and are toxic to many nontarget species, particularly beneficial insects as well as wildlife. They tend to degrade relatively rapidly in the environment, except for aldicarb, which became a problem when it was shown to leach in sandy soils and enter groundwater.

The Food Quality Protection Act

As a group, both the OP and methyl carbamate insecticides have continued to be widely used in California agriculture during the past half century. Growers favor the use of these synthetic organic pesticides because they are effective, relatively inexpensive and have a broad spectrum of activity. Their widespread use, however, has also brought with it environmental and human health concerns, including: pesticide residues on food, particularly as they relate to infants, children and vulnerable groups; pesticide contamination of rivers and streams via runoff from treated fields and orchards; drinking water contamination from the infiltration of pesticides through the soil; and the destruction of wildlife such as birds of prey as well as the destruction of beneficial insects and mites.

These concerns have been addressed by a number of state and federal laws, including the Food Quality Protection Act (FQPA) and the Clean Water Act. The FQPA was unanimously passed by both houses of the U.S. Congress and signed into law by President Clinton on Aug. 3, 1996 (US EPA 1996). This piece of legislation has had, and will continue to have, a major impact on agricultural pesticide use. The FQPA significantly amended two previous laws: the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) and the Federal Food, Drug and Cosmetic Act (FFDCA). The FQPA established a new human health–based standard that "reasonable certainty of no harm will result from aggregate exposure to the pesticide chemical residue." In this respect, "food quality" is a misnomer, since the law considers all potential pathways by which people may be exposed to pesticides when establishing acceptable food residue limits.

Previously under FIFRA and FFDCA, pesticides were registered by the U.S. Environmental Protection Agency (EPA) with the intent to "prevent unreasonable adverse effects on human health or the environment" by establishing maximum permissible tolerances of a pesticide residue on food. An important feature of the FQPA is its special consideration of health effects on children and other vulnerable individuals. This additional emphasis in the FQPA reflects the findings of a National Research Council (1993) report, *Pesticides in the Diets of Infants and Children*, which proposed that differences exist among segments of the population in terms of impacts from pesticide exposure.

The FQPA requires the EPA to reassess all pesticide tolerances. The tolerance reassessments must consider the cumulative effects of the aggregate exposure from all sources (dietary, drinking water and residential) of pesticides with a common mechanism of toxicity. In addition, the tolerance may be reduced 10-fold as a safety factor to provide additional protection for infants and children. This 10-fold safety factor need not be imposed when reliable information indicates that no harm will result to infants and children. The law calls for the tolerance reassessments to be completed within 10 years (in two 3-year increments followed by a 4-year increment), with priority given to pesticides that may pose the greatest risk to public health. The reregistration of all pesticides registered before 1984 under FIFRA will incorporate the new health-based standard of the FQPA.

Minor-use pesticides

In addition to establishing a new health-based standard of no harm, the FQPA also provides for the expedited registration review of "reduced risk" pesticides. A reduced-risk pesticide has lower human or nontarget organism toxicity, lower potential for environmental contamination and greater potential for increasing the adoption of integrated pest management (IPM) practices as compared to conventional insecticides. After a pesticide receives a reduced-risk classification, the EPA must make registration review decisions within 12 months, considerably faster than for pesticides that do not receive such designation.

The act also offers economic incentives to pesticide registrants (usually the manufacturer) who register "specialty" or "minor use" pesticides. Minor uses are registrations for crops with

Courtesy of Lear/Carson Collection, Connecticut College

Derek and Frances Richardson

Rachel Carson (shown, *left,* in 1951 during her service as a U.S. Fish and Wildlife Service scientist) warned of the environmental impacts of certain pesticides in her 1962 book, *Silent Spring*. *Right,* brown pelican populations severely declined during the mid-20th century because of exposure to DDT, which thinned their egg shells; the insecticide was banned for general use in 1972.

ANR Communication Services

The Food Quality Protection Act reflects findings of a 1993 National Research Council report, *Pesticides in the Diets of Infants and Children.* The law requires an additional 10-fold safety factor on some pesticide tolerances to provide additional protection for young people.

less than 300,000 acres in production, which the EPA administrator determines do not provide sufficient economic incentive to support registration and for which there are no effective pesticide alternatives, or uses for which the available alternatives pose greater human risks. A pesticide can also receive minor-use status if it significantly aids in resistance management or improves IPM systems. The incentives may include an additional year of exclusive data use, waivers of certain data requirements and expeditious review that could bring the product to market sooner.

California's diverse crop production includes many minor uses, and this has often resulted in fewer available pesticide options for fruit, nut and vegetable growers relative to those for the producers of larger acreage field crops such as corn, cotton and soybeans. The FQPA also set a goal for the EPA to review all pesticide registrations on a 15-year cycle to ensure that all pesticides meet updated safety standards. Additional provisions of the FQPA are somewhat less likely to affect California agriculture.

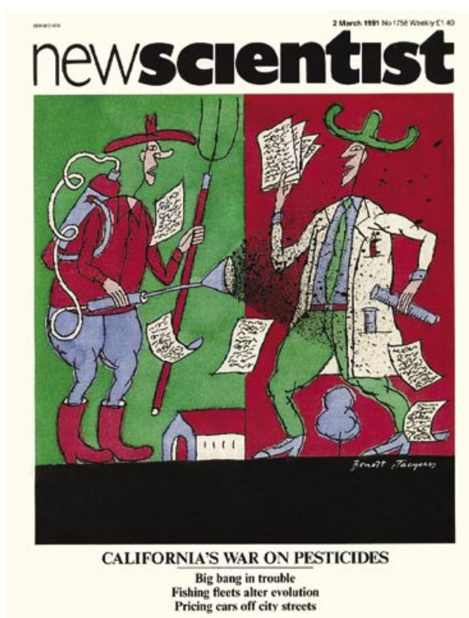
Focus on public health risks

The reassessment of all pesticide tolerances by the EPA presents a daunting task for that agency, since there were more than 9,700 in 1996 when the law was enacted. A pesticide tolerance is the amount of allowable pesticide residue on an individual commodity at harvest, and each pesticide (active ingredient) may have many individual tolerances. Therefore, the EPA is giving priority to pesticides that may pose the greatest risk to public health, first focusing on the reassessment of OP and methyl carbamate insecticides.

The OP insecticides bind to the enzyme acetylcholinesterase in the central and peripheral nervous system. This deactivates the acetylcholinesterase, resulting in repeated, uncontrolled stimulation (firing) at the nerve junctions. The EPA has tentatively considered the OP insecticides to act through a common mechanism of toxicity. While dietary exposure to a particular OP may be low, the simultaneous exposure to multiple OP insecticides may result in some segments of the population exceeding acceptable daily allowances (Byrd 1997). The implementation and ramifications of the OP insecticides having a common mode of toxicity has not been clarified at this point.

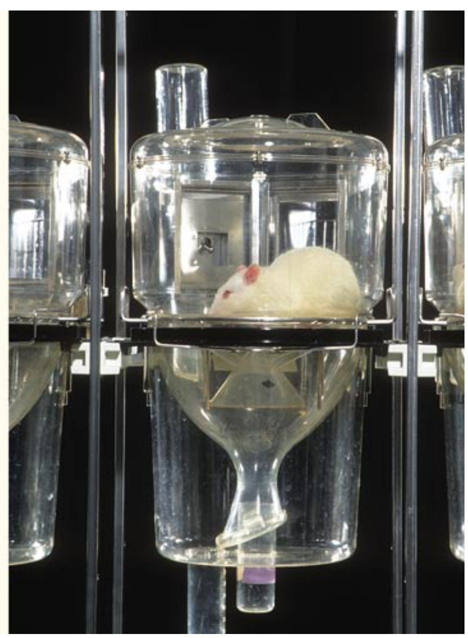
When the FQPA was passed in 1996, 49 OP pesticides were registered for use in pest control in the United States. When the EPA released the *Revised OP Cumulative Risk Assessment* (2002), 14 pesticides had been canceled or proposed for cancellation and 28 others had partial use bans. Voluntary and mandated cancellation or restriction on a number of uses for OP insecticides — such as azinphos-methyl, chlorpyrifos, ethion, ethyl parathion and methyl parathion — has had particular significance for California growers.

For example, the EPA accepted voluntary label restrictions on azinphos-methyl, which included reducing the maximum seasonal rate in pome fruit, lengthening the intervals between last application and harvest, and increasing the intervals between an application and worker reentry. Restrictions on chlorpyrifos included canceling in-season uses on apples and grapes, reducing the maximum number of applications in alfalfa, and increasing the intervals between an application and worker reentry for citrus, nuts and stone fruit. Actions on methyl parathion included lengthening the interval between an application and worker reentry, and canceling most food crop uses (particularly for commodities consumed by children) and all ornamental and public health uses. All registrations have been canceled for both ethyl parathion and



Pesticide regulation has long been controversial in California (March 1991 cover shown).

Jack Kelly Clark



Toxicological research on animals helps to inform pesticide regulatory decisions.

Jack Kelly Clark

***Left,* former UC Davis graduate student Till Angermann monitors an autosampler to test the effects of best management practices for reducing dormant-season organophosphate runoff from orchard crops. *Right,* closed loading systems are important when handling certain organophosphate insecticides.**

ethion. In addition, the EPA has accepted voluntary action on phosmet including the cancellation of its uses for domestic pets, household ornamentals and fruit trees, and diazinon is no longer registered for urban uses. It is anticipated that further restrictions on OP insecticides including product cancellations will be imposed in the future.

Pest control alternatives

The regulatory focus of the FQPA is the reduction of the human health effects of pesticides, but it is understood that economic and environmental consequences will also result from its implementation. The quantitative and qualitative impacts of the modification or cancellation of OP insecticide use depends on the availability and adoption of effective alternative control measures. A study of the 13 top-valued California crops having a total market value of about $10 billion (Metcalfe et al. 2002) estimated that a total ban of OP insecticides on these crops would result in a loss of over $203 million for growers and consumers.

Qualitative effects include changes to IPM programs that use OP insecticides therapeutically, based on pest monitoring and established treatment thresholds. Other qualitative effects include: positive or negative impacts on beneficial arthropods, depending on the specificity and other properties of the alternative control measure; reduced ability to practice resistance management through the elimination of alternative modes of toxification and the suppression of detoxification mechanisms; and unintended negative consequences to nontarget organisms.

In addition, overall pesticide use may increase if the alternatives are not as effective as the OP insecticide and multiple applications of the alternative insecticide are required to achieve adequate pest control. Overall pesticide use may also increase if the alternative insecticide is highly pest-specific, so that different insecticides must be used for the control of a pest complex that could previously be controlled with a single OP insecticide.

The research and development of control measures to replace OP insecticides must be pursued to maintain an economically viable agricultural industry in California. Some pest control measures are becoming widely adopted as OP uses are lost, most notably the substitution of chloronicotinyl (neonicotinoid) and synthetic pyrethroid insecticides. Further restrictions on the availability and uses of OP insecticides have created market opportunities for new and novel pesticides, and some of these have found significant market niches. Nonchemical approaches, perhaps thought to be less effective or too costly in the past, are becoming preferred choices for some growers. For example, while still a small percentage of total U.S. and California production, the organic industry has experienced tremendous growth in recent years.

The articles in this issue of *California Agriculture* present pest management measures that can be used singularly or in an integrated manner as OP replacement strategies. They include: other synthetic insecticides that already have many labeled uses (see page 11); newly registered and novel synthetic insecticides (see page 29); natural and biological toxins that are registered or exempt from tolerances, including genetically modified crop plants (see page 35); pheromone mating disruption and other semiochemical approaches (see page 16); and biological and cultural control measures (see page 23). The authors of these articles — many of whom provided the pest-management technical expertise for a California Department of Food and Agriculture (CDFA) evaluation on the economic importance of OP insecticides in California agriculture (Metcalfe et al. 2002) — broadly review the nature of these specific controls, their advantages and disadvantages compared to other management measures, current uses and prospects for future use.

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REVIEW ARTICLE

Managing resistance is critical to future use of pyrethroids and neonicotinoids

Frank G. Zalom
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Frank J. Byrne

Synthetic pyrethroids and neonicotinoids are the most readily available alternatives to the organophosphate and carbamate insecticides. Pyrethroids have become widely used in California, and problems with insecticide resistance and nontarget impacts have already been identified. Neonicotinoids are a new class of insecticide with uses only now being realized. Managing insecticide resistance will be crucial to preserving these new materials as organophosphate uses are lost.

Neonicotinoid and pyrethroid insecticides have become important replacements for organophosphates. UC Riverside staff research associate Greg Ballmer uses a micropipette to extract xylem from a grapevine in the Temecula Valley.

Insecticides are often referred to as having a broad or narrow spectrum of activity, depending on the diversity of pest species they kill. Narrow-spectrum insecticides are generally thought of as being less disruptive to biological control and more environmentally benign because of their specificity to a few target pest species. In the presence of a complex pest community, however, use of an insecticide with a high degree of specificity can require additional applications of products that target other taxa.

The ability of organophosphate (OP), organochlorine and methyl carbamate insecticides to control a broad range of insects with a single application led to their widespread use for pest control. With the cancellation of DDT by the U.S. Environmental Protection Agency in 1973, followed by bans on the use of most other organochlorines, agricultural use of the OP and methyl carbamate insecticides became dominant, with more than 200 OP insecticides available worldwide at their peak.

OPs and methyl carbamates are still widely registered for use on California crops and have been regarded as especially important tools for growers of vegetable and fruit crops, which are unique and economically important components of California's agricultural industry. California Department of Pesticide Regulation (DPR 2003) reports of OP usage for 2002 (the most recent data published) indicate that chlorpyrifos, diazinon and malathion are the most widely used OPs, while methomyl and carbaryl are the only two methyl carbamates used to any great extent (table 1).

The widespread use of these products has led to the development of pesticide resistance in many insect populations (Roush and Tabashnik 1990). Their use has also raised concerns about surface-water contamination, resulting in the listing of some California rivers as impaired waterways under the U.S. Clean Water Act. The U.S. Food Quality Protection Act (FQPA) of 1996 has focused particular attention on the human risks of exposure to OPs and has already imposed restrictions on their use (see page 7).

In a recent report funded by the California Department of Food and Agriculture (Metcalfe et al. 2002), pyrethroid and neonicotinoid insecticides were identified as the most likely alternatives to the OPs. Even before the OPs are withdrawn, however, the number of applications of

TABLE 1. Usage of organophosphate and methyl carbamate insecticides in California, 2002

Chemical (trade name)	Pounds a.i.* applied	No. applications
Organophosphates		
Chlorpyrifos (Lorsban)	1,446,547	36,802
Diazinon	689,603	31,757
Malathion	619,811	14,653
Phosmet (Imidan)	405,088	7,533
Dimethoate (Cygon)	332,543	24,355
Methyl carbamates		
Methomyl (Lannate)	321,476	17,216
Carbaryl (Sevin)	256,030	3,354

* Active ingredient.
Source: DPR 2003.

these alternative insecticides is fast approaching that of the OPs in California agriculture (table 2). This is alarming, because it suggests that application of these materials will continue to increase, raising immediate concerns about the potential development of resistance.

Although non-OP alternatives are already available for most crops, phasing out the OPs will require some adjustment to current management programs as suitable replacements among the remaining insecticide classes are sought. Pyrethroids are fast-acting insecticides that kill a broad spectrum of insect pests. They are most often applied as foliar sprays, by air or ground. For a number of crop uses, they are serving as a direct substitute for an OP. All currently registered neonicotinoids in California agriculture are available as foliar formulations and compare favorably with the OPs in terms of efficacy against specific groups of insect pests, impacts on natural enemies, and worker and environmental safety.

Pyrethroids increasingly popular

Pyrethroid insecticides are more stable analogs of the natural insecticides found in extracts from Chrysanthemum flowers *(Tanacetum [Chrysanthemum] cinerariaefolium)*. Research to develop synthetic pyrethroids began in the 1940s to enhance their efficacy, facilitate large-scale production and improve stability. Allethrin (Pynemin) was the first synthetic pyrethroid to be developed and was registered in 1949 for public health and urban uses, primarily against mosquitoes and houseflies. This was considered a first-generation pyrethroid, because it was chemically similar to a component of the natural pyrethrum extract.

Second-generation pyrethroids were registered in the 1960s to control urban insects. Resmethrin was about 20 times more effective than pyrethrum for controlling houseflies and had longer residual activity, but like allethrin was photolabile (containing molecules that break down quickly in light) and therefore unsuitable for outdoor use. Permethrin was the first synthetic pyrethroid with sufficient photostability for agricultural applications.

Permethrin and fenvalerate became the most widely used of the third-generation pyrethroids and were particularly significant for their broad spectrum of insecticidal activity at relatively low rates, as well as their improved photostability, which resulted in residual activity of up to 1 week on foliage. Permethrin (Pounce or Ambush) is still the most widely used pyrethroid in California, and is commonly applied to leafy vegetables and some tree crops.

TABLE 2. Usage of synthetic pyrethroid and neonicotinoid insecticides in California, 2002

Chemical name	Pounds a.i.* applied	No. applications	Common agricultural uses
Pyrethroids			
Bifenthrin	47,443	5,646	Cotton, corn, strawberry, alfalfa
Cyfluthrin	57,524	10,258	Alfalfa, cotton, orange, corn
Cypermethrin and (s)-cypermethrin	306,291	8,326	Lettuce, cole crops, onion, cotton
Deltamethrin	13,001	956	Greenhouse, nursery
Esfenvalerate	30,758	24,623	Almond, cotton, artichoke, stone fruit
Fenpropathrin	34,525	4,012	Cotton, grape, strawberry, orange
Lambda-cyhalothrin	58,381	22,642	Alfalfa, lettuce, rice, tomato
Permethrin	385,403	46,267	Lettuce, celery, spinach, almond
Neonicotinoids			
Acetamiprid	6,632	3,519	Cotton, lettuce, celery, pear
Imidacloprid	224,730	41,924	Lettuce, grape, cotton, cole crops
Thiamethoxam	11,091	2,826	Cotton, tomato, melon, pepper

* Active ingredient.
Source: DPR 2003.

A number of fourth-generation pyrethroids have been registered during the past 20 years, the most commonly used being esfenvalerate (Asana) and lambda-cyhalothrin (Warrior or Karate). Because they are more effective against insects at lower dosages than the third-generation pyrethroids, these contemporary pyrethroids are generally applied at much lower rates (typically 10% of the third-generation rates). The fourth-generation pyrethroids are photostable and relatively nonvolatile, so their residual activity is longer than that of earlier pyrethroids.

Top, **UC Riverside extension entomologist Nick Toscano examines a Coachella Valley grapevine trunk for adult and nymph populations of vine mealybug, part of a field trial of various treatments. *Above*, vine mealybug damages grapevines, causing them to lose vigor and diminishing grape quality.**

Efficacy and cost. Pyrethroids have become the favored insecticide alternatives to the OPs for growers because in many cases, they are a direct substitute in terms of the range of insects killed, treatment timing and residual activity. Perhaps the only arthropod groups for which they are not as effective are soil insects and mites, and certain insects with piercing-sucking mouthparts. The availability of pyrethroids continues to increase as more products are registered for additional California crops, including fruits and vegetables. In general, they are cost-competitive as a direct substitute for the OPs and in some cases are even less expensive.

Toxicity. In addition to efficacy and cost, pyrethroids present a lower risk to workers and applicators, as indicated by oral and dermal LD_{50} data (table 3). LD_{50} is the dose that kills 50% of test animals to which a product is administered and is expressed as milligrams per kilogram of body weight. Pyrethroid toxicity to amphibians, mammals and birds is relatively low compared to the OPs;

Perhaps the most immediate insect-control problem for California agriculture will not be finding a suitable replacement for the organophosphates, but rather to delay the onset of and manage pest resistance to the pyrethroids and neonicotinoids that are replacing them.

however, most aquatic invertebrates and fish are highly susceptible (Smith and Stratton 1986). Acute toxicity expressed as 96-hour LC_{50} values (the concentration lethal to 50% of a group of organisms within 96 hours) for esfenvalerate to juvenile fish was reported at 0.25 micrograms per liter (μg/L)(Werner et al. 2002), while the respective 96-hour LC_{50}s of diazinon are as much as 1,000-fold higher (EXTOXNET 2003). Molluscs are relatively insensitive to both OPs and pyrethroids, but have been shown to bioaccumulate these chemicals, thereby representing a potential hazard to higher trophic levels within the food chain.

Water quality. The off-site movement of pyrethroids, a concern with the OPs in California surface waterways, is generally believed to be minimal due to their hydrophobic chemical properties and generally high soil-adsorption coefficients, which indicate that they will bind to surfaces they come into contact with rather than run off. However, data has recently been collected that found permethrin, esfenvalerate, bifenthrin and lambda-cyhalothrin in 75%, 32%, 25% and 12%, respectively, of sediment samples taken from surface-water bodies in California's Central Valley (Weston et al. 2004). With increases in pyrethroid use likely, this may prove to be problematic in the future (see page 5).

Secondary pests. Beneficial insects and mites are an important component of integrated pest management (IPM) since they can reduce the need for insecticides when present at sufficient densities. Pyrethroids have been shown to seriously affect beneficial arthropods present in agricultural crops, and they are generally not compatible with biological control programs. They also tend to persist for longer periods in the environment and can be especially disruptive when used in perennial crops. Pyrethroid use has been associated with outbreaks of secondary pests such as spider mites in orchards both during the season in which they are applied and possibly in subsequent seasons (Bentley et al. 1987). This will lead to increased use of miticides and other chemical pesticides in order to control these outbreaks.

Neonicotinoids more selective

There are four neonicotinoid insecticides (synthetic chemicals based on the structure of nicotine) currently registered for agricultural use in California — acetamiprid (Assail), imidacloprid (Admire or Provado), thiacloprid (Calypso) and thiamethoxam (Platinum or Actara). Nitenpyram is registered in California for flea control in cats and dogs. Others are under development.

Imidacloprid was introduced in 1991 as the first commercially available neonicotinoid and is by far the most widely used (table 2). Like all neonicotinoids, it is a remarkably potent neurotoxic insecticide, which acts as a nicotinic acetylcholine receptor agonist. The target-site selectivity of imidacloprid and other neonicotinoids is a major factor in their favorable toxicological properties because they act at much lower concentrations in insects than in mammals. Imidacloprid was developed from nithiazine, a heterocyclic nitromethylene that was first reported in 1978. Although it exhibited considerable insecticidal activity, nithiazine was not made commercially available due to its photolability.

Efficacy and cost. The efficacy of the neonicotinoids both as persistent systemic treatments and as less-persistent foliar sprays offers exceptional flexibility that is similar to that of some OPs. For example, imidacloprid is currently available for systemic, seed, soil, chemigation (applied via the irrigation system) and foliar applications. The systemic activity of neonicotinoids enables their integration into California agriculture as a satisfactory alternative to the OPs for the control of sucking insects, as well as some Coleoptera (beetles) and Diptera (flies). However, the neonicotinoids will not control some insect orders — such as the Lepidoptera — as effectively as the OPs, preventing their direct substitution for OPs and pyrethroids in many cases. This characteristic of neonicotinoids is good for resistance management in that growers must utilize other available chemistries for some species rather than relying solely on one insecticide class for controlling all insect pests. One limitation is their cost, which tends to be much higher than either OPs or pyrethroids.

Toxicity. Neonicotinoids share with the pyrethroids a relatively low risk of dermal toxicity to mammals (table 3), and their oral LD_{50}s make them suitable for use on fruit and vegetable crops. As their registered crop uses expand on California's "minor use" or "specialty" crops (generally those grown on 300,000 acres or less), they will likely replace many OPs. Where they have already been registered, such as on lettuce and cole crops, their use is well established (table 2).

Jack Kelly Clark

Left, **xylem is placed in a pressure bomb and will later be tested in the UC Riverside laboratory for neonicotinoid insecticides that kill the glassy-winged sharpshooter, *center.* The insect carries the pathogen that causes Pierce's disease, which has killed vines in the Temecula Valley, *right.***

Water quality. Neonicotinoids are more similar to OPs than pyrethroids in their potential to move through the soil and run off in surface water. The California Pollution Contamination Prevention Act of 1985 established a set of specific numerical values (SNV) for pesticides and required DPR to place active ingredients on a list of candidates as potential leachers if their water solubility value exceeds 3 parts per million (ppm) or if the soil adsorption coefficient is less than 1,900 cm^3/g, and if one of three persistence parameters is exceeded. The three major neonicotinoids currently registered in California all exceed the SNVs and are on the list, suggesting that care is needed when using these products to protect water quality.

Imidacloprid is soluble in water (5.14 g/l), has moderate binding affinity to organic materials in soils (K_{oc} = 262) and a relatively long half-life in soils (365 days). Acetamiprid is also water-soluble (2.95 g/l), has similar binding affinity to organic materials in soils (K_{oc} = 260), but is short-lived in soils (1 to 8 days). Thiamethoxam is water-soluble (3.26 g/l), but has low binding affinity to organic materials in soil (K_{oc} = 43 to 77) and is more persistent (385 to 408 days) than the others. Soil type and irrigation practices will therefore be important considerations for growers in order to optimize neonicotinoid efficacy while preventing possible unwanted environmental effects.

Nontarget organisms. The impacts of neonicotinoids on nontarget organisms remain unclear. For example, there is some controversy over the safety of systemic treatments to both natural enemies and bees that may encounter neonicotinoid residues in nectar and pollen (Schmuck et al. 2001). This is a current area of research to better define specific risks and evaluate mitigation measures if necessary.

Pest resistance is a major concern

The effective deployment of new insecticides within pest management programs should include strategies for delaying the development of pest resistance. The two most common mechanisms conferring resistance to the OP and pyrethroid insecticides are target-site insensitivity and detoxification. Target-site insensitivity arises from a reduced binding between the insecticide and its intended target. The OPs bind to and inhibit the activity of the synaptic enzyme acetylcholinesterase (AChE), resulting in the disruption of the normal transmission of nerve impulses across the synapse. In resistant insects, insensitivity of the AChE to binding by the OP restores synaptic function even in the presence of the OP.

Top: *left,* UC Riverside postgraduate researcher Jian Bi catalogues peppers for an efficacy study of various alternatives to organophosphate insecticides, including neonicotinoids, pyrethroids, insect growth regulators and organic products; *right,* Ballmer collects insects using a suction sampler. Bottom: *left,* an adult potato psyllid; *right,* psyllid damage to a red pepper.

Pyrethroids bind to sites on the sodium channel and in so doing disrupt the transmission of impulses along the nerve axon by holding the channels in an open position (Bradbury and Coats 1989). Pyrethroid resistance occurs when mutations in sodium channel genes reduce the capacity of the pyrethroids to bind effectively, thereby enabling the channels to function normally. Currently, there is no evidence for target-site resistance in neonicotinoids. This is important because target-site resistance can act as a foundation upon which other resistance mechanisms develop. These in turn can disrupt management programs due to cross-resistance to other insecticide classes.

Cross-resistance occurs in an insect when a resistance mechanism selected for in response to exposure to one insecticide also confers resistance to a second insecticide to which the insect has not been exposed. Target-site cross-resistance is very common within individual insecticide classes due to the similarity in binding sites. However, cross-resistance between insecticide classes having different modes of action is viewed as a more serious problem, because insecticides to which an insect has previously been unexposed may be jeopardized through the selective forces of an unrelated insecticide. This can have a serious impact on the development of pest management strategies, particularly when emergency registrations of new insecticides are under consideration as potential control agents. Detoxification mechanisms are an extremely important source of cross-resistance between insecticides that differ in their target sites. There are three broad groups of detoxification enzymes — the carboxy-

TABLE 3. Oral and dermal toxicities of commonly applied insecticides on California crops*

Chemical name	Oral LD_{50} rat; mg/kg	Dermal LD_{50} rabbit; mg/kg
Organophosphates		
Chlorpyrifos	96–270	2,000
Diazinon	1,250	2,020
Dimethoate	235	400
Pyrethroids		
Esfenvalerate	458	> 2,000
Lambda-cyhalothrin	1,593	> 2,000
Permethrin	430–4,000	> 2,000
Neonicotinoids		
Acetamiprid	1,064	> 2,000
Imidacloprid	> 4,870	> 2,000
Thiamethoxam	> 5,000	> 2,000

* Higher LD_{50} values indicate lower oral or dermal toxicity.

Photos: Jack Kelly Clark

***Left,* pyrethroids can be disruptive of natural enemies, such a the western orchard predator mite. *Right,* whiteflies are often the target of neonicotinoid applications.**

lesterases, the cytochrome P450s and the glutathione-S-transferases — and each of these has been implicated in resistance to the OPs and pyrethroids.

Unfortunately, resistance to pyrethroids has already been reported for a number of insect species in California and elsewhere. The neonicotinoids, however, are relatively new to California agriculture, and there has yet to be a substantiated case of resistance arising from their application under field conditions. Continuous laboratory selection of a whitefly population collected from melon crops in the Imperial Valley resulted in 80-fold resistance to imidacloprid, illustrating that resistance genes are present in California whiteflies. Resistance has been documented in field populations of the silverleaf whitefly *(Bemisia)* in Arizona and worldwide in Spain, Israel and Guatemala (Byrne et al. 2003). In the northeastern United States, resistance to imidacloprid was detected in the Colorado potato beetle *(Leptinotarsa decemlineata)* just 2 years after its initial use (Zhao et al. 2000).

The OPs are occasionally used in mixtures with pyrethroids to synergize their activity. The synergistic effect is believed to occur when the OPs inhibit pyrethroid-hydrolyzing esterases, thereby enabling toxic doses of the pyrethroid to accumulate at the target site. Mixtures of the OP acephate (Orthene) and the pyrethroid fenpropathrin (Danitol) were used effectively for whitefly control on cotton, although in recent years reliance on this strategy has suffered due to the development of target-site resistance to the pyrethroid, a mechanism that is not synergizable by the OP. In Arizona, a resistance management strategy was introduced in 1996 to combat whitefly resistance problems. A strategy of incorporating insect growth regulators (IGRs), pyrethroids and nonpyrethroid conventional insecticides in a multistage program proved successful, as documented by a dramatic reduction in the total number of pesticide applications (Ellsworth 1998) and the restoration of susceptibility to synergized pyrethroids and nonpyrethroids (Dennehy et al. 1997).

Delaying the onset of resistance

The ultimate impact to California agriculture of losing OP insecticides will depend very much upon how alternative insecticides are deployed. Perhaps the most immediate insect-control problem for California agriculture will not be finding a suitable replacement for the OPs as insecticides, but rather to delay the onset of and manage pest resistance to the pyrethroids and neonicotinoids that are replacing them.

The pyrethroids have an established history of use in California and much is known about their efficacy as pest control agents, as well as their negative impacts on nontarget species and the environment. They are prone to resistance, and a concern is that they may face additional problems with resistance without their OP synergists. By contrast, the neonicotinoids are a new class of insecticide and their influence in pest control is only now being realized as new products are developed and new uses identified. There is no evidence of resistance to neonicotinoids at present in California agriculture, although resistance has been documented elsewhere. It will be necessary for growers and pest management specialists to use both classes of materials judiciously and in combination with other alternatives as feasible, to avoid resistance problems and maintain environmental quality.

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REVIEW ARTICLE

Pheromone mating disruption offers selective management options for key pests

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Pheromones are used by insects (and numerous other species) to communicate. When these messages are disrupted, pest insects fail to reproduce and mate. A sprayable formulation of microencapsulated pheromone is applied by helicopter.

The direct management of insect pests using pheromones for mating disruption, or "attract and kill" approaches, can provide excellent suppression of key lepidopteran pests in agriculture. Important successes to date include codling moth in pome fruit, oriental fruit moth in peaches and nectarines, tomato pinworm in vegetables, pink bollworm in cotton and omnivorous leafroller in vineyards. Large-scale implementation projects have yielded significant reductions in pesticide use while maintaining acceptably low crop-damage levels. Because of some difficulties with high populations of pests, these programs should not be viewed as stand-alone strategies but rather as one tactic within a suite of integrated pest management options.

Pheromones, defined as chemicals secreted externally by an organism to send information to members of the same species, are used extensively by insects to communicate with each other. Pheromones may signal information as diverse as the sexual receptivity of the producer, perceived dangers or the dominance of an individual in a colony. Researchers have interfered with these communication systems as a means to selectively control or manage pest species in agricultural and forest systems.

A variety of approaches employ pheromones to manipulate or disrupt the natural behaviors of insects, such that population levels are reduced and crop damage diminishes. These strategies include mass trapping efforts over huge expanses of forests or plantations, to the regional disruption of mating processes by pests, to smaller "attract and kill" approaches in specific fields. While many different groups of insects use pheromones, most successes to date have been with lepidopteran pests (butterflies and moths); these successes have allowed for more biologically intensive approaches to control pests.

Advantages and disadvantages

Many advantages of pheromone-based pest management systems are common to other biologically based management approaches, including virtually no detectable residues for some dispensing systems, negligible health risks, a more rapid registration process and no accumulation in wildlife or groundwater. Additional benefits include reduced worker re-entry or preharvest intervals and limited impacts on other management practices, such as irrigation scheduling. Pheromone-based mating disruption has also been identified as a strong tool for managing insecticide resistance. Whereas resistance to pheromones applied over broad areas might be expected, there is only one documented case of resistance, when an incomplete pheromone blend was deployed against the tea tortrix in Japan. However, the correction of the blend eliminated the problem (Mochizuki et al. 2002).

A key benefit of pheromone-based programs is that they are highly selective. Typically, only the primary target species responds to the pheromone, and nontarget effects on biological control agents within a field or outside of a cropping system are not observed. The use of pheromones against key pests does not result in outbreaks of secondary pests or pest resurgence, creating opportunities for the biological control of other pest species.

However, the high degree of selectivity may also be a significant obstacle to large-scale implementation, in cases where secondary pests become a problem as insecticides are eliminated. Insecticide applications targeting the key pest sometimes inadvertently control other pests as a collateral benefit. For example, outbreaks of leafrollers (such as *Pandemis pyrusana*) have been reported in California apple orchards utilizing pheromone-disruption programs to control codling moth without organophosphates (OPs)(Walker and Welter 2001). Similar results were seen in apple orchards under a variety of programs using the mating disruption of codling moth (Nicholas et al. 1999);

when the OP azinphos-methyl was removed, populations of the wooly aphid *(Eriosoma lanigerum)*, lightbrown apple moth *(Epiphyaas postvittana)*, San Jose scale *(Quadraspidiotus perniciosus)* and budworm (*Helicoverpa* spp.) increased.

Other possible limitations include: (1) the lack of an identified pheromone for some pest species; (2) high development and production costs; (3) requirements for specialized application techniques or equipment; and (4) the need to supplement the pheromone program in high pest-pressure situations. Pheromone programs are most effective with low to moderate population densities, whereas high-pressure situations in which damage from previous years exceeded 1% to 2% often require supplemental insecticide applications to prevent commercial damage. Treatment thresholds have been developed using modified pheromone lures, but they vary between crops and regions. Mating disruption, like most other pest management strategies, needs to be viewed within the context of an entire pest management system rather than as a stand-alone program.

Monitoring the target pest with pheromone traps also can become problematic, because the pheromones used to disrupt mating will also prevent moths from locating traps. Even in conventional fields, pheromone traps are rarely used as the sole indicator of pest problems; rather, they are often used in combination with other approaches, such as direct damage assessments. The use of high-dose lures that still attract some moths even under mating disruption has proven useful for tracking the flights of some pests (such as codling moth) or as a supplemental risk-assessment tool. Other species, such as oriental fruit moth *(Cydia molesta)*, do not exhibit this response. However, it may be possible to develop nonpheromonal attractants for use in mating disruption (Light et al. 2001).

Approaches in the field

Mass trapping is a direct control strategy in which large numbers of pests are captured and removed. This strategy has been successful in controlling large weevils in tropical crops such as oil palms, palmito palms (grown for hearts of palm), plantains and bananas. In oil palm plantations in Central and South America, the palm weevil *(Rhyncophorus palmarum)* is a vector of the lethal red ring nematode. Pheromone-based mass trapping using one trap per acre is now the principal control method (Oehlschlager et al. 2002). The key biological factors behind these successes appear to be the relatively long life and slow reproductive rate of the weevils, and the fact that the aggregation pheromones attract both sexes. Success is critically dependent on efficient mass-trapping to remove weevils faster than they can reproduce.

Pheromones may signal information as diverse as the sexual receptivity of the producer, perceived dangers or the dominance of an individual in a colony. Researchers have interfered with these communication systems as a means to selectively control or manage pest species.

In situations with other insects that do not have these biological characteristics, and particularly with sex pheromones that only attract one sex, mass trapping is generally less effective despite some larger projects collecting billions of individuals (Ryan 2002). It has been successful with smaller or confined populations such as those found on islands (the sugarcane wireworm [*Melanotus okinawensis*]) or with small, localized infestations of introduced pests targeted for eradication efforts, such as the white-spotted tussock moth *(Orgyia thyellina)* in New Zealand.

Pheromone-based mating disruption, which is the most commonly used approach, may work via a number of overlapping mechanisms that interfere with mate location and reproduction. Obviously, if males are prevented from locating or copulating with sufficient numbers of females, pest populations will decline. This approach works without the direct mortality of target individuals, preventing offspring and subsequent damage.

Attracticides, or "lure and kill" strategies, combine an attractant with an insecticide, eliminating individuals that contact the lure. Many limitations of mass trapping also apply to programs that target males only. Depending on how the system is implemented, it may also interfere with the male's location of

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By carefully monitoring crop damage and insect populations, and applying pheromones to disrupt mating, growers have successfully protected orchard crops from insect pests. *Left*, former UC staff researcher Jeannine Lowrimore counts codling moths in a trap; *top right*, shoot-strike damage; *bottom right*, male peachtree borers in a pheromone trap.

Jay Brunner/Wash. State Univ.

Pheromones can be applied using a variety of dispensers, including *(clockwise from top left)*: microencapsulated pheromones, sprayed like insecticides; hand-applied dispensers, with a reservoir and permeable membrane to regulate release; hollow fibers; and twist-tie ropes.

females through false trail-following, as well as the primary effect of the male's attraction to insecticide-laced baits.

Mechanisms of mating disruption

Limitations to developing mating disruption programs include a lack of understanding about the mechanisms of mating disruption for different types of dispensers, the biological or behavioral characteristics of the target pest, and how pheromones move and distribute themselves within agricultural systems (Cardé and Minks 1995; Sanders 1997). Surprisingly, the principle mechanisms of action for even some of the most successful programs (such as codling moth in pome fruit) are unclear.

Researchers have shown that the pheromone plume is not a uniform cloud, but rather a series of filaments of pheromone interspersed with pockets of zero to low concentrations due to natural turbulence in the air (Sanders 1997). The male is exposed to a series of rapidly changing concentrations, which requires both the interpretation of the odor and a resetting of the antennal receptors within milliseconds to perceive the next pheromone molecule (Leal 2003). The male proceeds to fly upwind in a series of surges interspersed with crosswind casting when it detects pockets of air with reduced concentrations of pheromone. For most species, a turbulent plume with pockets of high and low concentrations is required for proper upwind flight; if a column of air is filled uniformly with pheromone, then the sensory structures may fatigue and no longer respond to the pheromone.

Sanders (1997) and Cardé and Minks (1995) have reviewed different mechanisms of mating disruption. Sensory adaptation is a reduction in the firing rates of the sensory structures after prolonged exposure to the pheromone, whereas habituation is a reduction in the insect's response to the pheromone due to some change in the central nervous system. Both of these mechanisms can generate the same nonresponsive outcome. Different species respond differently to prolonged exposures in pheromone-treated fields. Habituation, which may result in arrested movement, has been proposed as a possible mechanism for high-dose exposures from devices that periodically release pheromones in large aerosol puffs (puffers), or in close proximity to passive dispensers. Both can occur with either complete or partial pheromone blends.

The camouflage of a female's pheromone plume presumes that the overlapping plumes from multiple pheromone dispensers generate a "fog" of pheromone, so that the males can no longer distinguish the pheromone emitted by a female from the elevated background. The false-trail-following mechanism produces direct competition between calling females and synthetic dispensers, as males spend time and energy locating "false females." This diversion of the male's activities results in either a decrease in the proportion of females mated or a delay in mating.

The proposed mechanisms by which mating disruption might work are not mutually exclusive, and several mechanisms may be important for the same insect under different conditions. For example, Cardé et al. (1998) demonstrated that the mating disruption of the pink bollworm occurs from a combination of mechanisms including camouflage, competition between pheromone dispensers and females, habituation, and some advancement of the rhythm of the male's response to the female's pheromone, which may result in asynchrony in sexual behaviors.

The use of antagonistic compounds, agonists, pheromone mimics and synergists is broadly grouped under the term *parapheromones*, loosely defined as anthropogenic compounds structurally related to natural pheromone compounds that affect the behavior or physiology of the insect's communication system (Renou and Guerrero 2000). This group includes compounds of plant origin used to annihilate (with an attractant plus a lethal agent) the males of important dipteran pests, such as bait sprays for fruit flies or walnut husk flies. While parapheromones alter neural activity, change insect behaviors and depress or synergize trap capture, their utility in the field for management purposes has received limited testing and remains highly variable.

However, studies have also shown that even in programs with minimal crop damage, significant mating may still occur. Alternative mechanisms are being explored that focus on the effects of delaying mating rather than its complete suppression. Delays in mating by virgin females or males has been shown in multiple species to result in depressed egg-laying and increased sterility of the eggs laid (Jones and Aihara-Sasaki 2001; Fadamiro and Baker 1999). Therefore, exclusive focus on the complete prevention of mating may not be warranted. Mating disruption still remains a useful term if disruption is to include both the prevention of mate location and mating, and factors that interfere with or delay the normal mating processes.

Pheromone-dispensing technologies

A variety of dispensing technologies have shown promise and success under commercial conditions and are now available to growers. Each varies in terms of ease of application, cost and the mechanism of disruption. Challenges for pheromone dispensers include protecting components from degradation by environmental factors and the uniform release over time of different types of compounds (such as aldehydes, alcohols or acetates) with varying chemical and physical properties.

MECs. Microencapsulated pheromones (MECs) are small droplets of pheromone enclosed within a polymer capsule, which controls the pheromone release rate. The capsules are small enough to be applied as suspensions with the same commercial equipment used to spray insecticides. The effective field longevity of these materials generally ranges from days to weeks depending on climatic conditions, capsule size and properties, and the chemistry of the pheromone components. However, the material is applied directly to the commodity, an important consideration in food crops.

Hand-applied dispensers. Larger, hand-applied dispensers include systems with an impermeable reservoir fitted with a permeable membrane for regulating pheromone release, and analogous laminate dispensers that consist of a central pheromone-containing core sandwiched between two polymer films. These dispensers can be cut into various shapes and sizes ranging from larger, hand-applied dispensers to smaller, confetti-like flakes that can be applied by specialized ground or air applicators. Pheromones can be mixed into paraffin wax or aqueous paraffin emulsions and applied directly to the tree using hand-dispensers (Atterholt et al. 1999) or potentially in modified sprayers.

Hand-applied dispensers also include pheromone-impregnated polymer spirals, and twist-tie "ropes" that consist of a pheromone-filled plastic tube with a wire spline along one side. The wire allows these dispensers to be twist-tied directly to the plant or hung indirectly with a clip. New technologies using alternative "rope dispensers" without a spline have been developed as well. The larger reservoirs of the hand-applied dispensers (ropes, laminate systems, spirals) allow for effective lifetimes of 60 to 140 days, such that single applications early in the season may suppress mating all season.

Hollow fibers. Hollow fibers have been employed since the 1970s in mating disruption programs. The fibers consist of a short, impermeable plastic tube that is sealed at one end and filled with pheromone. After an initial burst of pheromone from the fiber, this technology has a relatively constant emission rate over time. These fibers are often combined with an adhesive material during application and may require specialized ground or air equipment to apply.

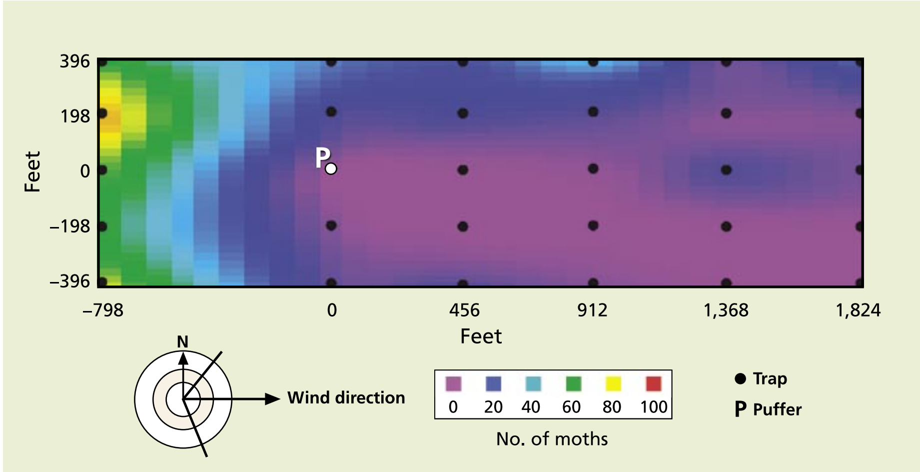

Fig. 1. Downwind area of trap suppression by a single puffer with a 12-hour "on" cycle, placed in a walnut orchard coincidental with the release of a uniform grid of sterile, marked codling moth. Number of moths is 5-day cumulative trap-catch total.

High-emission dispensers. High-emission dispensers were developed to emit larger quantities of pheromone and use fewer dispensers per acre to cut down on labor costs (Shorey and Gerber 1996; MafraNeto and Baker 1996). The only commercially available dispenser of this type at this time is the Suttera puffer. The puffer uses a pressurized aerosol can filled with a pheromone, which dispenses metered puffs of pheromone at fixed time intervals (such as every 15 minutes). The number of units per acre varies depending on orchard size and patterns of distribution, but approximately one-half to one dispenser per acre is typical for codling moth in pears.

Recent research attempting to define the effective area of trap suppression of codling moth, using uniform releases of sterile moths, revealed a surprisingly long plume that was typically greater than 1,500 feet long and between 300 and 500 feet wide (fig. 1). In addition, researchers are beginning to test the possibility of using large, passive-release devices consisting of polymer bags loaded with large doses of pheromones (Mahr and Baker 2001). These devices are intended to work in the same general way as puffers, but with no batteries or moving parts they are potentially more reliable.

Current uses to control insects

Pheromone-based devices have achieved the successful control of insect pests in almost all types of agriculture, including perennial orchards, vineyards, annual vegetables and fiber crops. The following five insect pests have enjoyed historical and recent successes with pheromone-based management systems.

Codling moth. A recent success involves the management of codling moth in pear and apple orchards in California and the Pacific Northwest (Calkins and Faust 2003)(fig. 2). In 2001, the mating disruption of codling moth was used on about 135,000 acres of pome fruit, or roughly 45% to 50% of the acreage from the Sacramento Valley to the Pacific Northwest. Adoption rates in southern

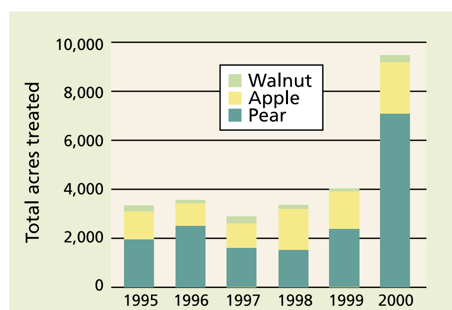

Fig. 2. Codling moth pheromone applications in California in walnuts, apples and pears. To show use trends rather than absolute rates, data includes all delivery technologies and multiple applications to the same acre within a year. Sources: UC Integrated Pest Management Web site, www.ipm.ucdavis.edu; California Department of Pesticide Regulation pesticide-use tracking data.

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In Lake County, 15 pear growers utilized high-dose "puffer" dispensers on about 1,300 acres. The high-dose aerosol cans, *inset,* are hung high in trees, releasing the pheromones at regular intervals.

apple-growing regions are lower due to higher pest population levels, presumably the result of more generations per year. While the dominant release device from 1995 to 2000 was hand-applied dispensers (Isomate C+ rope dispensers and Checkmate CM laminate dispensers), others such as puffers were successfully used on more than 1,300 acres of pears in Lake County.

The use of mating disruption in pome fruit accelerated after the development of the first such areawide program in the Randall Island region of the Sacramento River Delta in 1993. Five growers and their pest control advisors committed 760 contiguous acres to a long-term program to reduce codling moth populations over time, using a combination of mating disruption and reduced insecticide. Codling moth populations in an organic apple orchard directly across the river plus additional conventional sites were used for comparison.

In the Randall Island project, population levels in pheromone-treated areas — as documented by mean trap counts — were reduced over the 6-year period to less than 10 moths per trap from highs of about 80 moths per trap (fig. 3). Fruit damage was held to less than 1% in all years with final damage levels for 1998 to 1999 of less than 0.1%. The number of insecticide applications for codling moth was reduced 75%, from an average of four to approximately one per season.

This pattern was repeated with four additional areawide sites, initiated by a team of entomologists from UC, Oregon State University, Washington State University and the U.S. Department of Agriculture's Agricultural Research Service in Wapato, Wash. Ultimately, 17 additional sites were established in four Western states. Although the areawide research programs are no longer active, the infrastructure and momentum developed have allowed the approach to flourish. Studies have shown that codling moth also can be controlled in walnuts with hand-applied dispensers in smaller, more limited trials, but program costs were higher than conventional programs given the high costs of application to larger-canopied trees (Grant et al. 2003). A similar result was achieved in an areawide program in Lake County by Cooperative Extension, local pest control advisors and growers using pheromone "puffers" on more than 1,300 acres owned by 15 growers.

Tomato pinworm. The mating disruption of tomato pinworm *(Keiferia lycopersicella)* was originally developed using hollow fibers in the 1970s and 1980s (Van Steenwyk and Oatman 1983). It has been particularly successful in Mexico, where conventional insecticide programs were failing because of extraordinary levels of resistance that jeopardized the whole industry by the late 1980s (Trumble 1997). Some damage suppression was achieved in cherry tomatoes, but damage levels were still variable and excessive in both conventional insecticide and pheromone-treated plots. A pest management program was developed to address resistance issues and provide a more sustainable system, while considering its overall economics. For winter and spring plantings, conventional sites suffered excessive damage of 75% to 90%, while damage was reduced to 33% to 35% in the IPM plots.

Overall economic evaluations demonstrated substantial economic returns from the IPM program compared to conventionally treated plots. Pheromone treatment remains relatively local and site-specific in California given that tomato pinworm is a greater pest in fresh-market than processing tomatoes. Newer products, including hand-applied or sprayable formulations, have been introduced. However, the use of the tomato pinworm mating-disruption program was fairly flat from 1995 until 2000, when an increase occurred (fig. 4).

Pink bollworm. Pink bollworm *(Pectinophora gossypiella)* has been the target of an intensive, long-term and successful mating-disruption effort (Staten et al. 1997) in both the United States and abroad. A variety of strategies have been employed, including applications of hollow fibers, chopped laminate flakes, sprayable microencapsulated pheromone, twist-tie ropes or laminate membrane dispensers. Problems with successful mating disruption in fields with high moth populations were detected and supplemental control tactics were used. Combinations of sterile insects and mating disruption were implemented in large-scale programs in the Imperial and Mexicali valleys.

Successful mating disruption in the late 1980s in the Coachella Valley resulted in significant decreases in insecticide use (7.3 applications in 1985 to no treatments in 1988). However, the immigration of mated moths from the Imperial Valley to the Coachella Valley in 1989 appears to have resulted in decreased program efficacy. The isolation and areawide suppression of populations improved the efficacy of the mating disruption program, similar to later experiences with codling moth. A recent, interesting twist is the introduction of transgenic cotton with the Bt gene, which has been reported as highly effective against pink bollworm. Mating disruption has declined with

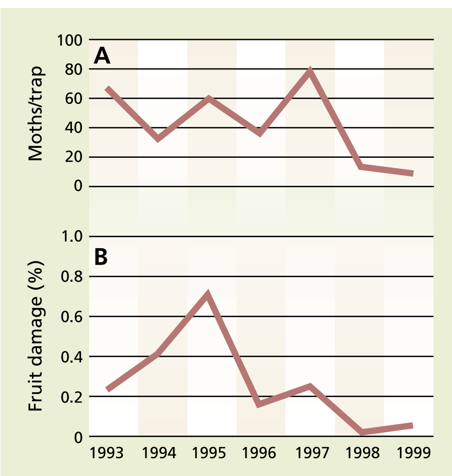

Fig. 3. Codling moth (A) trap totals and (B) damage levels for the season in pheromone-treated plots in the Randall Island project.

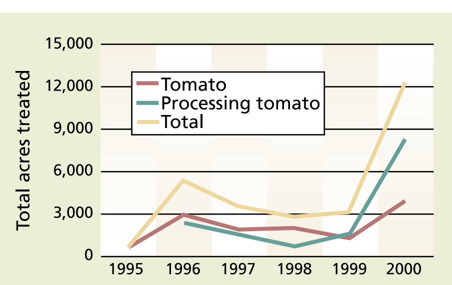

Fig. 4. Tomato pinworm pheromone use in California for processing and fresh-market tomatoes. Data from DPR includes all delivery technologies and multiple applications to the same acre within a year. Sources: see figure 2.

the introduction of Bt cotton, except in areas under the pink bollworm eradication program that are not using transgenic cotton.

Oriental fruit moth. Mating disruption has been used worldwide to control oriental fruit moth in stone fruit, peaches and nectarines using both hand-applied and sprayable formulations (Pickel et al. 2002). In 1995, a series of replicated field plots was established in California to evaluate three hand-applied dispensers (laminate, membrane and rope dispenser) in peach orchards. Season-long control was achieved, with approximately 34% of the orchards having no detectable damage and 63% having less than 3% damage, the current processor standard. However, typically one orchard out of 21 in each year had damage in excess of 3%, which again reinforced that mating disruption in orchards with high moth populations needs to be supplemented with other control strategies. Overall full-season costs for the pheromone program were significantly higher than for conventional treatments, such that growers developed a modified program using a single application of the hand-applied pheromone dispensers supplemented with insecticides later in the season. The partial pheromone program appears to be more cost effective at this time.

More recently, both puffer-type dispensers and sprayable microencapsulated formulations have seen some use. Oriental fruit moth is an easily disrupted pest, resulting in a large increase in applications from 1995 to 2000 (fig. 5). Increased adoption rates will depend on growers' perception of risk from oriental fruit moth, the availability of effective, less expensive insecticide alternatives, and the complex of pests within the orchard.

Omnivorous leafroller. The mating disruption of omnivorous leafroller with hand-applied or sprayable formulations has increased since 1998 in California vineyards, with more than 35,000 acre-applications made. Given that this pest is only important in the state's warmer grape-growing regions, the need for pheromones is geographically

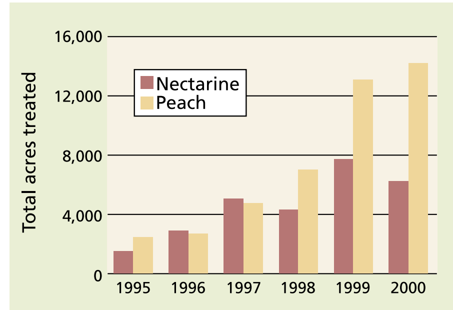

Fig. 5. Oriental fruit moth pheromone applications in California peaches and nectarines. Data from DPR includes all delivery technologies and multiple applications to the same acre within a year. Sources: see figure 2.

restricted. Sprayable formulations may be preferable to address more-local or less-severe infestations of omnivorous leafrollers, a pest that is unpredictable in distribution and severity.

Future directions

While mating disruption provides an excellent management option for reducing insecticide use, it often requires supplemental insecticides to control high pest populations. The successful implementation of mating disruption will require curative, rapid treatments to address increasing or unexpected population surges. As outlined in Metcalfe et al. (2002), the implications of eliminating OP insecticides will depend on the existence of alternative strategies, yet the implementation of pheromones may also require development of selective insecticides as supplements.

Programs are being developed to address other lepidopteran pests in systems for which the key insects may be managed by pheromones or other selective management tools. As key pests like codling moth come under control, research is under way to improve the mating disruption of other orchard pests, such as the oblique-banded leafroller *(Choristoneura rosaceana)* and Pandemis leafroller *(Pandemis pyrusana).* Research is also ongoing in programs that have had partial success, such as for navel orangeworm *(Amyelois transitella).* Opportunities with stored-product pests such as the Indian meal moth *(Plodia interpunctella* [Hubner]) or Angoumois grain moth *(Sitotroga cerealella)* are being explored (Fadamiro and Baker 2002). While most successes have been with lepidopteran insects, research in other insect orders — such as Heteroptera (e.g., stink bugs) or Coleoptera (beetles) — is promising (McBrien et al. 2002; Millar et al. 2002).

Some pests are highly mobile and better suppressed at regional rather than local scales. Coordinated areawide efforts have been much more effective than patchworks of treated and untreated areas. Newer formulations such as puffers, attract-and-kill formulations and sprayable formulations are offering opportunities to increase program flexibility, mix strategies and reduce costs.

Perhaps the greatest challenges lie with understanding the mechanisms of mating disruption systems for different target species and dispensers, which will allow the design of better applications and protocols. Finally, the implementation of mating disruption may require a shift in the scale at which growers, pest management consultants, extension specialists and university researchers approach management systems, given that overall program performance is strongly correlated with large-scale, multigrower implementation efforts.

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REVIEW ARTICLE

Biological and cultural controls...

Nonpesticide alternatives can suppress crop pests

Nicholas J. Mills
Kent M. Daane

Biological controls (the use of natural enemies) and cultural controls (the modification of cropping practices) provide valuable alternatives to organophosphate insecticides (OPs) for the suppression of major arthropod crop pests in California. We discuss the successes and limitations of these two approaches with regard to tree fruits and nuts, vines, and field and row crops. For example, a historic success story is that the cottony cushion scale remains innocuous in citrus production, more than 100 years after its successful suppression by the vedalia beetle. More recently, growers' use of groundcovers and road maintenance helps keep dust down on orchard roads to limit the buildup of web-spinning mites, and good vineyard management is now synonymous with cultural controls for grape pests. Although such alternatives may not always be as effective and predictable as conventional insecticide programs, recognition that partial suppression can greatly reduce the need for OPs will lead to the more widespread adoption of alternatives.

Biological control has a long and rich history in California, beginning with the importation of the vedalia beetle for cottony cushion scale in 1889. *Above,* some of the UC pioneers of biological control and integrated pest management on an insect collection trip in Palm Canyon in 1948. From left to right: (top row) Huffaker, Fisher, Basinger; (middle row) Bartlett, Hagen, Smith, Sellers, Huges, Compere, Steinhaus; (bottom row) Flanders, Finney, Fleschner, Timberlake, Dietrick, DeBach. *Right,* cottony cushion scale was featured in a pest identification manual for California published in 1888.

Biological and cultural controls can provide alternative strategies to pest management tactics that rely heavily on broad-spectrum, neurotoxic insecticides, particularly the organophosphates (OPs). Biological control suppresses pests via the action of their living natural enemies. Categories of natural enemies, in order of frequency of use in biological control, include: parasitoids (parasitic wasps and flies that require only a single host in which to complete their development); predators (insects, spiders and predatory mites that must consume many prey individuals to complete their development); pathogens (bacteria, fungi and viruses); parasites (soil-inhabiting entomopathogenic nematodes); and antagonists (less damaging competitors).

Three broad categories describe how natural enemies are used in biological control: classical biological control, augmentation and conservation. In classical biological control, host-specific natural enemies are imported from the exotic pest's region of origin. On average, a new invasive pest has arrived in California every 2 months during the past decade (Dowell 2002) and, with increasing global trade and travel, this rate seems likely to continue or even increase. In the best-case scenario, the imported natural enemy will establish and provide long-term suppression at low pest densities. A historic and stellar example is the 1889 importation to California of the vedalia beetle from Australia to control cottony cushion scale, which was devastating the citrus industry.

In the second approach, when natural enemies of either exotic or indigenous pests are unable to persist year-round or to build populations quickly enough to suppress pest damage, their numbers can be augmented through the periodic release of commercially produced natural enemies. The inoculation of small numbers of natural enemies can be used to improve colonization at critical periods for season-long pest suppression. Likewise, the inundation of large numbers of natural enemies can be used for immediate suppression, but often without a longer-lasting impact.

The third approach involves the conservation of natural enemy populations of both exotic and indigenous pests through habitat manipulation or the alteration of crop production practices. Natural enemies are often limited by the availability of essential resources such as nectar or overwintering sites, and the landscape within or surrounding a crop can have a major impact on the effectiveness of biological control among sites and regions. In addition, natural enemies often have a lower tolerance to many pesticides. As such, conservation tactics include habitat

The economic benefits of classical biological controls are evident from the multitude of historically important pests now held at low densities and all but forgotten.

enhancements for natural enemies and the use of selective pesticides.

Cultural controls include the various means by which the crop can be made less attractive, less available or less palatable to pests. The time frame for the effectiveness of cultural controls can range from a single harvest to the more long-term suppression of pest activity.

There are six key approaches to cultural control, presented here in order of frequency of use. Sanitation is the removal of residual populations of pests from crops, often during winter. Planting and harvesting dates can be altered to avoid coincidence with periods of high pest activity. Crop rotation, particularly effective against soil pests, displaces crops on an annual basis from pests with poor dispersal capabilities. Trap crops are used to attract colonizing pests into perimeter plantings where they can be readily destroyed by insecticide treatment or crop destruction. Diversification of the crops grown within and between fields can be used to reduce the attractiveness of a crop and the frequency of pest colonization. Nitrogen or irrigation levels can be manipulated to influence the susceptibility of a crop to pest damage.

We discuss some of the successes and limitations of these biological and cultural practices in tree fruits and nuts, vines, and field and row crops, as potential alternatives to OP insecticides.

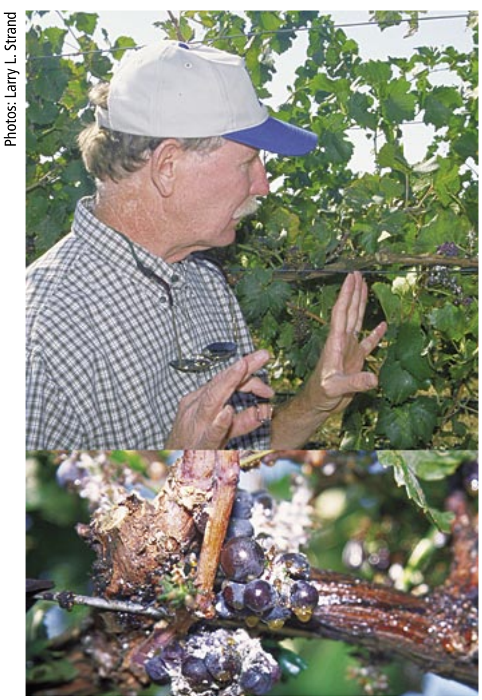
Successes in tree fruits and nuts

Classical biological control. There are numerous examples of successful biological control for the long-term suppression of exotic pests by imported natural enemies in tree fruits and nuts. The cottony cushion scale remains innocuous in citrus production, more than 100 years after its successful suppression by the vedalia beetle. Illustrating how consistent this control has been, flare-ups of cottony cushion scale occurred only after insect growth regulators applied to control California red scale caused the disruption of vedalia beetle pupation and egg hatch (Grafton-Cardwell and Gu 2003).

Other citrus pests — including California red scale and purple scale in coastal areas, woolly and bayberry whiteflies, and citrophilous, Comstock and longtailed mealybugs — have long been suppressed through the action of imported parasitoids and predators. The olive scale, once a ubiquitous and destructive pest, is seldom encountered in California olive groves due to the effective action of two complementary parasitoids, *Aphytis paramaculicornis* and *Coccophagoides utilis*. Similarly, walnut aphid was considered the most important pest of walnuts before the importation of the parasitoid *Trioxys pallidus* in 1969, and is now only an occasional problem when pesticides used against other pests disrupt the parasitoid.

The great advantage of classical biological control for tree fruits and nuts is that it can provide sustained control of exotic pests without the need for further intervention. The perennial nature of these crops, and their low level of seasonal disturbance for management and harvesting, provides a more favorable environment for natural enemy persistence and pest suppression. One drawback is that not all invasive pests of tree fruits and nuts have provided the same dramatic results. The best successes have occurred with indirect pests, such as aphids, scales and whitefly, which do not damage the harvestable part of the crop; successes against direct pests, such as fruit or nut borers, have been more limited. However, all exotic pests are potential targets for classical biological control, and even partial suppression can significantly reduce the frequency and extent to which OPs need to be used.

Photos: Larry L. Strand



In many crop systems, the success of natural enemies relies on the use of least-toxic or narrow-spectrum insecticides. *Top,* Walt Bentley of the UC Statewide Integrated Pest Management Program investigates the use of mating disruption for the vine mealybug, *bottom*.

Augmentation. The most effective program involving periodic releases of commercially produced natural enemies in tree fruit and nut crops is the use of the parasitoid *Aphytis melinus* for control of California red scale in citrus (Collier and Van Steenwyk 2004). Approximately 5,200 parasitoids are released per acre every 2 weeks from mid-February to mid-August to provide consistent reduction of red scale in the San Joaquin Valley. Augmentation of *A. melinus* has been a commercially viable program in citrus with costs comparable to the use of OPs, but it can be rendered ineffective by disruption from broad-spectrum pesticide sprays for thrips, soft scales or glassy-winged sharpshooter. In this regard, for coastal citrus the parasitoid *Metaphycus helvolus* has been released in combination with *A. melinus* to provide additional suppression of black scale.

Among other tree fruit and nut crops, experimental releases of the egg parasitoid *Trichogramma platneri* for the suppression of codling moth in pears and walnuts have shown that four weekly releases of 200,000 parasitized eggs per acre each generation can reduce damage by 60% for moderate populations of codling moth (Mills et al. 2000). In addition, releases of commercial predatory mites *(Galendromus helveolus* and *Neoseiulus californicus)* have proved effective against the persea mite in avocado. A minimum of 2,000 predatory mites must be released per tree when 50% of the leaves have one or more motile stages of the persea mite present (Hoddle 2002).

Conservation. Although cover crop management is considered important for the conservation of natural enemies in orchards, there is little clear evidence that natural enemies active on the orchard floor suppress pests in the orchard canopy. In contrast, the use of selective pesticides to preserve naturally occurring biological control has been the single most effective approach to conservation biological control in tree fruit and nuts. The majority of natural enemies are negatively affected by OPs and other neurotoxic insecticides, so switching to more selective products can often lead to a substantial reduction in damage due to secondary pests (see page 29). Without insecticide disruption, two-spotted and Pacific spider mites are under effective natural control in most deciduous tree fruit and nuts through the action of western predatory mites, other predaceous mites and predatory beetles *(Stethorus picipes)*.

Another example of effective naturally occurring biological control is that of citrus thrips in citrus orchards. The predatory mite *Euseius tularensis*, together with other generalist predators, often provide effective suppression of citrus thrips — particularly in Valencia, but also in navel oranges — unless disrupted by insecticide sprays. Similarly, the use of pheromone mating disruption to replace OP sprays for codling moth management in apples and pears in the Western region has led to substantial economic savings on treatments for secondary pests due to the enhanced activity of indigenous natural enemies (see page 16).

Cultural control. Sanitation is the most important form of cultural control in tree fruit and nuts. Sanitation of overwintered "mummy" nuts in the tree, by shaking or hand-poling, and on the ground, by disking or flail mowing, is of particular importance for suppression of navel orangeworm in almonds, pistachios and walnuts. In addition, harvesting as soon as possible after hull-split can significantly reduce nut damage. These two approaches, if used correctly, can often provide effective control. Similarly, the removal of remaining and rat-tail fruit (small, thin fruit resulting from secondary bloom that hang onto the trees into late summer) after harvest has been shown to reduce overwintering codling moth populations in pears.

Maintaining a groundcover and using water on roadways to reduce dusty conditions in orchards can also be very effective in reducing the buildup of web-spinning mites. In addition, the avoidance of water stress can prevent high population densities, as water stress leads to increased reproduction in mites.

Examples from vineyards

Classical biological control. Despite a 50-year history of research and development of biological control systems in California vineyards, there are few successful examples of imported natural enemies (Flaherty and Wilson 1999). However, the partial successes from vineyards provide some important insights for classical biological control.

In the 1950s, the wasp *Apanteles harrisinae* and the parasitic fly *Ametadoria misella* were imported to suppress the western grapeleaf skeletonizer. While neither parasitoid effectively reduced skeletonizer populations, nearly 40 years later, *A. misella* was shown to be an important vector of a virulent granulovirus, which is now part of effective biological control for skeletonizer. In the 1980s, egg parasitoids, which were originally identified as *Anagrus epos*, were imported from Arizona, New Mexico and Mexico to control the variegated grape leafhopper. A later taxonomic revision found that the imported parasitoids were a complex of closely related *Anagrus* species, each with slight differences in their geographic range, and none of which were *A. epos*, including the *Anagrus* commonly found in California vineyards (Triapitsyn 1998)!

Jack Kelly Clark

Some biological control agents can eat others, often referred to as "intraguild predation." Jay Rosenheim, *top*, UC Davis associate professor of entomology, showed that some predators such as the assassin bug, *bottom*, will feed on other predators.

In the 1990s, a parasitic wasp, *Pseudaphycus flavidulus*, was imported to control obscure mealybug in Central Coast vineyards. Although it can be an effective natural enemy, the invasive Argentine ant disrupts its potential impact. This example highlights the importance of effective competition from natural enemies after release (Rosenheim and Wilhoit 1993). Currently, one of California's larger biological control programs is being conducted for the glassy-winged sharpshooter, which vectors the bacteria that cause the devastating Pierce's disease. While egg parasitoids (*Gonotocerus* spp.) have been shown to kill more than 75% of the eggs deposited in the late season, significantly reducing overwintering populations, the level of control in vineyards may not be high enough since economic injury levels are set to near zero tolerance. Often, biological control agents do not provide the level of pest reduction needed when pests vector plant diseases in vineyards.

Augmentation. Predatory mites are released to control the Pacific spider mite in San Joaquin Valley vineyards, although release timing and rates have been problematic (Flaherty and Wilson 1999). One possible improvement, and an interesting concept in augmentation, is the combined release of predaceous mites along with less-damaging species of phytophagous mites in order to supply predators with an early-season prey. Although the parasitoid *Anagyrus pseudococci* was imported for the classical biological control of vine mealybug, its impact is limited by ant activity and the short period during which mealybugs are found in exposed locations on the vines. However, a combination of least-toxic ant control, using sugar or protein baits, and inoculative releases of *A. pseudococci* timed to the movement of mealybugs to exposed locations on the vine, has reduced mealybug damage (Daane et al. 2003).

Another example from integrated pest management (IPM) in vineyards is the importance of matching the augmented natural enemy to the targeted prey and release environment. Green lacewings are released for leafhopper control, but studies suggest that less than 30% pest reduction has been achieved (Daane et al. 1993). There are three reasons for the poor success. First, while green lacewings are considered generalist predators, leafhoppers are not a preferred host. Second, the release methods commonly used for lacewing eggs result not only in poor distribution, but also in high egg mortality. Third, released lacewings are often subject to a harsh environment, including mortality from other predators.

Conservation. Cover crops have been popularly used to reduce vineyard pests such as leafhoppers. Still, the beneficial role of cover crops with respect to natural enemies is not clear. It is likely that cover crops have a dual role, changing both the susceptibility of the vines to pests and the ability of the vineyard to support natural enemies, leading to a combined impact on pest densities (Costello and Daane 2003).

A classical example of conservation biological control from California vineyards is leafhopper control by *Anagrus* egg parasitoids. Vineyard leafhoppers overwinter as adults, while *Anagrus* parasitoids overwinter as larvae and must find alternate leafhopper hosts for the winter, such as the blackberry leafhopper or prune leafhopper (Flaherty and Wilson 1999). Blackberry or prune refuges have been planted near vineyards in order to increase parasitism levels, but in practice these refuges have not resulted in decreased leafhopper densities because of the small size of the refuge relative to the vineyard. A small blackberry or prune refuge will produce a correspondingly small number of blackberry or prune leafhoppers. *Anagrus* densities reach a peak in vineyards toward season's end, and these adult parasitoids will overwhelm leafhoppers in the refuge. The result is such a high percentage parasitism of blackberry or prune leafhopper eggs that their populations are often eliminated, thereby reducing the number of overwintering *Anagrus*. The refuge works, but in the wrong direction!

The judicious use of selective pesticides also conserves vineyard natural enemies. Even sulfur, which is approved for use in organic vineyards, can result in increased spider mite densities (Hanna et al. 1997). The most important recent advance in vineyard IPM is the identification and use of the vine mealybug sex pheromone (Millar et al. 2002). Properly monitoring for this new, invasive pest will reduce insecticide use.

Cultural control. Good vineyard management is now synonymous with cultural controls for vineyard pests. As the season begins, basal leaves can be removed to improve the control of powdery mildew, and this practice can also lower leafhopper densities. Throughout the season, dusty conditions and vine water stress are important components of spider mite control, as mentioned for other crop systems. At the opposite extreme, too much irrigation water and excessive vine vigor results in increased leafhopper densities (Daane et al. 1995). For these reasons, maintaining balanced vine vigor — either through the use of appropriate groundcovers, irrigation and fertilization practices, or cultivar selection — has become an essential part of vineyard pest management. At the end of the season, vines are cleaned of unharvested grape clusters, and this sanitation practice reduces omnivorous leafroller populations.

Phil Phillips

Jack Kelly Clark

In classical biological control, natural enemies are imported from the pest's native range, identified and screened in quarantine. *Top*, Serquei Triapitsyn, UC Riverside principal museum scientist, has traveled through the native range of the glassy-winged sharpshooter to identify new egg parasitoids, such as *Gonotocerus ashmeadi*, *bottom*, for the control of this invasive vineyard and citrus pest.

Field and row crop strategies

Classical biological control. In general, examples of success in the classical biological control of exotic pests in field and row crops are less common than in other cropping systems, in part due to a lower incidence of exotic pests in these crops. More importantly, the annual nature of these crops, their greater level of seasonal disturbance, and the highly dispersive nature of many of the associated pests are important barriers for the establishment and impact of introduced natural enemies. For example, despite the establishment of three parasitoids *(Eretmocerus emiratus*, *E. mundus* and *Encarsia sophia)* in California to combat the silverleaf whitefly, the highly migratory nature of this pest and its ability to readily colonize newly established fields has enabled it to escape effective parasitoid control.

In this regard, perennial field crops such as alfalfa have the greatest potential for success in the introduction of natural enemies for classical biological control. In California, for example, both alfalfa aphids and weevils have been partially controlled by introduced parasitoids (Summers 1998). Two different strains (previously considered separate species) of alfalfa weevils are present in California: the western alfalfa weevil (confined to cooler regions) and the Egyptian alfalfa weevil (found in warmer regions). Initial releases of the larval parasitoid *Bathyplectes curculionis* in the 1930s reduced western alfalfa weevil to almost undetectable levels in the mid-coastal region, but the parasitoid has not been effective in the warmer Central Valley where the Egyptian strain predominates.

Release of a second strain of *B. curculionis*, probably originating from Iran, extended control of western alfalfa weevil to the mountain valleys in Northern California. Subsequently, *Microctonus aethiopoides*, an adult parasitoid of the Egyptian alfalfa weevil, has also been established, although to date it has not achieved the effective level of control seen in the northern and eastern United States. In addition, the control of spotted alfalfa aphid in California has been achieved by the combined action of three imported parasitoid species *(Trioxys complanatus*, *Praon exsoletum* and *Aphelinus asychis)*, together with the use of aphid-resistant cultivars.

Augmentation. Although lady beetles, *Trichogramma* egg parasitoids and entomopathogenic nematodes have all been used on occasion, there are few examples of the successful use of commercially produced natural enemies in field and row crops in California. This is perhaps surprising, as the periodic release of natural enemies has often been considered the most suitable of the three approaches to biological control in annual cropping systems (Obrycki et al. 1997). Possible reasons for the lack of success include the high cost of commercial natural enemy production, the lack of data showing effectiveness and economic feasibility, and the misconception that mass-reared natural enemies can be used like insecticides.

Trichogramma releases for the control of fruitworms as part of an IPM program for insect pests in fresh-market tomatoes provides an illustrative example (Trumble and Alvarado-Rodriguez 1993). The releases of 247,000 *T. pretiosum* per acre per week over a period of 5 to 9 weeks in multiple plantings in Sinaloa, Mexico, reduced fruitworm populations by 80% to 90%, and fruit damage was often comparable to plots treated with conventional insecticides. However, despite the lower cost of *Trichogramma* production in Mexico and the substantial success shown by these pilot studies, *Trichogramma* releases have only been adopted by growers of processing rather than fresh-market tomatoes, and there has been no adoption of this approach in California. Clearly crop value, control costs, the predictability of control and recognition of the value of partial success all play an important role in the likelihood of adoption of augmentative biological control.

Conservation. Dr. Ken Hagen was hired in 1951 as the first supervised control entomologist in California to monitor pest-to-parasitoid ratios for alfalfa caterpillar, thereby taking advantage of the control provided by an indigenous natural enemy *(Cotesia medicaginis)* and minimizing the need for insecticide treatments. The importance of indigenous predators and parasitoids as natural controls for other alfalfa pests, including aphids and beet and western yellow-striped armyworm, has subsequently led to the recommendation of strip or border cuts for harvesting to maintain refuges for natural enemies (Summers 1998). The perennial nature of alfalfa facilitates the maintenance and enhancement of natural enemy activity, and the use of effective monitoring techniques to minimizing the need for insecticide intervention is a key element of conservation biological control.

With respect to annual crops, the delays inherent in the colonization of crops by natural enemies each season often allow early-colonizing pests to escape natural enemy suppression. Encouraging early colonization to generate predation pressure ahead of the normal colonization of a crop by pests, a form of preemptive biological control, is intuitively appealing and has met with some success (Summers 1998). Shelter strips within fields and perimeter plantings are known to encourage early natural-enemy activity in field crops such as wheat, and the use of adult food sprays to attract green lacewing adults has provided promising preliminary results in cotton and sugar beet. In addition to the encouragement of early colonization, the use of nectar-bearing plants as perimeter plantings has proved valuable in restoring limited adult food supplies for both predators and parasitoids in a number of field crops, a good example being the use of alyssum to encourage syrphids as aphid predators in Central Coast lettuce.

David Rosen

Jack Kelly Clark

The invasive Argentine ant, *bottom (tending scale),* disrupts biological control agents of aphids, scales and mealybugs. UC researchers are developing programs that use small amounts of toxic insecticides mixed with sugar bait to control ants in citrus and vineyards. *Top,* Phil Phillips, Ventura County IPM advisor, tests a commercial liquid-bait station.

Cultural control. Because most field and row crops are annual systems requiring extensive manipulation for planting and harvesting, cultural controls can readily be incorporated for pest management. For example, sanitation, planting and harvesting schedules, and variety selection are integral to the effective suppression of silverleaf whitefly in cotton (UC IPM 2003b). Sanitation is used to remove crop residues and weeds within and around the crop and prevent early whitefly colonization. It is also essential that vegetables, melons and alfalfa, which can generate substantial whitefly populations, be harvested on as short a growing cycle as possible in cotton production areas.

Finally, the early termination of the cotton crop itself, the use of smooth-leaved Acala rather than Pima varieties, and the prevention of regrowth after harvest can also help to suppress whitefly populations. Although cotton is not a favored host of Lygus bugs, migration into cotton from surrounding weeds or crops, particularly alfalfa, can also be a problem. However, Lygus migrations can be minimized through regional cooperation, staggering the harvest of alfalfa fields in an area, leaving alfalfa strips within harvested fields, or using trap crops, all of which ensure that sufficient attractive alfalfa remains in the area to reduce Lygus bug migration to nearby cotton.

Other field crops in which cultural controls have been of particular importance in California are alfalfa (Summers 1998) and artichoke (UC IPM 2003a).

Effective alternatives for OPs

Biological and cultural controls have proven to be effective alternatives to OPs for some major agricultural pests. Classical biological control remains one of the best solutions for the control of newly invasive as well as long-established exotic pests. The advantages are clear — long-term pest suppression without the need for toxic pesticides. Once well established in a crop system, however, effective natural enemies are too often overlooked. Growers are naturally concerned with pests that are currently causing crop damage, and are often unaware of those pests that are present in the crop system but held in check by the continued success of introduced biological control agents. In this manner, the importance and activity of many introduced biological control agents are poorly marketed in comparison to insecticides that have a more visible treatment-and-effect relationship.

A recent example of the "invisible" action of an introduced biological control agent was provided by the flare-ups of cottony cushion scale caused by disruption of vedalia beetle activity following the use of insect growth regulators for control of California red scale. Nonetheless, all successful classical biological controls will, eventually, be overlooked as alternatives to insecticides unless disruption occurs, as the very attributes that result in pest suppression also lead to the reduced or even forgotten importance of the target pest. Further, we suggest that the economic benefits of classical biological controls are evident from the multitude of historically important pests now held at low densities and all but forgotten as key pests in the crop system.

Cultural controls can be effective in reducing the susceptibility of all crops — but in particular field and row crops — to damage by indigenous pests, and conservation and augmentative biological controls appear best suited for use in perennial crops. Cultural controls like augmentation and conservation require direct action and economic analysis by the farm manager. For this reason, their use is more often directly weighed against the cost and effectiveness of insecticides. In our opinion, the adoption of many biological and cultural controls then rests in managerial decisions based on intangible elements of the crop system.

For example, crops marketed as organic have a limited range of chemical controls available and, therefore, rely more heavily on biological and cultural controls for sustained pest management. In addition, farm size, time period before harvest and potential for crop damage will also influence decisions regarding the use of biological and cultural controls, which often require more extensive monitoring of the crop and often have a delayed action in the suppression of pest damage. Finally, perhaps the most obvious intangible element is a grower's personal decision on how to best manage their land, and protect and market their crop.

Can the practice of biological and cultural controls be increased? Their impact and use vary among targeted pest species and crops. Their use is dependent on numerous interrelated components: effectiveness, cost, practicality (how easily can they be used), compatibility with other pest programs and legislative restrictions on currently registered insecticides. The development and implementation of new biological and cultural controls are driven by need, which in itself often appears to be driven by the availability of effective and environmentally safe pesticides.

Still, the application of biological or cultural controls necessitates sufficient background research and demonstrations of efficacy, frequently requires greater monitoring by pest control advisors, and often faces a problem of compatibility between natural enemies and pesticide use within a crop. In addition, more widespread adoption of biological and cultural controls will require greater investment in research, broader recognition of the importance of multiple tactics and the value of partial suppression, and the development of more selective insecticides that can be used when other tactics fail. Although the current new generation of insecticides shows low mammalian toxicity, in many cases they remain incompatible with natural enemies, suggesting that new priorities need to be incorporated into the development of future products.

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Various novel insecticides are less toxic to humans, more specific to key pests

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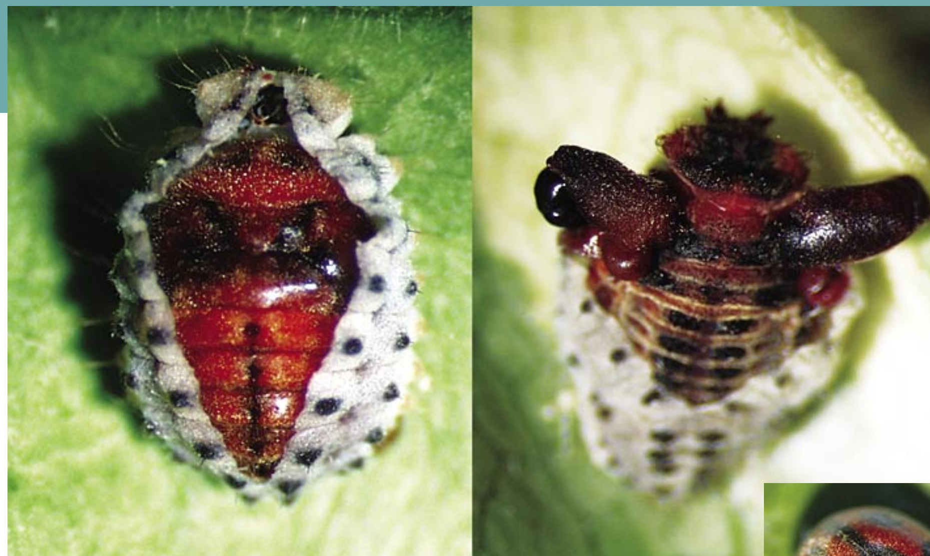



While often effective at controlling specific pests, less-toxic new insecticides can also have unintended impacts. When pyriproxyfen was sprayed to control red scale in citrus, it also caused gross abnormalities in vedalia beetle pupae, *left (normal)* and *right (abnormal)*. Vedalia beetles, *inset (adult stage)*, are predators needed to control cottony cushion scale; as a result, secondary outbreaks of the scale occurred.

A number of novel insecticides have recently been registered for insect control in agriculture. A major advantage of these new products is that they act on insect biological processes that humans do not experience, such as molting. Many also have greater selectivity to target specific species, so they are less likely to harm natural enemies when compared with the broader spectrum organophosphate, carbamate, neonicotinoid and pyrethroid insecticides. Such novel insecticides currently in use include four targeting lepidopteran pests, three targeting sucking insects, one specific to dipteran leafminers and one insect growth regulator that controls a wide range of insects. One negative aspect of these insecticides is that because of their narrower range of activity — controlling only a limited number of pests — growers may need to apply additional pesticides for secondary pest groups that have poor biological control, increasing the total number of treatments per acre and total pest-control costs.

A number of novel insecticides with unique modes of action were registered during the late 1990s and early 2000s for insect control in agriculture. These new insecticides have several advantages over older classes of insecticides. First, most of the products in this group act on insect processes that humans do not experience, such as molting. Low mammalian toxicity allows for short re-entry and preharvest intervals, allowing the insecticides to be easily incorporated into pest control programs. Many also have greater selectivity and so are less likely to harm natural enemies than the broad-spectrum organophosphate (OP), carbamate, neonicotinoid and pyrethroid insecticides. As such, they are less likely to cause outbreaks of secondary pests that are well controlled by natural enemies, and may be used as "clean-up" sprays to manage outbreaks of pests caused by broad-spectrum insecticides. The registration of these insecticides has helped to greatly reduce OP and carbamate insecticide use in California. This has had an especially significant impact in cotton, citrus and stone fruits, where OP and carbamate use has been reduced by as much as 70% since the late 1990s.

The new insecticides also have some disadvantages. Because of their narrower range of activity, each insecticide generally controls only one pest group within a crop. The grower may need to apply additional insecticides for secondary pests that have inadequate natural control, increasing the total number of treatments per acre and total pest-control costs. In addition, many of the novel insecticides have fairly short residual activity or affect only immature stages of insects, so the treatment timing is less flexible compared with broad-spectrum insecticides. Finally, the cost of the new insecticides is usually significantly higher than the older products.

It is fortuitous that in recent years insecticides from different chemical classes have been registered to control lepidopteran (primarily moths) and homopteran (primarily scales and whiteflies) pests, because many insects in these groups have developed resistance to the older pesticides. The simultaneous registration of insecticides with unique modes of action allows growers to alternate the insecticides used, reducing the rate at which resistance develops. Insecticide resistance in key pests will continue to be a major impetus for adopting novel insecticides.

Insecticides for Lepidoptera

Four insecticides that have activity primarily affecting lepidopteran pests — indoxacarb (Avaunt, Steward),

Insecticide resistance in key pests will continue to be a major impetus for adopting novel insecticides.

tebufenozide (Confirm), methoxyfenozide (Intrepid) and emamectin benzoate (Denim, Proclaim) — are registered for a number of crops in California. The greatest uses of these insecticides are in cotton, cole crops, lettuce, nuts, and stone and pome fruits (table 1).

In stone fruit, the use of these insecticides — in combination with *Bacillus thuringiensis* (Bt) products, spinosad and mating disruption during the growing season — has greatly reduced the need for dormant sprays of OP, carbamate and pyrethroid insecticides for peach twig borer *(Anarsia lineatella)*. This has benefited the stone fruit industry by reducing pesticide residues in surface water, by preserving natural enemies needed for other pests such as San Jose scale *(Diaspidiotus perniciosus)*, and by reducing secondary outbreaks of spider mite pests caused by broad-spectrum-insecticide disruption of their natural enemies.

The Central Coast Vegetable Integrated Pest Management Program for pest management in lettuce provides another example of the significant role that these narrow-spectrum insecticides play in Lepidoptera control. Lettuce is highly susceptible to pest damage at the seedling stage and during head formation. Many of the seedling pests — such as crickets, flea beetles, aphids and whiteflies — are controlled with broad-spectrum OP, carbamate, pyrethroid or neonicotinoid insecticides. These insecticides reduce or eliminate the natural enemies that attack the lepidopteran pests, sometimes causing outbreaks; selective insecticides help to bring the Lepidoptera back under control without creating additional problems.

In addition, there are a number of lepidopteran pests that attack both head and leaf lettuce, including cabbage looper *(Trichoplusia ni)*, beet armyworm *(Spodoptera exigua)*, corn earworm *(Helicoverpa zea)* and tobacco budworm *(Heliothis virescens)*. Lepidopteran pests can destroy seedlings, bore holes and leave frass or insect body contaminants throughout the growth cycle of the lettuce, necessitating multiple treatments. Indoxacarb and tebufenozide provide unique, selective chemistries for these pests and act as rotational alternatives to each other, as well as spinosad and Bt, helping to reduce the rate that insecticide resistance develops.

Indoxacarb. Indoxacarb is an oxadiazine insecticide that blocks the sodium channels in insect nerve cells, causing lepidopteran larvae to stop feeding within 4 hours, become paralyzed and die within 2 to 5 days (McCann et al. 2001). It is more effective as a stomach poison than as a contact poison. Indoxacarb is fairly selective, having activity primarily against lepidopteran larvae and certain species of sucking insects such as Lygus bugs. However, the activity of indoxacarb against the sucking insects is weaker than for Lepidoptera because of its slower bioactivation, lower sensitivity and a less favorable method of oral uptake in the sucking insects. Indoxacarb allows most predators and immature wasp parasites to survive (Hewa-Kapuge et al. 2003; Studebaker and Kring 2003). However, the wet residues of indoxacarb are toxic to bees and adult wasp parasites.

Indoxacarb controls important pests in alfalfa, apples, cole crops, cotton, lettuce and pears. Populations of obliquebanded leafroller *(Choristoneura rosaceana)* in Michigan (Ahmad et al. 2002) have exhibited resistance to indoxacarb in regions where it has not been used, suggesting cross-resistance to older groups of insecticides. This emphasizes the need for the rotation of indoxacarb with emamectin benzoate, the dibenzoylhydrazine insect growth regulators (IGRs) and other insecticides to maintain the efficacy of all groups of insecticides.

Tebufenozide. Tebufenozide is a dibenzoylhydrazine stomach poison that acts as an IGR specifically for Lepidoptera. It mimics a molting hormone and blocks the completion of the normal molting process (Retnakaran et al. 2001). The insect stops feeding within a few hours and undergoes a premature lethal molt within 3 to 7 days, becoming trapped within the shedding head capsule. Tebufenozide must be ingested to take effect and is thus slow-acting, with a residual activity of 14 to 21 days. Application timing is critical, because it is more active on early larval stages (Waldstein and Reissig 2001). It is nontoxic to honeybees and is selective, not affecting most natural enemies (Dhadialla et al. 1998).

The crops for which tebufenozide is currently registered include cole crops, cotton, grapes, lettuce, tomatoes and some nuts, pome and stone fruits. Low levels of resistance to tebufenozide have been found in codling moth *(Cydia pomonella)*, beet armyworm and obliquebanded leafroller populations that were not exposed to this insecticide (Moulton et al. 2002; Ahmad et al. 2002), suggest-


Jack Kelly Clark

Because lettuce is highly susceptible to insect damage at the seedling stage, many growers spray broad-spectrum insecticides. Some newer, more selective insecticides can bring lepidopteran pests under control without hurting their natural enemies and causing secondary pest outbreaks.

ing that there may be cross-resistance to older classes of compounds, including OPs. There is also likely to be cross-resistance between tebufenozide and methoxyfenozide, because they have the same mode of action. These insecticides will need to be used infrequently, alternated with other insecticide chemistries, and coupled with alternative methods of control, such as mating disruption, to delay resistance in key pests.

Methoxyfenozide. Methoxyfenozide is a dibenzoylhydrazine IGR, similar to tebufenozide in its mode of action, its ability to induce a lethal molt and its specificity for Lepidoptera (Carlson et al. 2001). Methoxyfenozide was only recently (2003) registered in California and its use is likely to increase due to its better binding with lepidopteran receptors and longer residuality compared with tebufenozide. Methoxyfenozide has a much lower ability to bind with receptors in nonlepidopteran species, making it a highly selective insecticide and useful in a number of crops. Low levels of resistance to methoxyfenozide in codling moth, beet armyworm and obliquebanded leafroller have been found, necessitating prevention precautions similar to those for tebufenozide.

Emamectin benzoate. Emamectin benzoate is a second-generation avermectin analog with exceptional activity against lepidopterans, acting by decreasing the excitability of neurons. Shortly after contact or feeding exposure, the insect larvae stop feeding, become irreversibly paralyzed and die in 3 to 4 days. Emamectin benzoate toxicity is broader spectrum than methoxyfenozide, tebufenozide or indoxacarb, which is a benefit in that it kills a wide variety of lepidopterans (Argentine et al. 2002). However, its broad-spectrum activity also makes fresh residues toxic to natural enemies (Studebaker and Kring 2003). Natural enemy survival improves after about 5 days due to rapid photodegradation. The toxic activity lasts longer for the pest because the photodegradate moves through plant tissue (translaminar activity) and is toxic to the plant-feeding pest.

Emamectin benzoate is used primarily against pests in cole crops and lettuce. (It is registered for cotton in other

Photos: Jack Kelly Clark


Omnivorous leafroller moth


Peach twig borer larva attacking almond

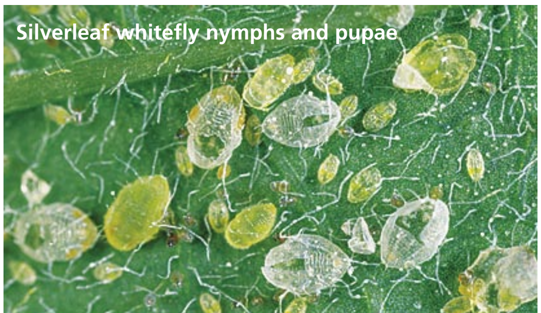
TABLE 1. Novel insecticides primarily targeting Lepidoptera*

Crop	Pests controlled
Indoxacarb	
Alfalfa	Egyptian alfalfa weevil *(Hypera brunneipennis)*, various Lepidoptera
Apple, pear	Codling moth *(Cydia pomonella)*
Cole	Various cutworms, cabbage looper *(Trichoplusia ni)*, diamondback moth *(Plutella xylostella)*
Cotton	Cabbage looper, beet armyworm *(Spodoptera exigua)*, western yellow-striped armyworm *(Spodoptera praefica)*; suppression of Lygus bug *(Lygus hesperus)*
Lettuce	Corn earworm *(Helicoverpa zea)*, tobacco budworm *(Heliothis virescens)*, beet armyworm, various loopers
Stone fruit†	Codling moth, oriental fruit moth *(Grapholita molesta)*
Tebufenozide	
Cole	Cabbage looper, diamondback moth
Cotton	Alfalfa looper *(Autographa californica)*, cabbage looper, saltmarsh caterpillar *(Estigmene acrea)*, western yellow-striped armyworm
Grape	Various leafrollers, skeletonizer *(Harrisina brillians)*
Lettuce	Various loopers, beet armyworm
Stone fruit	Codling moth, peach twig borer *(Anarsia lineatella)*, oriental fruit moth, omnivorous leafroller *(Platynota stultana)*, obliquebanded leafroller *(Choristoneura rosaceana)*
Tomato	Beet armyworm
Walnut, pistachio, pear, apple	Codling moth, obliquebanded leafroller, green fruitworms *(Orthosia hibisci, Amphipyra pyramidoides)*
Methoxyfenozide	
Artichoke	Artichoke plume moth *(Platyptilia carduidactyla)*
Cotton	Beet armyworm, western yellow-striped armyworm; suppression of *Heliothis* species
Grape	Omnivorous leafroller, grape leaffolder *(Desmia funeralis)*, orange tortrix *(Argyrotaenia citrana)*
Nuts, stone fruit	Navel orangeworm *(Amyelois transitella)*, peach twig borer, oriental fruit moth, various leafrollers
Pome fruit	Various leafrollers; codling moth suppression in conjunction with mating disruption
Vegetables, cole	Various armyworms, cabbage looper; suppression of diamondback moth
Emamectin benzoate	
Cole	Cabbage looper, tobacco budworm, beet armyworm, various loopers
Lettuce	Corn earworm, tobacco budworm, beet armyworm, various loopers

* Current uses in California.
† Likely to be registered within a few years.

states, but not California.) Emamectin benzoate provides a rotational insecticide for the control of caterpillars and so helps to reduce the development of resistance. Populations of obliquebanded leafroller tested with emamectin benzoate have shown only slight levels of resistance (Waldstein and Reissig 2001).

Photos: Jack Kelly Clark


Silverleaf whitefly nymphs and pupae


San Jose scale

TABLE 2. Novel insecticides targeting sucking insects*

Foliar-applied pyriproxyfen	
Crop	**Pests controlled**
Apple	Apple leafminer *(Phyllonorycter* species*)*
Citrus	California red scale *(Aonidiella aurantii)*
Cotton	Silverleaf whitefly *(Bemisia argentifolii)*
Pear	Pear psylla *(Cacopsylla [Psylla] pyricola)*
Stone fruit, pome fruit, nuts	San Jose scale *(Diaspidotus perniciosus)*
Buprofezin	
Crop	**Pests controlled**
Almond	San Jose scale, apple leafhopper
Citrus	California red scale
Cotton	Silverleaf whitefly
Grape	Mealybugs *(Pseudococcus* species and *Planococcus ficus)*, leafhoppers *(Erthroneura elegantula* and *E. variabilis)*
Stone fruit†	San Jose scale
Pymetrozine	
Crop	**Pests controlled**
Cole, lettuce, celery, tomato	Various aphids, various whiteflies
Cotton	Cotton aphid *(Aphis gossypii)*

* Current uses in California.
† Likely to be registered within a few years.

Treatments for sucking insects

Three insecticides — pyriproxyfen (Esteem, Knack, Seize), buprofezin (Applaud, Courier) and pymetrozine (Fulfill) — have activity primarily affecting sucking insect pests such as whiteflies and armored scales, many of which have developed resistance to OP, carbamate or pyrethroid insecticides. The greatest uses of these insecticides for whitefly control are in cotton and tomatoes, for California red scale *(Aonidiella aurantii)* in citrus, and for San Jose scale in nuts, and stone and pome fruits (table 2). Their cost is often significantly higher than OPs, carbamates and pyrethroids.

Pyriproxyfen. Pyriproxyfen is a pyridine compound that acts as a juvenile hormone mimic IGR, inhibiting egg production and the metamorphosis of immature stages into adults (Ishaaya et al. 1994). It is most effective in late-stage larvae or nymphs and early pupal stages when juvenile hormone is normally low. It is active primarily against sucking insects such as scales, pear psylla *(Cacopsylla [Psylla] pyricola)* and whiteflies. It is also effective against fire ants and apple leafminers (*Phyllonorycter* species). Because of its persistence and efficacy, pyriproxyfen has been extremely effective in reducing California red scale and San Jose scale populations that developed resistance to OP insecticides. It is safer for hymenopterous parasites than OP insecticides, greatly increasing parasite numbers and so improving the control of both target and nontarget pests within crop systems. Pyriproxyfen is toxic to crustaceans, limiting its use around bodies of water.

Citrus provides an example of two potential problems associated with the use of IGR insecticides in agriculture. First, pyriproxyfen is not fully compatible with natural enemies because it is highly toxic to predatory coccinellid beetles, halting both egg hatch and pupation (Grafton-Cardwell and Gu 2003). The heavy use of pyriproxyfen in citrus for California red scale control created a cottony cushion scale *(Icerya purchasi)* problem due to the loss of vedalia beetle *(Rodolia cardinalis)*. It may also be responsible for pest resurgences in other crops due to its effect on coccinellid predators of armored scales, mealybugs and mites.

Second, pyriproxyfen has a narrower range of activity compared with the carbamate and OP insecticides. Pyriproxyfen has no effect on the secondary pests forktailed bush katydid *(Scudderia furcata)* or citricola scale *(Coccus pseudomagnoliarum)*, which lack natural enemies, and so these insects have become primary pests that must be controlled with additional insecticide treatments. In past years, katydids and citricola scale were easily controlled by the OP treatments applied for California red scale.

Currently, pyriproxyfen is used in California to control pests in apples, citrus, cotton, nuts, pears, and stone and pome fruits. In bait form, it is effective against the protein-feeding native southern fire ant *(Solenopsis xyloni)*. An extensive resistance-management program has been developed for cotton that limits the number of applications of pyriproxyfen to one per growing season to reduce the rate of resistance development. Caution should be exercised by growers as to the frequency of application, because resistance has begun to develop in whitefly populations in other areas of the world, even when the number of applications per season was limited to one (Horowitz et al. 2002).

Buprofezin. Buprofezin is a thiadiazine IGR that disrupts molting by preventing chitin development (Uchida et al. 1985). It is active primarily against sucking insects such as scales, whiteflies, mealybugs and leafhoppers, although it also has activity against beetles. Buprofezin is slow-acting but persists a long time. It has poor ovicidal activity, but treated adults of some pest species may lay sterile eggs. It has little or no effect on lepidopteran (moths), dipteran (flies) or hymenopteran (wasp) insects. Buprofezin is toxic to crustaceans, limiting its use around bodies of water.

In citrus, buprofezin is not as effective as pyriproxyfen in controlling California red scale because it requires the majority of the scale population to be in an immature stage (Grout and Richards 1991). Buprofezin is less toxic than OPs and carbamates to a number of natural enemies, especially wasp parasites, allowing their numbers to greatly increase. However, similar to pyriproxyfen, it is highly toxic to coccinellid beetles, preventing larval molting (Grafton-Cardwell and Gu 2003). Buprofezin use has led to outbreaks of cottony cushion scale in citrus due to the loss of vedalia beetle. It also may be responsible for pest resurgences in other crops due to its effect on coccinellid predators.

Currently, buprofezin is used in California to control pests in almonds, citrus, cotton and grapes. Buprofezin has been an important component of the silverleaf whitefly management program for cotton, where it has helped delay resistance to insecticides. In grapes, buprofezin can be rotated with the neonicotinoids to control mealybugs and leafhoppers and so help to manage resistance. Because of its selectivity favoring hymenopteran parasites, buprofezin and parasites work together to control grape and vine mealybugs. Buprofezin is likely to receive registration for San Jose scale in stone fruit in the near future.

Pymetrozine. Pymetrozine is a pyridine azomethine. It is active primarily against sucking insects such as aphids and whiteflies. Its mode of action is not fully understood, but differs from other insecticide groups. It interferes with feeding behavior, resulting in the complete cessation of feeding within hours of contact (Harrewijn 1997). Aphids remain alive for 2 to 4 days before they die of starvation. Pymetrozine has been shown to reduce both direct damage and virus transmission by aphids (Bedford et al. 1998). Because of its specificity for sucking insects, it is relatively nontoxic to most natural enemies (Sechser et al. 2002).


Liriomyza leafminer adult


Tunnels produced by leafminer larvae

Photos: Jack Kelly Clark

TABLE 3. Current uses of cyromazine in California

Crop	Pests controlled
Cole, lettuce, pepper, spinach, celery, tomato, cucurbit	Dipteran leafminers (*Liriomyza* species)

Pymetrozine is active against important pests in cole crops, lettuce, celery and tomatoes. It has been registered for California cotton since 2001 to control cotton aphid *(Aphis gossypii)*, but has not yet been incorporated into management programs to any extent. Pymetrozine must be applied when populations of cotton aphids are low, but in California the treatment threshold for aphid populations has traditionally been fairly high. When used for whitefly control, pymetrozine causes adults to stop feeding, but it must be used in combination with other insecticides such as IGRs to reduce whitefly populations below the economic threshold.

Controlling dipteran leafminers

Cyromazine (Trigard) is a triazine insecticide used as a chitin-synthesis-inhibitor IGR, which disrupts the molting of larval and pupal cuticles. It has translaminar activity that quickly penetrates into leaves. It is active against a very narrow range of insect pests, notably the larval stages of dipteran leafminers. Because of its high level of specificity, cyromazine is much less toxic to natural enemies, compared with IGRs such as diflubenzuron, making it highly compatible with integrated pest management (IPM) programs (Schuster 1994). Cyromazine is nontoxic to crustaceans, bees, fish and birds.

The current uses of cyromazine are for *Liriomyza* leafminers in cole crops, lettuce, peppers, spinach, celery, tomatoes and cucurbits (table 3). Cyromazine is important as a new chemistry for controlling dipteran leafminers, as a number of species have developed resistance to the older groups of insecticides around the world. Because leafminers often require multiple insecticide treatments, it will be important to rotate cyromazine with other insecticide chemistries to combat resistance.

A product with broad activity

Diflubenzuron (Dimilin, Micromite) is a benzoylphenylurea chitin-synthesis-inhibitor IGR that disrupts molting. It is slow-acting, requiring up to 14 days for population reduction, because it is active against all molting stages. The symptoms of diflubenzuron poisoning in grasshoppers include slowed movement, uncoordinated jumping, loss of legs, decreased feeding and malformed wings (Weiland et al. 2002). It is used against a variety of insects including rice water weevils *(Lissorhoptrus oryzophilus)*, beetles, various Lepidoptera, grasshoppers, Mormon crickets *(Anabrus simplex)* and katydids. It does not cause mortality to adults, but does sterilize the females of some species.

Because diflubenzuron is primarily active through ingestion, it is less toxic to a number of natural enemies, especially wasp parasites. Similar to other IGRs, the eggs and immature stages of predatory beetles, as well as lacewings, can be sensitive to diflubenzuron (Ables et al. 1977). However, effects such as reduced egg hatch can be rapidly reversed when the predators enter an untreated environment (Peleg 1983). Diflubenzuron is toxic to crustaceans; however, populations recover rapidly because it rapidly dissipates in water.

Currently, diflubenzuron is used to

control pests in artichokes, citrus, cotton, rice, nuts and stone fruits (table 4). Diflubenzuron is also registered to treat grasslands infested with grasshoppers — which often devastate nearby crops — providing an important replacement for OP and carbamate insecticides. Resistance to diflubenzuron in codling moth populations occurs in France (Sauphanor et al. 2000), indicating the need for the careful rotation of this insecticide with insecticides that have different modes of action.

Pros and cons

Novel insecticide classes play a critical role in the IPM of many California crops. Excellent efficacy, high selectivity and low mammalian toxicity make them attractive replacements for OPs and carbamates, and the majority are considered by the U.S. Environmental Protection Agency to be "reduced risk" insecticides. However, their high level of selectivity can increase the need for other insecticides if they allow secondary pests that lack effective natural enemies to gain primary pest status. In addition, the new insecticides are not always completely selective, and the predatory beetles have been especially sensitive to some of them. Other problems include short residuality and high cost.

Nonetheless, major impetuses for the adoption of these chemistries include human health concerns and pest resistance to OPs, carbamates and pyrethroids. The wide variety of new modes of action is extremely helpful for delaying resistance in key pests such as whiteflies, scales and aphids. As growers and pest control advisors become familiar with the unique characteristics of these insecticides, their adoption is likely to increase.

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Jack Kelly Clark

Devastating grasshopper

TABLE 4. Current uses of diflubenzuron in California

Crop	Pests controlled
Almond, stone fruit	Peach twig borer
Artichoke	Armyworms, artichoke plume moth
Citrus	Citrus leafminer *(Phyllocnistis citrella)*, citrus peelminer *(Marmara gulosa)*; being tested for katydid *(Scudderia furcata)*
Cotton	Beet armyworm
Grassland (near crops)	Grasshopper, Morman cricket
Rice	Rice water weevil *(Lissorhoptrus oryzophilus)*
Walnut	Codling moth

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REVIEW ARTICLE

Microorganisms and their byproducts, nematodes, oils and particle films have important agricultural uses

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The insect and mite control potential of natural and biological toxins has been recognized for several centuries. Bacteria, viruses, protozoa and fungi are the primary groups of microorganisms known to reduce insect populations; they often occur naturally in fields and function as components of biological control. Beneficial nematodes are also being used for pest control, especially against soil insects. The isolation of toxic metabolic compounds from microorganisms continues to be a fruitful research area, although there are barriers to their successful marketing and distribution. Another, more controversial way to deliver these insect-specific toxins to the target pest is through genetically modified plants, such as those modified to express* Bacillus thuringiensis *(Bt) toxins. Oils and particle films also have important niche uses for pest control.

Natural and botanical products have been used to control insect pests for centuries. Kaolin is a mineral-based particle film that is sprayed onto crops as a barrier to repel insects and prevent feeding.

As pest management moves forward in the 21st century, alternative control measures are needed to suppress insects and mites. Federal regulators are closely scrutinizing the organophosphate (OP) and carbamate insecticides under the Food Quality Protection Act (NRC 2000); in California, surface-water contamination is of particular concern in the Sacramento and San Joaquin river water basins (USGS 2000). The recognized adverse effects of synthetic chemical pesticides (such as the OPs, chlorinated hydrocarbons and carbamates) on the environment and human health emphasize the need to advance and refine current pest-management strategies (see page 7).

The insect-control potential of natural and biological toxins has been recognized for several centuries. As early as 2700 B.C., unintended epizootics (outbreaks of disease affecting many animals of one species at the same time) by natural enemies (microorganisms) were reported in beneficial insects such as silkworms and honeybees. The first record of microorganisms being intentionally used to control crop pests was in the 18th century (a fungus against a weevil pest). Bacteria, viruses, protozoa and fungi are the primary groups of microorganisms known to reduce insect populations. These organisms often occur naturally in fields and function as a component of biological control. Research on these microorganisms as "biopesticides" has resulted in the ability to isolate, culture and formulate some for use in integrated pest management (IPM) programs. These formulations have improved the shelf life of the resulting products, their miscibility with water or oil, and the ability to spray them with commercial application equipment, as well as provided some protection against environmental extremes that occur after application.

Entomopathogenic (insect-parasitic) nematodes are another example of biological agents that are being used for pest control, especially against soil insects. Several species of beneficial nematodes are commercially available, and the animal itself acts as a distribution tool for symbiotic bacteria that actually kill the target pest. As with the microorganisms, the ability to produce and formulate these nematodes into insecticidal products has enabled their use in pest management programs.

A common feature of some microorganisms, principally bacteria and fungi, is their natural ability to produce metabolic byproducts that are toxic to many organisms. For example, the antibiotic penicillin was isolated from a fungus and is used to combat bacterial infections in humans. Other metabolic byproducts have toxic activity against arthropod pests. Instead of relying on the microorganism to produce these arthropod-active toxins in the field, the microorganism can be cultured in fermentation facilities and the resulting metabolites can be harvested, purified, formulated and used effectively against major arthropod pests. Two widely used commercial insecticides, spinosad and abamectin, were developed using this approach. Over the centuries, as microorganisms have evolved in their envi-

In most cases, the use of living organisms — with their inherent growth and survival criteria — introduces considerable complexity into arthropod management schemes.

ronment, the metabolites they produce have provided a competitive advantage; consequently, the isolation of these compounds continues to be a fruitful agricultural research area for the suppression of both arthropod pests and plant pathogens.

One additional way of protecting a microbial-derived toxin and efficiently delivering it to the target pest is through genetically modified plants that express an insecticidal protein, such as *Bacillus thuringiensis* (Bt). Although there is considerable controversy worldwide regarding the applicability and sustainability of this technology, it does undeniably represent an effective way to deliver a toxic dose to the pest (Shelton et. al 2002). Other types of natural and biological toxins that are useful in pest management include plant-derived compounds (such as rotenone, pyrethrum, sabadilla and azadiractin), inorganic products (sulfur), mineral/refined petroleum oils and mineral-based particle films.

Many of the alternative control agents that we discuss are not new to science. However, through innovative approaches and with a better understanding of how they kill insects and mites, many have come to the forefront in pest management. Others are still plagued with high production costs, inconsistent efficacy or special handling requirements, thereby limiting their usefulness in agricultural systems and as alternatives to broad-spectrum insecticides such as the OPs.

The natural epizootics of insect pathogens occur commonly in native and managed systems, significantly assisting pest management. However, except for Bt, the application of microorganisms for pest control in agricultural systems in California is extremely limited (Flint 1992). The reasons for this include: (1) the high cost of *in vitro* or *in vivo* production; (2) limited persistence and efficacy due to UV light degradation, high humidity requirements or temperature sensitivity in the field; (3) slow speed of kill; (4) poor shelf-life or special handling needs; and (5) high levels of specificity. The latter can preserve populations of natural enemies following application, but also makes it difficult to balance market size with registration costs. In addition, microorganisms generally only have one mode of entry into the host. Bacteria, viruses and protozoa must be ingested to cause an infection, whereas fungi cause an infection when the conidium (spore) attaches to and penetrates the insect cuticle.

Bt in widespread use

The notable exception, Bt, was used on nearly 800,000 acres in California in 2001 (DPR 2003). This bioinsecticide is registered on all California field, vegetable, orchard and floriculture crops. Bt strains (also known as subspecies) are active against particular groups of insects (Tanada and Kaya 1993). These include Bt *kurstaki* and Bt *aizawai*, which are both active against lepidopterous larvae (but differ in which caterpillar species are most susceptible); Bt *tenebrionis*, active against certain beetles; and Bt *israelensis,* active against mosquitoes and black flies.

Different Bt products are also characterized by different insecticidal proteins, (δ-endotoxins) known as Cry endotoxins A, B, C, and so on, and are further subdivided into Cry1Aa, Cry 1Ab, Cry1Ac, and so on. These differ in their toxicity to specific pests. Because these products must be ingested, they require warm weather for active feeding and are most effective on early instars. Crop damage may occur for a short time, since Bt products are slow-acting, but the problems of slow kill and short residual activity are offset by their lack of toxicity to other natural enemies (such as predators and insect parasites). Bt products are especially important for pest control in organic cropping systems. However, some Bt products are prohibited by some certifying agencies, either because they contain inert ingredients that are prohibited, or because they have been genetically modified using molecular techniques not acceptable for organic production and marketing.

Activity of other microorganisms

Active bacteria. Other bacterial species have activity against insects, such as *Paenibacillus* (formerly *Bacillus*) *popilliae*

Photos: Jack Kelly Clark

In the U.S. South, the cotton bollworm, *top*, is controlled with cotton genetically engineered to express *Bacillus thuringiensis* (Bt), but this pest is of minor importance in San Joaquin Valley cotton. *Bottom*, a cabbage looper killed by a foliar application of Bt, the most widely used "bioinsecticide" in the state.

and *B. sphaericus,* with efficacy against Coleoptera (white grubs) and Diptera (mosquitoes), respectively. Despite their commercial potential, these bacteria currently have limited market share.

Nucleopolyhedroviruses. Nucleopolyhedroviruses (NPV) can potentially be used against lepidopterous larvae. A number of NPVs are registered in the United States, with two of particular significance to California agriculture. The NPV from the beet armyworm *(Spodoptera exigua)* is registered in the United States with a provisional registration for use in California in 2005 (the California Department of Pesticide Registration is requiring further data with the actual product before full registration is granted), for use in field, vegetable and floriculture crops. A similar product contains an NPV from corn earworm *(Helicoverpa zea)* and controls this species and tobacco budworm *(Heliothis virescens)*; it has a provisional registration in California. Both viruses are expected to get full registration for use in California in 2005 or 2006.

Photos: Jack Kelly Clark

Naturally occurring microorganisms, as shown above, can be isolated, cultured and formulated into commercial products for pest control. ***Left to right,*** **a cabbage looper killed by a nucleopolyhedroviris, and a rose grass aphid and spirea aphid, both killed by fungal diseases.**

Other microbial products that have been used commercially in the United States or are registered with the U.S. Environmental Protection Agency (EPA) include a granulovirus (GV) of the codling moth *(Cydia pomonella)*, an NPV of the gypsy moth *(Lymantria dispar)*, an NPV of the Douglas-fir tussock moth *(Orgyia pseudotsugata)* and a fungus *(Lagenidium giganteum)* with activity on mosquitoes. Other microorganisms, such as the GV of the Indian meal moth *(Plodia interpunctella)* and a GV of the grapeleaf skeletonizer *(Harrisina brillians)*, have generated some interest but their market share may be too small for a commercial venture.

Barriers to acceptance. Despite their effectiveness, several important factors have hindered the acceptance of microorganism-based pest control products, as well as their limited commercialization and marketing. For instance, the slow speed of kill of the codling moth GV allows larvae to inflict shallow wounds in apples, reducing their marketability compared with apples in synthetic-chemical management programs (Kienzle et al. 2002). There is a narrow window for the virus to infect codling moth larvae, because once the larvae enter the fruit they escape viral infection. Moreover, the GV has short persistence on foliage and fruit (necessitating frequent applications) and a narrow host range, which is an advantage for preserving natural enemies but a detriment in terms of providing insecticidal control of other arthropod pests (Cross et al. 1999). With fungi, considerable research on pest control has been conducted on *Metarhizium anisopliae* and *Beauvaria bassiana* (the latter registered as a commercial product) to control foliage pests, but field uses are limited in California, especially by the naturally arid conditions present in many of the state's agricultural production areas.

Potential as replacements. At present, microorganisms appear to have limited potential for offsetting the loss of OP and carbamate insecticides in traditional agricultural production in California. Usage is limited, except for the significant use of Bt. In most cases, the use of living organisms — with their inherent growth and survival criteria — introduces considerable complexity into arthropod management schemes. The selection of microorganisms adapted for specific conditions where control is needed — Central Valley cotton fields, for example — may enhance their applicability. In addition, the use of molecular and classical genetics to improve the pathogenicity of microorganisms may improve their performance as insecticides. Classic research in this area has been done at UC Davis, where the *Autographa californica* NPV was engineered to encode an insect-selective neurotoxin isolated from the venom of a scorpion *(Androctonus australis)*(McCutchen et al. 1991). This greatly enhanced the activity and speed of kill of the NPV. However, the public's acceptance of genetic modifications to insect-pathogenic microorganisms is uncertain at this time.

Genetically modified Bt plants

Bt crops, genetically modified to express the Bt toxin, have been widely used for pest control in many parts of the United States as well as internationally. Cotton and field corn are the most commonly grown crops utilizing this technology in the United States (registrations are also in place on sweet corn and potatoes), and thus far their efficacy against target pests, primarily lepidopterous larvae, has been exceptional. However, genetically modified crops with efficacy on other groups of arthropod pests, such as sucking insects or mites, have not been marketed. The controversial aspects of this technology include resistance management, possible effects on nontarget insects, the escape of modified genes into wild plants or other cultivars, and allergenicity and other health concerns in humans. These issues, among others, are beyond the scope of this article, but the reader should be aware that the controversy exists.

In terms of replacements for synthetic insecticides (OPs) in California, Bt crops have had little impact through 2004. For crops available with the Bt technology in California's Central Valley, lepidopterous pests are of minor importance or are effectively managed by nonchemical means (such as cultural and pheromone management strategies for pink bollworm [*Pectinophora gossypiella*] in cotton (see pages 16, 23). The unique environmental and cultural conditions in California, compared with the rest of

Photos: Jack Kelly Clark

Other commercially available pest-control products utilize natural chemistries, functioning as components of pest control in agro-ecosystems. *Left,* the rice water weevil is infected by the fungus *Beauvaria bassiana* (bottom). *Center,* healthy northern masked chafer larva (left) and larva infected by the nemotode *Heterorhabditis bacteriophora* (right). Healthy spider mite adults, *right,* are killed by a microbial-based acaricidal product, abamectin, the metabolite of a microorganism.

the United States, often result in a unique suite of arthropod pests. The crop diversity of minor-acreage crops in California has thus far limited the development of Bt crops, as high volume sales are needed to offset development costs.

Entomopathogenic nematodes

Two genera of nematodes, *Steinernema* and *Heterorhabditis*, have been commercialized for pest control (Koppenhöfer and Kaya 2002). The nematodes are associated with bacteria in the genera *Xenorhabdus* for *Steinernema* and *Photorhabdus* for *Heterorhabditis*. The nematode penetrates into the insect host and releases bacteria that kill the insect within 2 days. Unlike other insect pathogens, nematodes are regulated by the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (APHIS) and, therefore, are exempt from registration with the U.S. EPA.

These biological control agents can be produced *in vivo* or *in vitro*, formulated and applied like other soil pesticides. Because their natural habitat is the soil, they require moisture. They function best against insect pests in cryptic habitats (such as soil-borne pests and stem borers). Some use occurs in greenhouses (for fungus gnats), landscape crops and mushroom production in California. Entomopathogenic nematodes have been proven effective against root weevils in citrus and scarab larvae in turf; however, in most cases synthetic insecticides are more widely used against these pests in California.

Byproducts from microorganisms

Abamectin. Abamectin (Agri-mek, Zephyr, Avid) is a microbial-based insecticide and acaricide (kills mites and ticks) that is widely utilized and performs like a conventional, synthetic insecticide. This toxicant, produced by the soil bacterium *Streptomyces avermitilis*, was isolated from a soil sample collected in Shizuoka Prefecture, Japan. Abamectin acts on insects by interfering with neural and neuromuscular transmission and paralyzes arthropods, resulting in the cessation of feeding and death 3 to 4 days after exposure. Abamectin is most effective when ingested by target arthropods, but also works on contact.

Abamectin penetrates leaf tissue and provides long-term (3 to 5 weeks) control of various mite species in field-grown roses and other ornamentals, strawberries, citrus, cotton and pears. A unique attribute of abamectin is that its acaricidal properties are coupled with activity on a few other insect species, especially dipterous and lepidopterous leafminers (*Liriomyza* and *Gracillariidae*, respectively), the lepidopterous tomato pinworm *(Keiferia lycopersicella)*, citrus thrips *(Scirtothrips citri)*, fire ants in turf and the homopterous pear psylla *(Cacopsylla pyricola)*. As with synthetic insecticides, the development of resistance is a concern; however, this has been largely avoided to date, except in greenhouse systems. With the exception of predatory mites, abamectin is fairly nontoxic to natural enemies.

Spinosad. Spinosad (Success) was fermented from the actinomycete bacterium *(Saccharopolyspora spinosa)*. The process yields several metabolites called spinosyns, of which two biologically active compounds form the basis for the insecticide. The active ingredients are derived from a soil-dwelling bacterium reportedly collected from an abandoned rum distillery on a Caribbean island in 1982. Spinosad kills susceptible species by causing the rapid excitation of the insect nervous system, leading to involuntary muscle contractions, tremors and paralysis. Insects must ingest spinosad; therefore, it has little effect on sucking insects and most nontarget predatory insects (it is highly toxic to syrphid fly larvae). Spinosad is relatively fast-acting — the insect usually dies 1 to 2 days after ingesting the active ingredient and there appears to be no recovery.

Spinosad has excellent activity on lepidopterous larvae including the cotton bollworm, peach twig borer *(Anarsia lineatella)*, armyworms (except western yellow-striped armyworm), loopers and the saltmarsh caterpillar *(Estigmene acrea)*. It also controls thrips. Registrations are in place on almonds, stone and pome fruits, citrus, cole crops and cotton. Spinosad is very short-lived, sometimes necessitating additional applications. A new formulation called Naturalyte was developed for the organic crop industry.

The organic mining of fermentation products (byproducts from microorganisms) could be a fruitful area for the discovery of other compounds with insecticidal properties in the future. The soil environment where actinomycete bacteria flourish is extremely complicated and diverse. For instance, milbemycins are structurally related to the avermectins, and pesticidal products based on these byproducts are under development. More than 30 different spinosyns have been isolated from *S. spinosa* alone, and these are being evaluated for pesticidal properties. Numerous other microbial species may also produce useful compounds.

Natural toxins from plants

Plant-derived compounds are another fruitful area for the discovery of natural toxins for IPM. Botanical insecticides are mainstays for pest control in organic systems, but receive limited use in conventional systems. They are used on vegetables, fruits and ornamentals.

Pyrethrum. Pyrethrum (as distinct from synthetic pyrethroids) is the most widely used plant-derived material, with about 125,000 acres treated in California in 2001. Pyrethrins are produced by certain species of chrysanthemums. The natural pyrethrins are contact poisons, which quickly penetrate the cuticle to the insect's nervous system. A few minutes after exposure, insects are paralyzed. This quick knockdown is one of the strong attributes of pyrethrins. However, enzymes in the insect swiftly detoxify the natural pyrethrins and some pests will recover. To delay the enzyme action so a lethal dose is assured, OPs, carbamates or synergists may be added. The short residual activity of pyrethrum on plant surfaces allows crops to be harvested shortly after application.

Azadiractin. Azadiractin is extracted from seeds of the neem tree *(Azadirachta indica)*. Chemically, azadiractin falls within a class of compounds known as tetranortriterpenoids. The properties of these insecticidal compounds include feeding and ovipositional deterrence, repellency, growth disruption, reduced fitness and sterility in a number of insect species. The active ingredient is structurally similar to insect hormones called ecdysones, which control metamorphosis. Therefore, the disruption of the insect's development and molting process (interfering with their life cycle) is likely to follow exposure.

Azadiractin is primarily used to control whiteflies, aphids, thrips, fungus gnats, mealybugs, leafminers and other arthropods on food, greenhouse crops, ornamentals and turf. Its acceptance and usage in conventional agriculture have been low, however, due to its erratic performance on major-crop insect pests. The more extensive use of this product in conventional agriculture is limited by its narrow application window (during the susceptible life stage), the need for frequent applications and a narrow pest spectrum.

Rotenone. Rotenone is a nonspecific insecticide with some acaricidal properties, which is used for pest control in a variety of crops. It is extracted from several plants in the pea family. Because of its toxicity to aquatic animals, especially fish, it should not be used near waterways.

Sabadilla. Sabadilla is extracted from seeds of the Mexican lily *(Schoenocaulon officinale)*, which contain the alkaloid veritrine as the active ingredient. It is mixed with sugar or molasses and applied as a baited toxicant for citrus thrips and avocado thrips. Activity is affected by the percentage of alkaloids in the extracted product and by the pH of the water used for the application. Because of sabadilla's variability in activity for thrips control and its rapid breakdown in light, spinosad and abamectin have largely replaced it in citrus and avocado. However, when thrips develop resistance to spinosad and abamectin, as citrus thrips has to OPs, carbamates and pyrethroids, interest in sabadilla is likely to resume.

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Above, **in 1915 a worker sprayed dry sulphur on young prune trees infected with brown mite near Yuba City. Today, sulfur is still widely used as a pesticide to control mites on grapes, citrus and other crops.** ***Right,*** **an air-blast sprayer with tower treats citrus crops with petroleum-based oils to control citrus red mite and California red scale.**

Other plants. Several other plants produce compounds that are reportedly toxic to arthropods. Cinnamaldehyde, derived from cinnamon oil, is the toxic element in the product Cinnamite. This product controls mites and aphids, as well as powdery mildew, on a range of crops. Oils of rosemary, wintergreen, clove, garlic and lemon are also sold and reported to have insecticidal properties. Certainly as insects and plants coevolved, plants developed defense compounds to ward off attack by these herbivores. The isolation of these compounds could provide useful crop-protection tools in the future, but they are not cost effective in commercial agriculture today.

Inorganic products. For arthropod control, sulfur is the most commonly used inorganic product. Sulfur has strong fungicidal properties and secondarily controls spider mites. Significant usage for spider mite control occurs annually on grapes, citrus, ornamental plants and cotton.

Petroleum oils and particle films

Petroleum-based oils have been used for a number of years to control insect pests, especially mites and scale insects. Early formulations caused several problems because they had components that were phytotoxic to plants. More recently, petroleum oils have become highly refined and rarely show phytotoxic effects. Their common distillation points are 415 and 440. The heavier 440 oils show greater efficacy, but also more potential for phytotoxicity. The 440 oils tend to be used in fruit and nut trees as dormant applications for mites and lepidopterous and armored scale pests, often in combination with other pesticides. The lighter 415 oils are used for in-season treatments alone or in combination with other pesticides such as spinosad and abamectin. In citrus, 0.5% to 2% oil is used in spring for citrus red mite *(Panonychus citri)* and in the summer as a 1.4% spray for California red scale *(Aonidiella aurantii)*. Phytotoxicity can be avoided by treating during the coolest periods of the day and ensuring that the orchard is well irrigated prior to treatment.

Presently, one product is available in the mineral-based particle film category. Kaolin (Surround) is a naturally occurring product, generally inert to mammals, which does not react with other materials (Glenn et al. 1999). When used as a pesticide, kaolin is sprayed as a powdered suspension on crops, where it forms a barrier film that repels and prevents target pests from penetrating

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Certified organic growers often rely on plant-derived materials such as pyrethrum (extracted from chrysanthemums), azadiractin (from neem seeds), rotenone (from several pea species), sabadilla (from Mexican lilly seeds), cinnamaldehyde (from cinnamon oil) and other natural insecticides.

the leaves or other parts of the plant. To be effective, the suspension must coat all parts of the plants. Kaolin was registered in California in 2000 for home use and commercial agriculture. Its target pests are widespread and include earwigs, thrips, true bugs, aphids, hoppers, whiteflies, scales, beetles, caterpillars and mites. Crop registrations include fruit, vegetable, and field and ornamental crops. Kaolin has been used extensively in grape vineyards to repel glassy-winged sharpshooters *(Homalodisca coagulata)* from landing and transmitting the bacterium *Xylella fastidiosa,* which causes Pierce's disease. However, kaolin caused outbreaks of California red scale in citrus because it prevents natural enemies from gaining access to the scales.

Contributions to IPM programs

Insect pathogens, their insecticidal byproducts and natural insecticides and acaricides will make important contributions to IPM programs in a post-OP era. These pathogens and natural toxins have been known for their pest control properties for decades and will continue to be important niche products in IPM systems. However, the utility of insect pathogens is limited by their specific requirements for growth, survival and infectivity. Certain toxic byproducts of microorganisms are important and robust tools for arthropod management today and may take on an added role in the future. Research advances could overcome the limitations of these control agents and will likely discover and refine other types of natural control strategies.

One such strategy is the area of "induced resistance," whereby plants, once injured by an arthropod, are more resistant to subsequent feeding and injury (Karban and Baldwin 1997). This induction has been shown for mite, thrips, aphid and leafminer injury in crops such as grapes, cotton and celery (Karban et al. 1997; Omer et al. 2001; Black et al. 2003). The isolation of the compounds involved in this type of plant defense and the defining of the scope of the activity is ongoing. One commercial product (Messenger) utilizes this technology through induction with harpin proteins.

Additional new natural pest-control tactics, microorganism byproducts, and natural insecticides and acaricides will likely be discovered to facilitate IPM programs. In conventional agriculture, insecticides and acaricides from microorganism byproducts are the "standards" for the control of certain important arthropods, and some natural products have important niche uses. These products are already important tools against many pests in organic production systems.

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Costs of 2001 methyl bromide rules estimated for California strawberry industry

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Methyl bromide has been widely used in California — especially in strawberry production — to fumigate soil prior to planting and prevent nematodes and other soil-borne pests. The California Department of Pesticide Regulation requires growers to warn the public of possible exposure to the toxic fumigant.

The California Department of Pesticide Regulation (DPR) restricts pesticide use to reduce negative impacts on human health and the environment. The DPR implemented methyl bromide use regulations in 2001. Our study demonstrates that the estimated 2001 costs of these regulations for the California strawberry industry were quite substantial (more than $26 million total), equivalent to roughly 25% of estimated industry returns over total cash costs in 2001. These impacts were unevenly distributed across growers. Growers with small fields in urban areas had higher per-acre costs than growers with large fields in agricultural areas.

The California Department of Pesticide Regulation's (DPR) mandate is to protect human health and the environment from the negative effects of pesticide use (Federighi 2001). In order to achieve this goal, the DPR uses a number of regulatory tools, including pesticide use restrictions. Use restrictions are rules that are not included on the pesticide's label, such as buffer zones or application limits based on the treatment date or location. Some use restrictions are intended to protect the applicator's health, such as protective equipment requirements or limits on the hours of exposure. Other use restrictions are intended to protect other people from exposure. Local environmental impacts may be reduced by measures such as prohibiting applications when the ambient air temperature is above a specified threshold.

The DPR's use regulations are administered through a permit process. In order to apply a restricted-use pesticide, the grower must obtain a permit from the county agricultural commissioner. Based on scientific assessments of the potential effects of a pesticide on human health and the environment, the DPR provides the commissioners with "suggested permit conditions," which reflect DPR's judgment regarding "minimum measures necessary to protect people and the environment" (Federighi 2001). At their discretion, commissioners may alter these conditions to reflect local circumstances.

We examined the cost impact of use regulations imposed in 2001 on methyl bromide, a widely used preplanting soil fumigant, on the California strawberry industry. Human exposure to high concentrations of methyl bromide can be irritating to the eyes, airways and skin, while acute and chronic exposure can lead to a degeneration of nerve cells. The regulations were aimed at reducing human exposure to methyl bromide by limiting emissions and restricting human activity near fumigation sites.

Furthermore, under the United Nation's Montreal Protocol on Substances That Deplete the Ozone Layer, methyl bromide is scheduled to be banned in the United States and other developed nations in the 2005 calendar year (but an exemption process allows critical uses to receive temporary waivers). The ban has been gradually phased in; the permissible quantity of methyl bromide sold nationally is declining, and the rate of decline is linked to a percentage of 1991 consumption. As of 2001 when we conducted our study, the main effect of the phase-out requirements on California strawberry growers was a higher price for methyl bromide, whereas in some other crops use had declined substantially. Overall, methyl bromide usage in California strawberry production had not declined dramatically, and remained at about 3.8 million pounds in 2001 (table 1). Since 2001 the use of methyl bromide in strawberry fields has not substantially declined.

Strawberry growers fumigate the soil prior to planting in order to control weeds, nematodes and other soil-borne pests. While there are chemical alternatives to methyl bromide for strawberry production, their future availability is also in question due to human health and environmental concerns. At the present time, one alternative fumigant, Growers in areas with higher population densities were much more likely to be heavily affected by the buffer zone, permission and notification requirements.

TABLE 1. Methyl bromide (MBr) usage in California, 1996–2003

Year	Total MBr applied in California	MBr applied to strawberries	Strawberry share of MBr usage	Calif. strawberry acreage using MBr	MBr applied per acre to strawberries*
	lb.	*lb.*	%		*lb.*
1996	16,022,069	4,383,611	27	21,345	205
1997	15,663,832	4,050,264	26	21,746	186
1998	13,569,875	4,257,364	31	20,291	210
1999	15,342,080	5,175,568	34	25,493	203
2000	10,862,836	4,234,905	39	22,580	188
2001	6,615,844	3,777,550	57	22,241	170
2002	6,594,515	3,706,589	56	20,501	181
2003	7,562,718	3,671,982	49	20,593	178

* Rate calculated using all MBr applied to strawberries, not only MBr reported on an acreage basis. Nonacreage use was less than 1% of strawberry use in 2002.

Source: DPR 2003.

1,3-D, is on California's Proposition 65 list of chemicals known to increase the risk of cancer, and is subject to township caps; these limits are intended to regulate lifetime exposure to 1,3-D. Another chemical alternative, chloropicrin, is currently being evaluated by the DPR under its risk assessment process. In 2001, all chloropicrin products were put into reevaluation by the DPR due to potential negative health effects at low doses (DPR 2004).

The overall economic impacts of the global methyl bromide ban are also unclear. Analyses of the economic viability of methyl bromide alternatives using field trial results have had mixed results (Goodhue et al. in press). According to DPR's pesticide use report, in 2002 roughly 25% of California's strawberry acreage was fumigated using methyl bromide alternatives, which suggests that some growers find them economically superior to methyl bromide (DPR 2003). It is difficult to evaluate the contribution of the DPR use regulations to this shift.

Our analysis focused on the impact of the 2001 methyl bromide use regulations on industry costs. We did not incorporate any changes in industry revenues that may offset these costs, nor did we measure the total social costs and benefits of the regulations. Estimating the human health and other benefits of the 2001 methyl bromide use regulations was beyond the scope of our analysis. Similarly, we did not attempt to measure the costs of the use regulations to anyone besides growers.

California strawberry industry

California's total fresh and processed strawberry sales were $805.8 million in 2001. In a typical year, strawberries rank as one of the top 10 most valuable crops in the state (CDFA 2002). In 2001, the leading counties in terms of value of strawberry production were Monterey (32.8%), Ventura (27.4%), Santa Cruz (17.8%), Santa Barbara (9.0%) and Orange (6.2%), together representing over 90% of the total value of production. Every year, growers expend almost $30,000 per acre to produce and harvest strawberries, so even a 30-acre farm has an outlay of about $1 million per year. Based on the UC cost and return budgets for strawberries, statewide net grower returns above total cash costs are roughly $103.7 million (Klonsky and De Moura 2001).

2001 fumigation regulations

The DPR methyl bromide use restrictions imposed in 2001 were complex. Two types of buffer zones were specified: an *inner* buffer zone and an *outer* buffer zone. The size of each buffer zone depended on such factors as the size of the application block (acreage fumigated in a 24-hour period), the application rate, the method of application, the proximity of the field to houses or other occupied buildings, and the willingness of neighbors to allow the fumigation to proceed. For both types of buffer zones, the operator had to obtain permission from the neighboring landowner to extend the buffer zone onto the adjacent property.

Jack Kelly Clark

Due to its impact on the ozone layer, methyl bromide is being gradually phased out. *Above,* one alternative fumigant is a mixture of 1,3-dichloropropene and chloropicrin, which is injected into the irrigation system. However, these chemicals are also subject to strict regulatory controls.

Courtesy of Hussein Ajwa/UC Davis

Shachar Shem-Tov/UC Davis

In 2001, state regulators imposed new regulations on methyl bromide applications, which included buffer zones to limit exposure. The authors found that many strawberry growers were forced to switch from bed fumigation, *left,* where the beds are formed and then treated, to more expensive flat fumigation, *right,* in which the process is reversed.

The inner buffer zone extended a minimum of 50 feet from the edge of the application block, and increased with the size of the acreage block and the application rate. Only individuals involved in the fumigation process were allowed into the inner buffer zone. These individuals were subject to additional use restrictions, which specified the maximum exposure times for various fumigation tasks. The inner buffer zone had to be on agricultural land or a public roadway and could not extend onto any adjacent nonagricultural land.

The outer buffer zone extended at least 60 feet from the edge of the block and increased with the size of the acreage block and the application rate. People were allowed into the outer buffer zone for transit purposes or to "conduct activities approved by the county agricultural commissioner." Here, individual exposure was limited to no more than 12 hours out of any 24. The outer buffer zone was not limited to agricultural land. Even if the buffer-zone requirements were not binding, the 2001 DPR regulations limited total acreage for a single fumigation block to a maximum of 40 acres in any 24-hour period.

A neighborhood notification requirement was also included in the use restrictions. It specified that property owners within 300 feet of the outer buffer zone had to be notified that an application permit had been approved at least 9 days prior to the initiation of fumigation. Those receiving the initial notification could choose to request specific notification of the exact date and time at least 48 hours prior to the initiation of fumigation.

Impacts of regulations

To evaluate the costs of the 2001 DPR methyl bromide fumigation regulations for the California strawberry industry, we collected copies of available, completed fumigation permits and worksite plans for strawberry fields in the five counties producing the most strawberries: Monterey, Orange, Santa Barbara, Santa Cruz and Ventura. In total we collected more than 400 worksite plans and permits for 2001 from the county agricultural commissioners' offices. Simulation analysis was conducted using work-plan data to determine the effects of the buffer zones. This involved the development of a mathematical model of the fumigation regulations; we then asked the model to solve for optimal fumigation practices, given the many different field configurations found in the work-plan data. Our analysis also utilized information from about 20 growers identified by the county agricultural commissioners' offices and encountered at field days and other venues.

Buffer zones. A notable impact of the DPR regulations on growers was that some acreage could no longer be fumigated with methyl bromide due to the buffer-zone requirements. This impact varied by location, field size and field shape. As a result, growers had to replace the strawberries that would have been grown on this acreage with a less valuable crop, or they suffered yield losses on their unfumigated strawberry acreage.

Fields with more nonagricultural borders lost a larger percentage of their total acreage, holding other factors constant. For example, a square 10-acre field with one 50-foot buffer extending into the field itself would not be able to fumigate 7.6% of its total acreage. If it had two adjoining buffered sides, the nonfumigated acreage would increase to 14% of the total; 21.6% and 28% of the total acreage would be nonfumigated for three and four buffered sides, respectively. Fields near urban areas were more likely to be unable to fumigate a greater share of acreage than those in agricultural areas.

For a given buffer-zone restriction, smaller fields lost a larger percentage of their total acreage. For example, a square 20-acre field with one buffered side had 1.07 nonfumigated acres, or 5.4% of the total. In contrast, a square 10-acre field had 0.76 nonfumigated acre, or 7.6% of the total. This difference increased with the number of buffered sides. If all four sides were bordered by nonagricultural uses, the 20-acre field's nonfumigated acreage would be 20.3% of the total, while the 10-acre field's nonfumigated acreage would be 28%.

The difference in percentage of acreage lost increased with the difference in field size. For a square 50-acre field, 3.4% of its acreage would be nonfumigated when it had one buffered side, and 13.1% would be nonfumigated when it had four buffered sides. Average field size by county varies: in the work plans we collected, it ranged from 28.1 acres in Santa Cruz County to 60.4 acres in Ventura County. In Santa Cruz County, 54% of the fields were less than 25 acres, compared with only 24% in

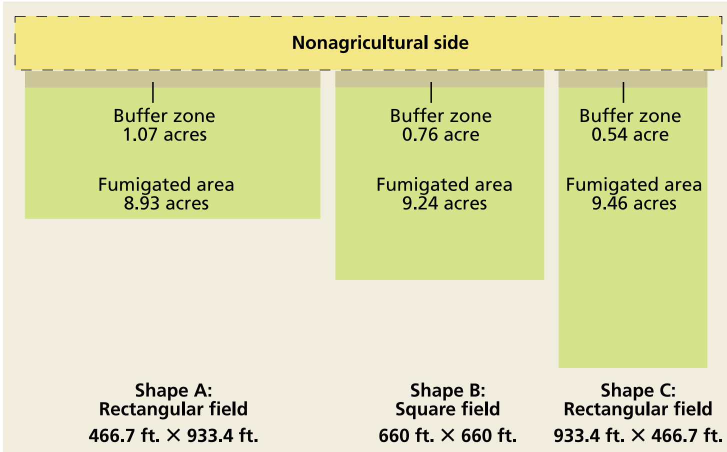

Fig. 1. Hypothetical acreage loss for a 10-acre field due to 50-foot buffer.

Ventura County. Ignoring any systematic variations in field shape and the number of buffered sides, the differences in field size suggest that the impact of the buffer-zone regulations varied across counties.

For a given field size and buffer-zone restriction, field shape also affected the share of nonfumigated acreage (fig. 1). The three fields in the figure are each 10 acres. Each field has one side where the adjacent property is in a nonagricultural use, so that the inner buffer zone reduces the fumigated acreage. For the square field (shape B), the inner buffer-zone requirement reduces the fumigated acreage by 7.6%. In contrast, for the rectangular field with a long side bordering the nonagricultural use (shape A), the inner buffer-zone requirement reduces the fumigated acreage by 10.7%. On the other hand, a rectangular field with a short side bordering a nonagricultural use (shape C) loses only 5.4% of its fumigated acreage. (In figure 1, the long side is twice as long as the short side.)

Our analysis helped to clarify what share in the effects of the regulations across counties was due to differences in field shape, and what share was due to differences in the proximity to residential areas and sensitive sites. We observed that growers in areas with higher population densities were much more likely to be heavily affected by the buffer zone, permission and notification requirements. Growers with smaller fields faced a proportionately greater loss of fumigated acreage than growers with large fields. We used data collected from actual permit applications to determine the acreage for individual fields that could not be fumigated due to inner buffer-zone requirements. Using per-acre net revenue estimates from 2001 cost and return studies by Klonsky and De Moura (2001), we found that there was an industry loss of $3.2 million due to the inability to fumigate acreage comprising inner buffer zones.

Processing-strawberry sales. On average, during the 4 years immediately prior to the enactment of the 2001 DPR regulations, approximately 417 million pounds of California strawberries were sold annually to processors, about 30% of annual production. The 2001 DPR regulations significantly lengthened the fumigation period, disrupting the normal pattern of sales to the processing market. The longer fumigation period reduced sales to the freezer market, because growers had to remove the plants from the previous season earlier than in prior years, which reduced production. Some growers in Southern California lost up to 4 weeks of processing-market sales. Assuming 2,500 pounds per acre per week of processing berries at the 2001 average price of 30.6¢ per pound (CPSAB 2001), the estimated revenue loss was $765 per acre per week. After harvest costs of about 14¢ per pound, the gross profit on these sales would be approximately $415 per acre per week or 16.6¢ per pound.

Many growers reported that they lost production at the end of the season due to the 2001 DPR fumigation regulations. Data from the California Processing Strawberry Advisory Board shows a decline in the 2001 freezer volume to 338.9 million pounds (or 25.7% of annual state production). This is below the previous 5-year average of 421.7 million pounds (30.5% of production). We estimate that about three-fourths of the total decline of 82.8 million pounds was due to the DPR regulations. This volume decline of almost 63 million pounds represents an estimated loss of approximately 1 week's production, on average, for every acre in the state. The revenue loss associated with this volume loss was approximately $10.4 million for California growers. This is likely to be a conservative estimate, as some growers lost much more than 1 week.

Additional fumigation days. The 2001 DPR regulations lengthened the time period necessary for methyl bromide fumigation for all growers in the state. As indicated, the extent to which the fumigation period was extended varied by factors such as field shape, location, pounds of methyl bromide applied and fumigation method.

Total fumigation costs per acre increased due to the diseconomies of fumigating relatively small pieces of land each day, with additional costs such as labor and equipment rentals. The diseconomies were more costly per acre for smaller fields. For instance, in Santa Barbara County it took one grower 9 days to fumigate a 9-acre field in 2001. In the same county, it took another grower the same number of days to fumigate a 40-acre field. Based on grower information and budget data, we estimate that nonchemical fumigation costs increased by at least 40% due to the longer fumigation period. This translates into a cost increase of about $400 per acre, resulting in an estimated industry loss of about $10 million. In all likelihood, this is a conservative estimate of the higher costs.

Bed vs. flat fumigation. Due to regulatory specifications for emissions ratios, the buffer-zone requirements were much more onerous for "bed" fumigation, where only the raised beds are fumigated, than for "flat" fumigation, where the entire field is fumigated

After the methyl bromide rules were implemented, growers reported increased costs and lost income due to lower yields on untreated acreage, reduced sales to the freezer market, and additional labor, equipment and notification costs.

prior to bed construction. The scientific studies consulted by the DPR indicated that bed fumigation had a much larger emissions ratio than flat fumigation, so that human exposure to methyl bromide was much greater given the amount of methyl bromide applied. In order to provide the same protection for human health, larger buffer zones were required for bed fumigation. Due to the larger buffer zones and the associated loss of fumigated acreage, some growers found it preferable to switch to flat fumigation. Flat fumigation is much more expensive, however, at least an estimated $1,000 per acre more than bed fumigation. This regulation benefited pesticide applicators, because most growers did not have the equipment necessary for flat fumigation and had to hire custom applicators.

Growers in Santa Barbara County were most affected by the 2001 DPR regulation. There are more than 3,000 acres of strawberries grown in Santa Barbara County, and this acreage was virtually all bed-fumigated prior to the growing season. In order to maintain economic viability, county producers switched between 20% and 25% of these acres from bed to flat fumigation in 2001, requiring a move to commercial applicators and increasing application costs for county producers by about $700,000. The switching costs in Ventura County were estimated at about $500,000 (500 acres); Monterey County, $700,000 (700 acres); Santa Cruz County, $300,000 (300 acres); and Orange County, $200,000 (200 acres). Total switching costs are therefore estimated to be approximately $2.4 million for 2001.

Notification costs. Overall, our analysis of the work-plan data indicated that notifications, and notification costs per acre, varied substantially across fields. Smaller fields tended to have higher notification costs per acre. Fields near urban areas or rural residential developments had a larger number of notifications and higher notification costs per acre, on average. The estimated notification costs ranged from $1.67 per acre in Santa Barbara County to $9.66 per acre in Orange County. However, the Orange County estimates were based on a relatively small sample, so those estimates may not accurately reflect average costs per acre for all fields, and the Santa Barbara estimates excluded prefumigation 48-hour notices, underestimating per-acre costs.

Based on information from growers, the average notification required 30 minutes to prepare the paperwork plus travel time to notify the neighbor (sometimes including multiple trips to find the neighbor at home). We valued the management/supervisor labor used for conducting notifications at $20 per hour, or roughly twice the cost of field labor. Together, these values indicate that the average per-acre notification costs were approximately $10, excluding mileage, copying and other costs. The overall notification cost was estimated by weighting the individual county estimates by production. This generated an average cost of about $5 per acre, or $125,000 for the state.

TABLE 2. Estimated statewide costs of 2001 DPR methyl bromide use restrictions to California strawberry growers

Cost	$ (millions)
Applying buffer zones	3.2
Lost processing-strawberry sales	10.4
Additional fumigation time	10.0
Switch from bed to flat fumigation	2.4
Notification	0.125
Total	26.125

Where do the regulations stand now?

Impacts on growers are just one part of the regulatory environment for agricultural chemicals. A complex set of political and legal processes came into play with the 2001 methyl bromide use regulations, and cost-benefit analyses that can be done using economic impacts are just one part of the picture. In February 2002, San Francisco Superior Court Judge A. James Robertson set aside the regulations. He ruled that the DPR improperly set up the regulations and should have consulted with the California Department of Food and Agriculture before implementing them.

The court ruling also imposed a new requirement that state agencies must consider the economic impact of the proposed regulations, although it is not entirely clear that such consideration will have any effect on regulations. In response, in 2002 the DPR introduced emergency regulations for methyl bromide application. A slightly revised version of the 2001 regulations was permanently introduced in November 2004 (see page 5). For the purposes of our analysis, the only notable difference between the 2004 permanent regulations and the 2001 temporary regulations is that the minimum, inner buffer-zone

Near Salinas, strawberry fields are directly adjacent to residential areas. If growers choose not to farm at the rural-urban interface due to regulatory concerns, such agricultural lands could be at greater risk of conversion to residential or commercial uses.

was reduced from 50 to 30 feet for very low emissions per acre and relatively small application blocks.

Costs of regulation considered

State-level pesticide use regulations are intended to protect human health and the environment. Our analysis does not imply that such regulations are not socially desirable, or that they are excessively costly when compared to their benefits. Rather, it estimates the costs of a specific set of regulations and illustrates how the cost burden of such regulations was distributed across growers. In many cases, such information can be used to suggest alternative sets of regulations that achieve the same health outcomes at a lower cost to growers.

We conclude that the short-term impact of the 2001 DPR use regulations for methyl bromide to growers in the strawberry industry was significant, with the total estimated costs exceeding $26 million (table 2). The two most significant components were the reduction in the volumes marketed for processing, due to the increased time needed to fumigate for the following season, and increased fumigation costs. To the extent that growers found it difficult to implement a plan consistent with the DPR regulations, or difficult to arrange a fumigation schedule, we have understated impacts on those growers. To the extent that industry revenues increased due to reduced production, especially for processed strawberries, our estimate of increased costs overstates the effect of the regulations on industry profits.

We found that the costs were unequally distributed across growers. Growers in urbanized areas, especially with small fields, were affected the most on a per-acre basis. Differences in the estimated emissions of different application methods led to large per-acre differences in the cost of the regulations for different growers. Some growers were forced to change their fumigation method and hire commercial applicators. In addition, grower costs increased because, in many cases, it took three to four times longer to fumigate each field. The extended fumigation period also reduced revenue from the processing market for the old crop.

Apart from the direct evaluation of the industry costs of the 2001 methyl bromide use regulations, our analysis illustrates three general issues associated with use regulations. First, regulations that alter the timing of pesticide application, by limiting acres or hours of applicator exposure per unit of time, may have costly indirect effects. In the case of strawberries, the harvest season was truncated by the lengthened application period, which reduced industry revenues. Second, regulations that vary by application methods may have different effects on the costs of different application methods. In the case of strawberries, the buffer-zone specifications resulted in so much lost acreage under bed fumigation that many growers were forced to move to more-expensive flat fumigation and hire commercial applicators. Third, buffer-zone regulations designed to limit human, nonapplicator exposure will have unequal effects across growers.

The types of costs borne by growers provide an indication of those that may accompany new restrictions on other chemicals. Our findings illustrate that new pesticide regulations may contribute to the increasing cost and difficulty of farming at the urban-rural interface, especially when agricultural areas are fragmented. If so, this type of regulation will encourage growers to stop farming at the interface, which may increase the rate of agricultural land conversion for residential and commercial construction. Accordingly, such regulations may influence the spatial distribution of California agriculture and may reduce the amount of open space remaining near California's urban areas.

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2004 Index

The following research articles, news stories and editorials appeared in *California Agriculture*, Volume 58, Numbers 1 through 4, January through December 2004; numbers are Jan-Mar (1), Apr-June (2), July-Sept (3) and Oct-Dec (4). Back issues may be purchased for $5 per copy, while supplies last; make checks payable to UC Regents. The complete contents of all 2004 issues, including PDF versions of research articles, can be found online at http://CaliforniaAgriculture.ucop.edu.

*** Sidebars.**

COMINGUP

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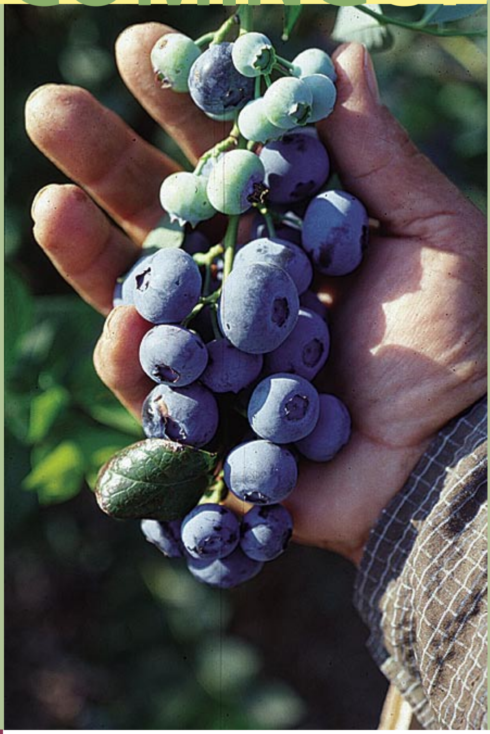

Courtesy of Manuel Jimenez

At the UC Kearney Research and Extension Center, research is developing sound information on cultivar selection and verifying production practices to assist Central Valley growers in establishing blueberries, a potentially lucrative specialty crop.

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