JANUARY–MARCH 2011 • VOLUME 65 NUMBER 1

California Agriculture

Growing bigger, better:
Artisan olive oil comes of age

Sustainable food systems: The global picture

Worldwide, public and private investments in agriculture and natural resources research benefitting our food systems have been enormously successful. These investments have fostered innovation and new technology, improved food security and human nutrition, developed new tools to maintain essential natural ecosystems, and generated economic benefits to producers, processors and consumers alike. Looking ahead, however, many signs point to the sobering reality that our current pace of innovation and gains in agricultural productivity will not be enough.

By 2050, the world population will top 9 billion people. Most of that growth will come in the world's developing countries. Improving dietary standards in rapidly developing economies like China and India have already increased demand for calories and protein, putting upward pressure on world cereal and oilseed prices while also increasing volatility in world markets. From a natural resources perspective, the United Nations estimates that in order to meet nutrition goals, world demand for water for irrigation will double by 2050, while demand for forest products is expected to increase 40% by 2060. Perhaps most compelling, global food demands are expected to double by the middle of the century.

At the same time, our understanding of the expected impact of global climate change points to more stress on the global food system. Populations in the developing world, already vulnerable to food insecurity, will likely be the most seriously affected. The International Food Policy Research Institute (IFPRI) just published a study on the impact of climate change on global agriculture, which suggests that climate change will result in additional price increases for the world's most important agricultural crops: rice, wheat, corn and soybeans. Increasing crop prices will in turn put upward pressure on feed, animal products and meat. Higher temperatures, especially in agriculturally important areas of the developing world, will reduce the yields of desirable crops, while changes in the amount and timing of precipitation will increase the likelihood of short-term crop failures and long-term production declines.

The message is clear. The historic challenges to produce safe and abundant food and fiber, to address poverty while safeguarding the environment and guiding sustainable energy development, and meanwhile to stimulate economic growth and jobs, must all now be assessed in the context of climate change and the need for sustainable development at the global level.

Feeding the world amid a changing climate forces us to critically review our traditional models and to realign our thinking with new priorities.

Dan Dooley
Vice President, Agriculture and Natural Resources
Senior Vice President, External Relations

The Merriam-Webster dictionary defines sustainable as "of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged." For those of us engaged in agricultural research and extension, the term sustainability has often focused on farm-scale practices and solutions and regional food-system issues. The rapidly emerging international view is that sustainability must be considered in a global context, especially as it relates to food production, environmental and social protection, and climate change.

Moreover, there is increasing awareness that intensive agriculture must and will play new roles in sustainable food systems, and that productivity gains from research, innovation, new technologies and education are essential. Feeding the world amid a changing climate forces us to critically review our traditional models and to realign our thinking with new priorities.

We must recognize that enhancing food security and adapting to climate change go hand-in-hand.

We must develop agricultural sustainability programs and policies that contribute to food security and climate change adaptation.

We must develop technologies to sustainably produce more with less.

Investment in research, development and delivery is a moral imperative.

We already know that meeting local and global food demand will require diverse production systems, and that those systems must make key adaptations based on understanding the biology of climate change, new pests and diseases, and crop adaptations. We also know that the challenges for public policy, resource management and science agencies are growing exponentially and intersect as never before.

For all segments of the University of California's Division of Agriculture and Natural Resources, these challenges offer both exciting opportunities to foster innovation through research and outreach, and great responsibility to align our priorities with those issues where we have the greatest potential to make the biggest difference.

Find links to resources for this editorial at: http://ucanr.org/repository/CAO/issue.cfm?issue=current

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News departments

For more information on California olives and olive oil health benefits, visit *California Agriculture*: http://californiaagriculture.ucanr.org

Editor's note:

Thank you to more than 10,000 subscribers who have renewed their subscriptions!

At the end of January, we will purge our mailing list. You can still renew for a short time or start a new subscription at: http://californiaagriculture.ucanr.org/subscribe.cfm

Research and review articles

The olive engravings used throughout this issue are from *The Olive in California* by Byron M. Lelong, published in 1888 and reprinted in *California's Olive Pioneers* (Robert Mondavi Institute for Wine and Food Science, 2009).

About California Agriculture

California Agriculture is a quarterly, peer-reviewed journal reporting research, reviews and news, published by the Division of Agriculture and Natural Resources (ANR) of the University of California. The first issue appeared in December 1946, making it one of the oldest, continuously published, land-grant university research journals in the country. The print circulation is currently about 15,000 domestic and 1,800 international, with a strong online presence.

Mission and audience. *California Agriculture*'s mission is to publish scientifically sound research in a form that is accessible to a well-educated audience. In the last readership survey, 33% worked in agriculture, 31% were faculty members at universities or research scientists, and 19% worked in government agencies or were elected office holders.

Indexing. The journal is indexed by AGRICOLA; Current Contents (Thomson ISI's Agriculture, Biology and Environmental Sciences, and the SCIE databases); Commonwealth Agricultural Bureau (CAB) databases; EBSCO (Academic Search Complete); Gale, including Lexis-Nexis; Google Scholar; Proquest; and others, including open-access databases. It has high visibility on Google and Google Scholar searches. We post all peer-reviewed articles to the California Digital Library's eScholarship Repository.

Authors and reviewers. Authors are primarily but not exclusively from ANR; in 2008, 15% were based at other UC campuses, or other universities and research institutions, and 13% in 2009. In 2008 and 2009, 14% and 50% (respectively) of reviewers came from universities and research institutions or agencies outside ANR.

Rejection rate. Our rejection rate ranged between 20% and 25% in the last three years, In addition, associate editors and staff sent back 24% of manuscripts for revision prior to peer review.

Peer-review policies. All manuscripts submitted for publication in *California Agriculture* undergo double-blind, anonymous peer review. Each submission is forwarded to the appropriate associate editor for evaluation, who then nominates three qualified reviewers. If the first two reviews are affirmative, the article is accepted. If one is negative, the manuscript is sent to a third reviewer. The associate editor makes the final decision, in consultation with the managing and executive editors.

Editing. After peer review and acceptance, all manuscripts are extensively edited by the *California Agriculture* staff to ensure readability for an educated lay audience and multidisciplinary academics.

Submissions. *California Agriculture* manages the peer review of manuscripts online. Please read our Writing Guidelines before submitting an article; go to http://californiaagriculture.ucanr.org/submit.cfm.

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WHAT DO YOU THINK?

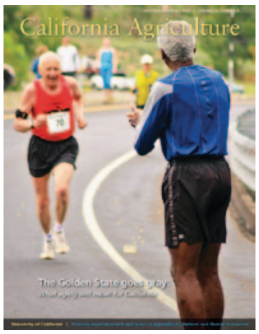
The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at: 1301 S. 46th St., Building 478 - MC 3580, Richmond, CA 94804 or calag@ucdavis.edu. Include your full name and address. Letters may be edited for space and clarity.

UC plant pathologist on cover

Editor's note: For the cover of the October-December 2010 issue ("The Golden State goes gray: What aging will mean for California"), we ran a stock image of senior runners at Lake Tahoe. The image was posted on Shutterstock with no information identifying the runners. We were delighted to receive the following letter.

That's my father on the cover!

My father is Donald C. Hildebrand, who was a plant pathologist at UC Berkeley until about 1992. He earned his Ph.D. there but is now retired. He and several collaborators named three new bacterial species that affected plants, and published a paper showing for the first time that crown gall of plants could be cured.



October-December 2010 *California Agriculture*

Several years ago I attended a dinner with him at UC Berkeley, where he was honored for donating enough money from the family to establish the Hildebrand-Laumeister Chair in Plant Pathology.

This picture was taken last year by my sister, Karin Hildebrand Lau of Sacramento, at a relay race in Tahoe. He was 77 in that photo. He now resides in Sisters, Ore., and will be 79 in a few months. He still actively runs every chance he can and is quite an inspiration! The runner with his back to the camera is Joe McCladdie, another member of the Lake Merritt Joggers & Striders' Over 70 team.

Thank you so much for choosing such a wonderful cover. This is certainly the way I will always remember him.

Katie Hildebrand O'Connor
Granite Bay

Father doubles artichoke yields

Editor's note: We received the following letter regarding Joseph Giannini, a grower from Pescadero who co-authored an article in the October 1973 issue, "Magnifico...a promising new globe artichoke variety," with Vincent E. Rubatzky, Richard H. Sciaroni and Marvin J. Snyder.

My father, Joseph Giannini, is now 98 years old, and we are putting together a booklet of all he quietly accomplished in the farming of Brussels sprouts and artichokes. Thank you for providing copies of the article that he published in *California Agriculture*.

We lived on a 30-acre farm in the heart of Pescadero in San Mateo County, and artichokes were his main crop. My father was born in Jackson, Amador County, on March 24, 1912. My grandparents moved the family back to Italy when dad was about 14 months old, and then came back to America when he was 17 so that he wouldn't lose his citizenship. He arrived with 16 cents in his pocket. He made it to Half Moon Bay and worked on farms, married my mother Mary Neves from Pescadero in 1941. They moved to Santa Cruz, where he and a friend trucked produce up and down the coast for a few years and then went into farming again.

October 1973 *California Agriculture* article on artichoke varieties

He had a Brussels sprouts farm in Davenport for 3 or 4 years and then purchased the 30 acres in Pescadero and planted artichokes. He harvested them from fall to spring and then cut down the plants and waited for the crop to produce again in the fall, which was the norm for raising artichokes at that time. After a few years, he began stumping the artichokes, removing the dried stalks that had produced the buds and leaving room for new growth. He increased his annual production from about 275 boxes to 500 boxes per acre. He worked with Richard (Hank) Sciaroni, keeping charts on the barn door as to whatever he was doing, and did this with a 3-year school education (in Italy).

Martha Giannini Muzzi
Moss Landing

H. White joins Cal Ag, CSIT staff

Nancy Warner

Hazel M. White

California Agriculture is pleased to announce that Hazel M. White has been hired as part-time senior editor. White will split her time between *California Agriculture* journal and the publications unit of Communication Services and Information Technology (CSIT), with responsibility for proofreading, copyediting, indexing and writing. White has more than 20 years of experience in editorial work, with a focus on gardening and horticulture. She served as managing editor for a new edition of the *Sunset Western Garden Book*, and continues to write *Sunset* magazine's monthly "What to do in your garden" feature. She is the author of 11 books, and has written numerous newspaper and journal articles on gardening, landscaping, sustainability and urban farming. White can be reached at hmwhite@ucdavis.edu.

New methods are transforming table olive and olive oil production in California

Olive production is evolving rapidly in California. The state's traditional, labor-intensive table olive culture is giving way to super-high-density, mechanically harvested plantings of the fruit for oil.

"The next decade could see California producing a significant amount of the olive oil consumed in the United States," says UC Cooperative Extension (UCCE) farm advisor Paul Vossen, whose work has helped cultivate California olive oil as a unique and growing agricultural market (see page 8).

Meanwhile, scientists are closing in on a mechanical harvesting system for table olive trees that could save the industry from being crushed by oppressively expensive hand-labor harvesting costs.

A long and storied history

Native to the Mediterranean region, olive cultivation began some 7,000 years ago for use as food, a beauty aid, in ceremonies and as fuel. The utility of olives is chronicled in ancient Egyptian hieroglyphics, Greek mythology, the Bible and Quran, Shakespeare's sonnets and innumerable cookbooks, old and new. Today, olives are the most extensively cultivated fruit crop in the world.

In 1769, the first olive cuttings were planted in California at the Mission San Diego. During the 1800s, many small olive plantations existed around the state, but a statewide industry didn't emerge until German immigrant Freda Ehmann of Oroville, working with Professor Eugene Hilgard of UC Berkeley, perfected the ripe-olive curing process at the turn of the century.

Canned black olives (which producers market as "black-ripe" olives) became a quintessential California product. Mild, versatile and meaty, California olives flavor pizza and Mexican dishes and appear on relish trays and in tapenade. Currently, California has about 27,000 acres in table olive production, the bulk in Tulare, Tehama, Glenn and Butte counties.

Olives are the most extensively cultivated crop in the world. *Below,* Lucca, a new variety developed at UC Davis, grows in a test plot.

Alexandra Kicenik Devarenne

Canning olive tonnage has declined in the past 5 years, but the price per ton has been steadily improving. In 2006, farmers harvested 123,589 tons of canning olives valued at $700 per ton, but in fall 2009, 23,034 tons were harvested valued at $1,200 per ton.

Just two major canneries process California table olives: Bell Carter Olive Company in Corning and Musco Family Olive Company in Tracy. The harvest runs from September to November, with crews climbing ladders to hand-pick the thousands of olives on a typical tree, labor that consumes 45% to 60% of table olive producers' gross returns.

UC Davis plant sciences specialist Louise Ferguson is working with a team of farm advisors to develop mechanical harvest methods for table olives, a particularly challenging task because of the high quality standard.

"There is zero tolerance for bruised fruit in the canned product," Ferguson says.

The scientists are studying two options — trunk shaking and canopy contact — but both have problems. With age, the trunks of olive trees become stout, fluted and knobby, which hinders mechanical shaking. Canopy contact is complicated by harvest timing. The fruit must be harvested before it is fully ripe, so significant force is required to remove them from the tree.

"Both methods now produce acceptable olives with about 65% harvesting efficiency," Ferguson says. "However, with some tree pruning and the development of a suitable conveying and catching platform for the harvesters, I believe that machines could be commercially available in 2 years."

Olive fruit fly

Olive fruit fly is a severe threat to all California olives. A pest for at least 2,000 years in Mediterranean olive production, it first appeared in California in 1998 and quickly spread to all commercial olive-growing regions in the state (see pages 14, 21 and 29).

The female olive fruit fly lays her eggs in immature fruit. After they hatch, feeding larvae destroy the pulp and introduce microbes that rot the fruit. For table olives, the presence of even a few infested fruit can lead to rejection of the entire crop. Oil olives can tolerate some infestation, as long as the fruit are not rotten.

Super-high-density orchards

During the last century, most of the olive oil used in California was imported from Spain and

Italy. Interest in local products, greater awareness about the health benefits of olive oil, and a growing appreciation for fine olive oil's unique flavor has buoyed the California olive oil industry.

In traditional olive orchards, about 50 trees per acre were often planted 30 feet apart, giving them plenty of space to reach their full natural size. Productive orchards have been maintained in some parts of the world for 100 years or more. But scientists, interested in boosting yield per acre, reducing labor costs and bringing olive plantations into full production quickly, have developed a new, super-high-density, hedge-row olive production scheme (see page 34). About 10 years ago, Spanish investors planted California's first super-high-density olive plantation near Oroville. The idea took off.

"They've introduced super-high-density all over the world — Chile, Australia, Portugal," says Joe Connell, UCCE farm advisor for Butte County. "The method was developed by a nursery near Barcelona, the largest olive nursery in the world. You can imagine the potential sales for a nursery when producers need more than 600 trees per acre to establish an orchard."

In addition, older olive tree trunks and branches become woody and gnarled, characteristics that will interfere with mechanical harvesting. The super-high-density orchards being established now may have to be removed and replaced in just 15 to 20 years, Connell says.

According to a 2009 UC Davis Olive Center survey, 12,137 acres of super-high-density olive trees were planted in California by the end of 2008, with 92% of growers reporting that they planted the trees between 2005 and 2008. Many of the plantations are coming into production right now.

Dan Flynn, director of the Olive Center, says California olive oil production numbers are experiencing parallel growth. In 2008, California produced 650,000 gallons of olive oil, and in 2009, 800,000 gallons. In 2010, olive oil production will exceed 1 million gallons. "There's a lot of high quality California oil this year," Flynn says. "California olive oil will be more readily available around the country."

Developing markets for olive oil

Developing a market for the oil will be important to the industry's success. Currently, more than 99% of the olive oil consumed by Americans is imported from other countries. Imported oil is generally cheaper and blander than the oil pressed by California's artisan producers, Flynn says.

In addition, an Olive Center study found that 69% of the imported oils sampled from California groceries had sensory defects. "This study rocked the olive oil world," Flynn says.

California's young olive oil industry uses up-to-date farming and pressing methods to make oils altogether different from European oils, whose producers are following the practices and traditions of the Old World. Fine California olive oils taste as spicy, peppery and pungent as the olives from which they were made.

"California olive oils are not just fats, but are like spices or condiments," says Sonoma County olive oil expert Vossen. "These fine olive oils impart delicious, subtle flavors to food."

With dozens of olive varieties at their disposal, a diversity of climate and soil types, and unconstrained by tradition, California producers are only now beginning to explore the range of flavors that can be coaxed from fine olive oil.

"Flavors range from the green end of the spectrum, with green apple, grass and green tea, to the ripe end, with buttery, nutty and tropical flavors. And they can be found everywhere in between," Flynn says. "Or, you can find all these flavors wrapped up in one very complex olive oil."

— Jeannette Warnert

Karin Higgins

UC President Mark Yudof (right) examines the UC Davis Olive Center's "President's Blend" olive oil, with UC Davis Chancellor Linda Katehi.

Campus trees yield olive oil, body-care products

UC Davis has been producing olive oil from its more than 2,000 olive trees since 2005, keeping the olives — which used to clutter the ground — out of the waste stream while generating revenue for teaching and research at the UC Davis Olive Center.

The center recently launched its "President's Blend" olive oil, and teamed up with UC Davis alumna Kacie Klein to produce a collection of olive-oil-based body-care products including lotion, body butter, hand-cut soap and lip balm.

Nicole Sturzenberger

Olives from the UC Davis campus, which once littered the ground, are now used to produce body-care products.

"These new products are all made with olive oil produced by the campus's historic olive trees, using olives and olive oil that would otherwise have gone to waste," says Dan Flynn, executive director of the Olive Center. The product sales support research into new olive cultivars, mechanical harvesting, olive fruit fly control, olive processing and the sensory evaluation of olive oil.

"Olives have the potential to be one of the leading crops in the state, with UC Davis being a leader in the industry, just like with wine and almonds," UC President Mark Yudof said.

UC Davis olive products are sold in the UC Davis Bookstore and can be ordered online from the its "Campus Produced" section at: http://ucdavisbookstore.com/MerchList/aspx?ID=16472&CatID=3016.

— Editors

REVIEW ARTICLE

UC Cooperative Extension sensory analysis panel enhances the quality of California olive oil

by Paul M. Vossen *and* Alexandra Kicenik Devarenne

California's olive oil industry has evolved from primarily a salvage operation of the table olive industry to a producer of world-class, premium, extra-virgin olive oil. In 1997, UC Cooperative Extension started the first California olive oil taste panel, which was officially recognized by the International Olive Council in 2001. Specific protocols were used to screen potential panelists and train them to identify defects and positive characteristics, identical to 43 other world taste panels. The UCCE panel helped the California Olive Oil Council develop a seal certification program using sensory analysis. Certification provides consumers with assurance that labeled oils are free of defects and warrant the "extra virgin" grade. Sensory evaluation using a unique UCCE profile sheet provides complete and detailed information about specific positive flavor characteristics of olive cultivars grown in California. The UCCE sensory panel has also contributed to a better understanding of the qualities of California olive oil and advancement of the industry by participating in research on pest management, cultural practices and processing.

California sensory panel members evaluate oils at an official tasting.

During the California olive oil revival of the past two decades, a quiescent industry has come dramatically to life (see box, page 9). Acreage planted in oil olives is increasing rapidly. By fall 2010, an estimated 28,500 acres were growing in California, a doubling of acreage from 3 years prior. Interest in planting new orchards is still high, but the economic crisis has reduced the rate of oil-olive acreage growth. A few large producers make about 80% of the state's olive oil, but more than 90% of the farms are small scale with less than 20 acres. Production of premium olive oil in California is predicted to double in the next 3 years from 800,000 to 1.6 million gallons. Many of these oils are excellent, taking top awards in global competitions.

But this was not always the case. The improvement in California's olive oil is due largely to the efforts of a scientifically selected and trained sensory evaluation panel. Only the most rudimentary quality testing on olive oil is currently being done by laboratory chemical analysis; a group of human beings following strict tasting protocols is now the standard tool for detecting, identifying and quantifying the many positive and negative attributes of olive oil.

Although people have been making and using olive oil for thousands of years, the methodical sensory analysis of olive oil is a recent development. Its use in measuring quality was advanced significantly in the early 1980s, when sensory researchers in Spain, Italy, Greece, Portugal and France began working together with the International Olive Oil Council (now the International Olive Council or IOC) to develop the first official tasting methodology. Their work applied the principles of sensory science to olive oil. Sensory evaluation evokes, measures, analyzes and interprets the responses of tasters to the flavors they perceive.

Worldwide, sensory analysis has become a key part of how olive oils are rated for market grade, and it has been used to help growers and processors produce a higher-quality product. Since the late 1980s, many researchers have used sensory evaluation to characterize olive oil flavors attributable to cultivar (variety), fruit maturity, terroir, irrigation, tree nutrition, pest damage, fruit handling and processing methods. Researchers have also taught sensory short courses and workshops for industry professionals and consumers about olive oil styles and quality.

Uses of a sensory panel

A trained sensory panel is an invaluable tool. It provides an objective sensory evaluation of olive oil that can be used by regulators to enforce label standards that protect consumers, producers and processors from fraud in the industry. IOC quality standards are used globally to determine whether an oil should be graded and marketed as "extra virgin" or "virgin," or refined and then sold as "olive oil" (see box, page 10). In order for an oil to be graded as "extra virgin," it must pass several laboratory chemical analyses and be evaluated by a sensory panel. The olive oil must be free of defects and have some fruitiness.

Official IOC tastings that rate oils for compliance to trade standards note the intensity of any defects. Only three positive attributes — fruitiness (either green or ripe fruit), bitterness and pungency — are quantified on the profile sheet. The official IOC profile sheet includes five standard defects: fusty/muddy sediment, musty, winey-vinegary, rancid and metallic. Space is left to note negative attributes other than the classic defects (IOC 2006, 2007c). Beyond evaluating by defined IOC standards, sensory panels help producers make better decisions regarding variety selection, pest management, cultural practices and harvest timing. With qualitative analysis, processors can also better select processing methods to maximize quality and assess how various cultivars might contribute desirable characteristics in blends.

Sensory evaluation in research

Variety. Sensory panels define the attributes of olive varieties and rate them according to the intensity of fruitiness, bitterness and pungency, but also provide an in-depth evaluation of fruit flavor characteristics. The content of volatile aromatics (aroma compounds emanating from the oil) and polyphenols (complex phytochemicals that act as antioxidants) make up much of an oil's flavor, and are highly variable between varieties. Qualitative analysis of the fruity characteristics of an olive oil provides valuable information about the sensory contributions of different cultivars, helping producers to select varieties and market product to consumers (Cimato et al. 1996; Romero et al. 2005; Tura et al. 2000; Uceda and Aguilera 2005; Vossen 2003, 2007a, 2007d).

Fruit maturity. Fruit ripeness can have a significant influence on the oil's flavor. Immature fruit produces oils with green fruity flavors such as fresh-cut grass, herbs, artichoke or mint. More mature fruit yields oils with ripe notes such as nutty, buttery, floral, apple, banana, berry or tropical. Sensory analysis of oils made from greener fruit has shown high bitterness and pungency, which correlates with laboratory analysis showing high polyphenol and antioxidant levels (Alba Mendoza et al. 1997; Romero and Díaz 2002; Vossen 2005).

Terroir. Climate, soil composition and other environmental factors that make up "terroir" may influence olive oil qualities, but this is a continuing area of research. Most scientists have indicated that the influence of terroir is minimal compared to variety and fruit maturity, but some studies have shown that oils from different areas are notably different in flavor (table 1). Sensory characteristics have also been used to identify oils by protected growing region (appellation) (Aparicio et al. 1997; Ranalli et al. 1999; Tous et al. 1997; Vossen 2007c).

Irrigation. Irrigation is the most commonly manipulated grower practice that specifically influences oil sensory

The sensory aptitude of potential tasters is screened by having them arrange oils along a scale for particular attribute intensities.

Olive oil in California

The olive came to California from Mexico with the Franciscan fathers. Although olive oil production likely started within a couple of decades of the 1769 founding of the first California mission in San Diego, the earliest written record is from 1803. After a period of decline in the mid-1800s, olive oil production expanded between 1870 and 1900; the state's first commercial olive oil mill is believed to have been established in Ventura County in 1871. Unable to compete with low-priced oil from Europe, around 1900 the California olive industry turned its attention to table olive production. Table olives dominated the domestic olive scene for more than 75 years. For years, the California olive oil industry was largely a salvage operation, using culls from table fruit production to produce low-quality oil for refining.

In the late 1980s, a small number of growers began to produce high-quality olive oil for the gourmet market. Some of these early producers harvested existing trees that had been regarded mostly as messy ornamentals for years. But other growers, for the first time in decades, planted olives with the intention of producing oil. Acreage of table olives declined during the same period, primarily because of competition from inexpensive imports in the California-style black olive market.

A 2004 survey of the California olive oil industry found 528 growers in 38 counties, producing almost 400,000 gallons of oil on 6,170 acres. From 2005 to 2008, another 13,400 acres were planted, and in the last 2 years an estimated 9,000 more have gone in, mostly in super-high-density orchard systems (see page 34). California olive oil currently represents only 2% of domestic consumption, so there is a vast market to be tapped. Since the domestic industry is producing extra-virgin olive oil that is as good as imports, consumer education and the enforcement of quality standards may be key elements in capturing more of the domestic market.

For more information go to: http://cesonoma.ucdavis.edu.

qualities (table 2). Large flavor differences have been documented in oils from trees given different amounts of irrigation water (ranging from 15% to 107% of seasonal need). Drought-stressed trees tend to produce excessively bitter and pungent oils. Trees maintained with a moderate water status (controlled deficit) tend to produce oils with higher overall fruitiness that is balanced with bitterness and pungency. Heavily watered trees generally produce bland olive oils with little fruitiness or pungency (Berenguer et al. 2006; Salas et al. 1997).

Olive fruit fly. Sensory evaluation of oils made in California from fruit with different levels of olive fruit fly damage showed that the conventional 10% threshold was often too conservative, and too generic to predict senory impacts. In blind sensory evaluations, no significant flavor differences could be detected in fresh oil from early damage by fly larva prior to the onset of soft fruit rot, even when fruit was 100% damaged. In 2008, however, the sensory panel found that off flavors could immediately be detected when fruit rot ranged from 1% to 5%. Therefore, with early harvest and rapid processing, minor olive fruit fly damage can be tolerated, which can save treatment costs and reduce environmental contamination (Hermoso et al. 2001; Vossen, unpublished data; Vossen and Kicenik Devarenne 2006a).

Harvest, transport and storage. Most olive oil defects come from improper handling of the fruit during and after harvest. If the fruit is compromised in any way, it should be milled within 24 hours of harvest. This includes broken skins, storage at temperatures above 40°F (5°C) or fermentation beginning in piled fruit (García et al. 1996).

Washing and leaf removal. In Italy and Spain, researchers found that when fruit was clean and dry (unwashed), it produced oils with a consistently better sensory rating than if clean and wet (washed) due to the lower moisture content of the paste. Normally, all leaves are removed, but researchers found that some leaves (up to 3%) left in the olives during crushing gave the oil more bitterness, green fruitiness and green color. This could be desirable if these characteristics are lacking (Hermoso Fernández et al. 1991; Di Giovacchino et al. 1996).

Crushing. Differences in paste characteristics have been demonstrated to produce various effects on oil sensory quality. Finer pastes tend to release more oil that possesses greener color and stronger herbaceous, grassy, sweet almond and cypress wood flavors. Coarse paste tends to produce less bitter and pungent oils (Di Giovacchino 1996; Koutsaftakis et al. 2000).

Malaxation. Changing the time, temperature and amount of oxygen exposure during malaxation (slow mixing) of olive paste influences the oil's

Olive oil definitions and regulations

Extra virgin and virgin. "Extra virgin" is a grade of olive oil narrowly defined by the International Olive Council (IOC). Its standards require oil to be produced entirely by mechanical means, without the use of solvents, under temperatures that will not degrade the oil (less than 86ºF [30ºC]). It must have a maximum free-fatty-acid level of less than 0.8% (an indication of the fruit's condition) and a peroxide value of less than 20 milliequivalent O_2 (a measure of oxidation). Most importantly, a trained and IOC-recognized sensory evaluation panel must find it free from defects and possessing some degree of fruitiness. The next grade of olive oil is "virgin," which may have a free-fatty-acid level up to 2% and some slight flavor defects.

The California Olive Oil Council awards the extra-virgin certification seal to member oils that are defect free.

Common and lampante. The grades "common" and "lampante" (lamp oil) are lower still, for oil possessing more pronounced defects. Lampante oil must be refined before it is usable.

While these standards are widely recognized in the United States, there is no guarantee that an oil labeled "extra virgin" meets IOC standards. In October 2010, new voluntary USDA standards for olive and olive pomace oil went into effect, essentially adopting the IOC laboratory and sensory standards. California, Connecticut and Oregon have done the same at the state level. Hopefully, these new standards will be broadly adhered to in the United States to protect both consumers and ethical producers.

TABLE 1. Sensory attributes of 'Arbequina' olive oils grown in three different zones in Spain

Attribute	Siurana	Garrigues	Andalucía
Fruity	2.4	2.2	3.1
Green	1.5	1.4	1.8
Bitter	1.1	1.8	0.6
Pungent	1.6	1.7	0.6
Sweet	1.8	1.8	2.4
Sensory rating*	7.7	7.4	8.9

* European Union rating scale, 0–9 points.
Source: Tous et al. 1997.

TABLE 2. Means of sensory characteristics of oils from trees receiving different amounts of irrigation

Treatment (% ETc)*	Fruity	Bitter	Pungent
15	3.60a†	6.00a	4.90a
25	3.20a	4.20b	3.90b
40	2.70b	1.70c	1.90c
57	2.60b	0.93d	1.10d
71	2.10c	0.30d	0.30e
89	1.80c	0.22d	0.22e
107	1.70c	0.20d	0.20e

* Evapotranspiration rate (water use by olive trees) with a coefficient corrected for olive trees compared to a general reference rate.
† Different letters indicate values significantly different at $P = 0.01$.
Source: Berenguer et al. 2006.

sensory characteristics. Longer malaxation times increase oil yield, lower polyphenol levels and lower the levels of aromatic volatiles responsible for some fruity flavor characteristics. Raising the paste temperature causes greater extraction of polyphenols, but every 22°F (12°C) increase in temperature doubles the loss of volatile aromatics. Paste malaxed at 95°F (35°C) produces oil that is sharply bitter compared with at 77°F (25°C). Malaxation tanks that exclude oxygen significantly increase bitterness and pungency. Many researchers are currently investigating the effects of low oxygen exposure on aromatic compounds that influence fruitiness (Angerosa 2002; Di Giovacchino et al. 2002; Hermoso Fernández et al. 1991).

Extraction system. Press systems have consistently produced oils with more defects than continuous-flow systems. Sensory evaluation of oil from continuous-flow processing systems that use different amounts of added water have shown that oils are higher in fruitiness, bitterness, pungency and green character when less water is added (Alba Mendoza et al. 1996; Hermoso Fernández et al. 1998; Kicenik Devarenne and Vossen 2007a).

Oil styles and excellence recognition. Providing industry professionals with accurate evaluations of olive oil flavor characteristics is extremely important. With flavor profiles of their oils, producers can make well-informed decisions about the styles of olive oils they want to produce, and consequently, better olive oils. UC Cooperative Extension (UCCE) has produced several informative handouts on how to define extra-virgin olive oil and interpret an olive oil label, and how untrained tasters can inadvertently promote the use of defective oils. Many untrained tasters are average consumers who are accustomed to defective flavors, identifying them with the taste of olive oil (Kicenik Devarenne and Vossen 2007b; Vossen 2007a; Vossen and Kicenik Devarenne 2006b).

The California sensory panel

During a 1996 study leave, farm advisor Paul Vossen realized that Europeans understood olive oil quality and were using sensory analysis to describe and promote positive characteristics. They were also using sensory analysis to weed out poor-quality oils and educate producers about defects, to help them avoid making production mistakes.

In 1997, the first California screening for sensory panel members was conducted at UC Davis, with the aid of Juan Ramon Izquierdo from the Spanish Arbitration Laboratory in Madrid. Using IOC procedures, potential panelists were screened for olfactory and gustatory sensitivity and also for motivation, availability and personality (IOC 2007a). Twenty people out of 75 were selected. Subsequent screenings added another 26 panelists. Altogether, 46 tasters were selected out of 217 applicants (21%). About half of those have chosen to remain active.

Olive fruit fly is a major pest of olives. The sensory effects of infestation depend on both the quantity and type of damage.

Trained panel members' minds and palates must become calibrated over time to an absolute scale of intensities for all the common flavor attributes of olive oil. The calibration process takes several years and is not permanent; panelists must continually receive training if they are to remain sharp. Training is conducted by a panel leader who provides the group of tasters with samples of known characteristics and intensities in order for them to learn and remember specific positive and negative attributes. Panelists must also taste oils from all over the world to learn the characteristics of each variety, so that varietal differences are not confused with defects.

The IOC recognizes sensory panels that are approved by a government agency such as the U.S. Department of Agriculture. Panels from around the world take compulsory proficiency tests called ring tests, in which they all taste and rate the same five oils. The results are compared using a standard procedure that is analyzed statistically for variability, accuracy and uniformity. In 2001, the UCCE sensory panel participated in a series of ring tests and became one of 41 officially recognized IOC taste panels, the first one in the United States to have received such recognition (IOC 2007b). (Many of the original tasters are now members of the UC Davis Olive Oil Taste Panel, recently certified by the IOC.)

Tasting protocols

Samples are presented "blind" and in the most appropriate order, so that errors of contrast are minimized (see box, page 12). Oils are identified with a random three-digit number or letter combination that is not familiar in any way, to prevent order bias. Special blue glasses are used to obscure the oil color, so that color bias does not influence the panelists' evaluations, and tasters are isolated from one another with dividers. For the most accurate evaluation, olive oils are warmed to 80°F (26.5°C) on a warming mat. Because flavors based in oil coat the mouth, throat and nasal cavity, they tend to linger, which influences the reaction to subsequent samples and quickly fatigues the senses. A resting time of 5 minutes is required between oils, and green apples and water are used as palate cleansers to minimize sensory fatigue. Panelists usually taste from three to five oils in 30 minutes (IOC 2007c).

Sensory panelists place a short, vertical mark on a horizontal, unstructured, 10-centimeter line scale where the flavor intensity is perceived to be. Data on profile sheets containing individual oil ratings is compiled by a technician and analyzed with a statistical computer program developed by the IOC. The software places each oil into a specific category — extra virgin, virgin, common or lampante — based on the IOC standards for defect-intensity levels and the presence of fruity characteristics.

The minimum IOC sensory definition of an extra-virgin oil, for example, is one in which the mean score of the eight panelists is zero defects with some fruitiness. This means that five out of eight must agree in their profile-sheet characterizations. If the coefficient of variation (relative robust standard deviation) of the main defect is greater than 20% in a defective oil, or greater than 10% in an extra-virgin oil for the fruitiness characteristic, the test must be repeated.

Tasters must be very close in identifying the primary defect in each oil, if it has one, and the intensities of the defect must be within 2 points on the 10-centimeter scale. For fruitiness, the intensity must be within 1 point on the scale. The statistical program makes a calculation (median, interquartile interval, robust standard deviation, relative robust and standard deviation) based on each panelist's evaluation of each oil, and a minimum of eight panelists must be used for an official oil evaluation (IOC 1999).

The International Olive Council conducts "ring tests," sending the same five oils to panels around the world for testing to ensure that its standards are being upheld.

UC and the olive oil industry

In 1999, the California sensory panel began providing feedback to the state's olive oil industry in the form of a seal certification program, in partnership with the California Olive Oil Council (COOC), a trade organization. UCCE farm advisor Vossen was responsible for training the sensory panel and maintaining scientific protocol. The COOC seal was awarded to oils that the sensory panel judged "extra virgin" according to IOC standards. Producers also benefited from panelist comments regarding their oil's characteristics. If an oil failed certification, the farm advisor confidentially informed the producer of the nature of the defect and its likely cause. From 1999 through 2004, the number of defective oils dramatically declined from 50% to less than 3%. If an oil was deemed defect-free (and therefore certifiable) but there was room for improvement, the panel's comments regarding harvest maturity or other factors were passed along to the producer. The COOC seal was the first attempt by the domestic industry to give consumers an assurance of quality when purchasing California olive oil.

In 2005, a new UCCE profile sheet was developed for more detailed analysis of extra-virgin olive oils in California. It records taster impressions of additional aspects, including the oil's harmony and complexity. By selecting from a list of descriptors such as artichoke, banana, almond or fresh-cut grass, the tasters note undertones in the olive oil. Previous sensory panel analysis emphasized defect identification. Descriptive analysis provides extremely valuable data on the more subtle and complex aspects of olive oil. This can help producers adjust harvest timing, tailor processing methods to particular varieties and pinpoint attributes for blending.

UC has also been addressing the needs of the California olive oil industry with training programs, such as the 2-day Olive Oil Sensory Evaluation Short Course, taught once or twice per year since 1999. Likewise, special trainings have been conducted for chefs, food writers, producers, consumers and educators. In addition, UCCE short courses on olive production

How to taste olive oil

Olive oil is best tasted in a blue, tulip-shaped, stemless glass. The tasting glass is covered with either a lid or hand, and the oil gently swirled. The open glass is placed close to the nose and the taster takes a deep breath, making a mental note of the aroma, since much of what we call flavor is actually smell. Next, the taster sips about 5 milliliters of oil and holds it in their mouth for 10 seconds, taking care to coat all parts of the mouth and tongue. While the oil is in the mouth, air is sucked in to further volatilize its aromatic components before swallowing. Then the mouth is closed while the taster breathes out through the nose. The retronasal cavity connecting the mouth to the olfactory area allows the volatile aromas to be perceived once again.


Blue glasses are used to taste olive oil, in order to prevent color bias.

The mouth and throat detect flavors such as bitterness, pungency, sweetness and astringency. Most people taste bitterness primarily toward the back of the tongue and mouth. Pungency is a physical irritation perceived in the throat, which is why it is essential to swallow some of the oil in order to appreciate all of its sensory characteristics.

topics, regional grower meetings and field days have also provided valuable science-based information. Two UC Division of Agriculture and Natural Resources publications, the *Olive Production Manual* and *Organic Olive Production Manual,* continue this tradition.

Looking to the future

Due to UC research and support, and the efforts of the sensory panel volunteers, it has become a rarity to find defects in a California olive oil. Research continues to explore the effect of terroir on olive oil, and a database is being created of characteristics in single varietal oils grown in different parts of the state. This will help growers select varieties that are horticulturally suited to their location. Ongoing research on how olive fruit fly can damage the sensory aspects of olive oil will help producers further adjust their pest control measures to minimize environmental and financial impacts, while preserving oil quality. A research project comparing different processing systems will provide valuable information for producers seeking the best methods for their particular fruit, depending on variety and ripeness.

The UCCE sensory panel is providing feedback on specific flavor characteristics of individual oils that helps producers to choose varieties, adjust harvest maturities, schedule irrigation and generally improve the quality of their oils. California-specific data produced by the sensory panel — using internationally recognized scientific standards and methods — will continue to be essential to the growth of the California olive oil industry.

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Understanding the seasonal and reproductive biology of olive fruit fly is critical to its management

by Hannah J. Burrack, Ray Bingham, Richard Price, Joseph H. Connell, Phil A. Phillips, Lynn Wunderlich, Paul M. Vossen, Neil V. O'Connell, Louise Ferguson *and* Frank G. Zalom

The olive fruit fly was first detected in Los Angeles in 1998 and in all the olive-growing regions of California soon after. Following its initial detection, UC researchers and Cooperative Extension farm advisors, county agricultural commissioners and the California Department of Food and Agriculture Pest Detection and Emergency Project established a statewide monitoring program to determine the extent of the olive fruit fly's occurrence, track its seasonal biology and evaluate monitoring tools. Fly populations and infestations can reach high levels throughout California but tend to be lower in the San Joaquin Valley. Trap captures typically exhibit a bimodal distribution with peaks in the spring and fall. Olive infestation is related to fly densities, climate and fruit size. Gravid, mated females vary in density throughout the year but are present at some level year-round. The data is being used to develop models that will better predict when the adults are active and olives are at risk.

Jack Kelly Clark, UC Statewide IPM Program

First detected in 1998, the olive fruit fly spread quickly throughout the state's olive-growing regions. The table olive industry has zero tolerance for damaged fruit, but infestation levels of 10% or more may be acceptable for olive oil. *Above*, the adult fly's exit holes; larvae feed just below.

The olive fruit fly was first detected in California in 1998 in the Los Angeles Basin and was subsequently found in all olive-growing areas within 4 years (fig. 1). The olive fruit fly (*Bactrocera oleae* [Rossi]) is the primary pest of olives worldwide and is particularly troublesome due to its multiple, overlapping generations each year. This life history makes understanding olive fruit fly phenology and infestation patterns particularly important for effective management.

The insect's historic range includes all of Europe and Africa, and extends at least as far east as India (Augustinos et al. 2002; Nardi et al. 2005). Molecular studies of *B. oleae* in California suggest that the invasion originated from Mediterranean populations. Australia is the only country where olives are grown that is not colonized. In the traditional olive-growing regions of Europe and the Middle East, the olive fruit fly is the primary economic pest. *B. oleae* has become the most important pest of California olives (Collier and Van Steenwyk 2003; Daane et al. 2005), and in commercial production control necessitates regular applications of insecticidal bait sprays from fruit-set through harvest.

The majority of California's crop is processed for table olives and is grown in the Sacramento and San Joaquin valleys, in Butte, Glenn, Tehama and Tulare counties (Connell 2005). Olive oil is also produced from California olives. At the onset of the olive fruit fly invasion, oil production occurred primarily in coastal counties, including Napa and Sonoma. In recent years, oil production has been increasing in the traditional table olive–producing counties. *B. oleae* is managed differently in these two production systems: there is zero tolerance for infestation in table olives, while a threshold of roughly 10% infestation is acceptable for oil olives, although even greater levels can produce high-quality oil if the fruit is processed quickly (Kicenik Devarenne and Vossen 2007).

This production difference is particularly notable in Butte County, where high fly densities and associated damage resulted in crop rejection by table olive processors. Consequently, olives grown in Butte County are crushed for oil. Super-high-density oil plantings have been established in Butte County since 1999. These plantings — in which olive trees are spaced more closely, varieties with smaller fruit are planted and deficit irrigation is used — appear to be less conducive to olive fruit fly infestation (Vossen 2007) (see page 34).

Statewide monitoring program

We and other researchers were interested in understanding the seasonal activity patterns of *B. oleae* in California as compared to its previously known range, in order to predict where and when the fly was most likely to become a significant pest. In 2002, UC researchers and Cooperative Extension farm advisors, California Department of Food and Agriculture Pest Detection and Emergency Project personnel, county agricultural commissioners and pest control advisers assembled a network of monitoring sites throughout the state, in order to determine olive fruit fly population dynamics within and between California's diverse climatic and geographic regions. A network of 28 monitoring sites in 16 counties was established and data was collected from 2002 through 2006 (table 1).

This large dataset allowed us to track *B. oleae* activity patterns and to relate these patterns to fly and fruit biology. The end-product of this work will be predictive models for fly activity and fruit infestation. Because the initial goal of this monitoring effort was to track *B. oleae* seasonal biology, sites with active, relatively large populations were selected, and all traps were placed in olive plantings that received no insecticide applications for the duration of the study. Therefore, all population fluctuations observed were due to local biotic and abiotic factors, not anthropogenic effects.

The selection of untreated sites with large *B. oleae* populations led to a lack of locations in the San Joaquin Valley, because most olive plantings in this area are used for commercial table olive production and may be treated with pesticides if *B. oleae* are present. In addition, other researchers documented that populations in the San Joaquin Valley appear naturally lower than coastal and Sacramento Valley locations (Rice et al. 2003; Yokoyama et al. 2006). The olive fruit fly had already been detected in 35 counties prior to 2002. After the monitoring program was initiated, it was found in nine more counties (fig. 1), although the detection years do not necessarily indicate initial invasion. This is particularly clear in the case of Colusa County, which was surrounded by counties in which the fly had been detected, but for which there were no records of olive fruit fly until 2004.

Geography and seasonal activity

Statewide monitoring began using four ChamP yellow sticky traps per site baited with ammonium bicarbonate food lures attractive to both sexes and a spiroketal pheromone lure attractive to males (Yokoyama et al. 2006). Plastic McPhail traps (Liquibaitor trap, Great Lakes IPM, Vestaburg, Mich.) baited with an aqueous torula yeast food lure attractive to both sexes were shown to be more attractive than ChamP traps (Burrack et al. 2008), and in 2003 all monitoring locations began to use two to four of the McPhail traps.

Every week the traps were checked, flies were counted and sexed, and lures were changed. Trapping was conducted from April through December at most locations, with a subset of locations (Butte 1, Napa 1, Napa 2, Napa 3, Napa 4, San Diego 1, San Luis Obispo 2, Solano 4, and Yolo 1) continuing year-round. Weekly trap

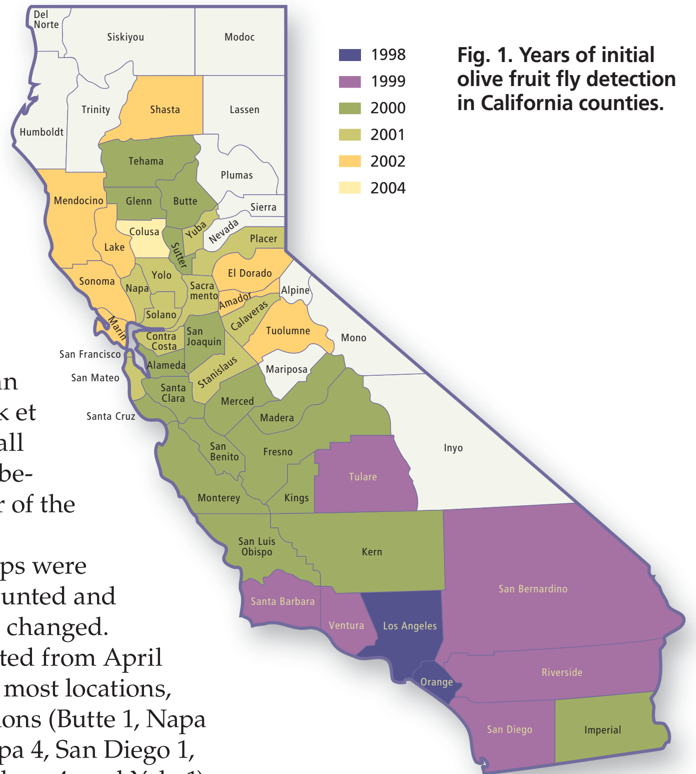


Fig. 1. Years of initial olive fruit fly detection in California counties.

TABLE 1. Olive fruit fly monitoring locations, geographic classifications and years active

County	Site	No. of traps	Geographic area	Years active
Amador	1	4	North, inland	2005
Butte	1	4	North, inland	2002, 2003, 2004, 2005
Calaveras	1	2	North, inland	2002, 2003, 2004, 2005
Marin	1	2	North, coastal	2002, 2003, 2004
Napa	1	2	North, coastal	2002, 2003, 2004, 2005, 2006
	2	2	North, coastal	2002, 2003, 2004, 2006
	3	2	North, coastal	2002, 2003, 2004, 2006
	4	2	North, coastal	2002, 2003, 2004, 2006
Sacramento	1	2	North, inland	2002, 2003, 2004
	2	2	North, inland	2005
	3	2	North, inland	2004
	4	2	North, inland	2004
San Diego	1	2	South, coastal	2002, 2003, 2004, 2005
San Luis Obispo	1	2	South, coastal	2002, 2003, 2004, 2005, 2006
	2	2	South, coastal	2002, 2003, 2004, 2005, 2006
Santa Barbara	1	2	South, coastal	2004
	2	2	South, coastal	2004
Shasta	1	2	North, inland	2002, 2003, 2004, 2005
Solano	1	2	North, inland	2002, 2003, 2004
	2	2	North, inland	2002, 2003, 2004, 2005, 2006
	3	2	North, inland	2002, 2003, 2004
	4	4	North, inland	2002, 2003, 2004, 2005, 2006
Sonoma	1	2	North, coastal	2002, 2003, 2004, 2005
	2	2	North, coastal	2003, 2004, 2005, 2006
Tulare	1	4	South, inland	2005
Ventura	1	4	South, coastal	2005
Yolo	1	4	North, inland	2002, 2003, 2004, 2005, 2006
Yuba	1	2	North, inland	2003, 2004

Alexandra Kicenik Devarenne

Jack Kelly Clark

Yellow sticky traps, *left,* are used to monitor the fly's population densities in different locations throughout the year. *Right,* an adult olive fruit fly caught in a trap.

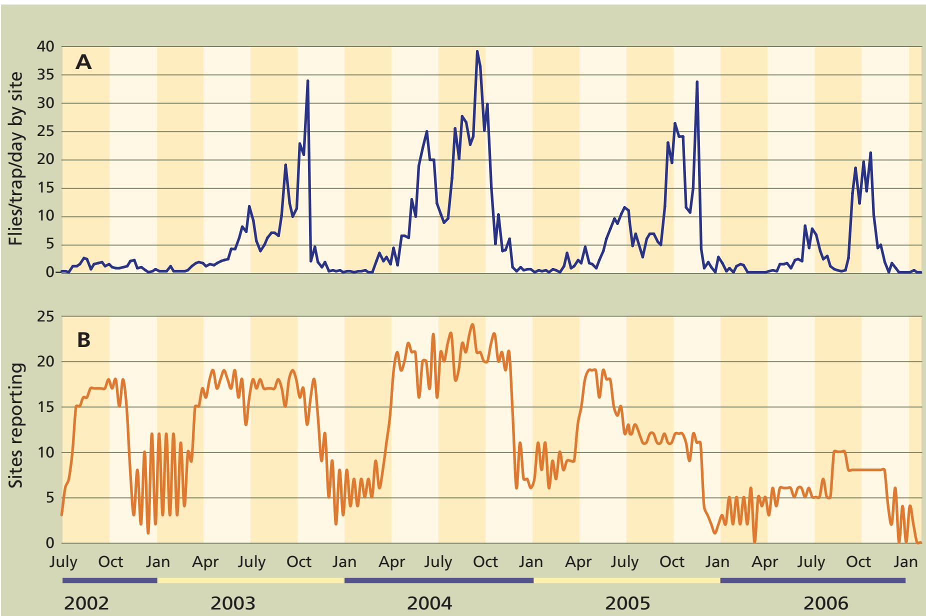


Fig. 2. (A) Average flies per trap per day caught at all monitoring locations over 4 years and (B) number of trapping locations reporting each week.

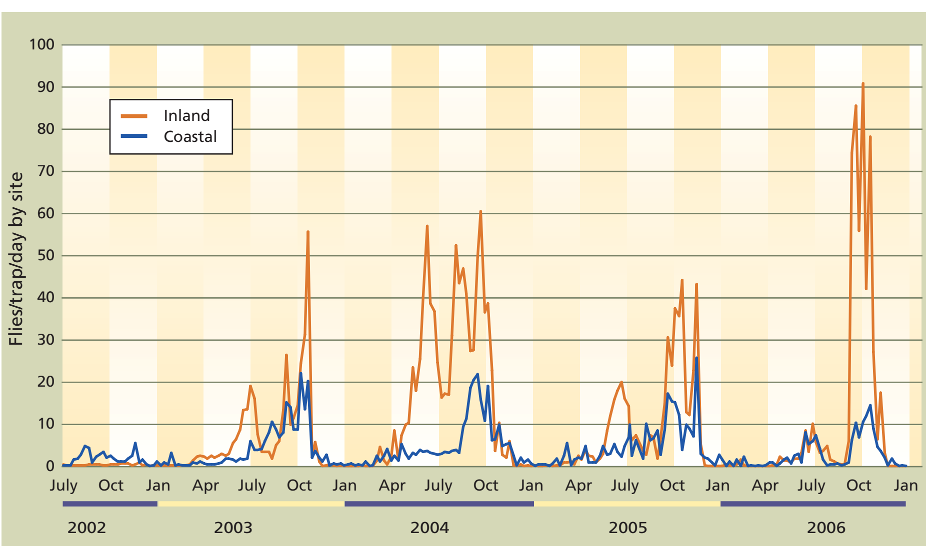


Fig. 3. Flies per trap per day caught at combined inland and coastal trapping locations over 4 years.

captures were converted to flies per trap per day to allow for comparison between locations. Flies per trap per day were summed, divided by the number of locations reporting data for the week, and graphed to allow observation and comparison of population density trends.

Olive fruit fly flight activity has a bimodal distribution, with the highest trap captures observed in spring and fall (fig. 2A). Depending on location, spring peaks occur in March, April or May and fall peaks are in September, October or November. The majority of the pooled trapping data points represented at least 15 monitoring sites (fig. 2B), except for the winter dates. Overall fly activity was low in the winter, and the locations selected for winter monitoring were among those with the highest *B. oleae* trap captures during the previous summer and fall. Flies were still present during winter at these locations, but were trapped in lower numbers. Trap captures were lower in 2002 than in subsequent years, likely due to the use of a less efficient trap and the shorter time since initial *B. oleae* establishment in more northern locations.

When sites were grouped into broad geographic categories, differences in seasonal activity became apparent. We considered a trapping site to be coastal if it was either in a county directly bordering the ocean or west of the summit of the coastal mountain range. Coastal locations have milder climates than those inland, with cooler summers and warmer winters. We considered trapping locations to be northern when they were situated at greater than 37° N latitude (roughly Santa Cruz), with the remainder categorized as southern. Both coastal and inland locations included sites with very high (10,000 or more flies; San Diego, Butte and Solano 2) and very low (under 1,000 flies; Marin and Tulare) trap captures (table 2). Trap data from the same geographic areas was pooled and graphed.

The sites from Northern and Southern California displayed similar activity patterns and are not presented, but fly trap capture patterns at inland versus coastal locations differed markedly (fig. 3). The pooled inland locations exhibited similar bimodal trap capture patterns to those observed for combined data from all sites (fig. 2A), but pooled coastal locations lacked a spring peak and displayed a gradual increase of fly captures, with the greatest numbers captured in the fall (fig. 3).

Tracking olive infestations

Olive infestation and olive size were tracked in 2004 and 2005 at seven locations, and fly density was tracked during 2005. Manzanillo and Mission olives, the most commonly grown varieties in California (Connell 2005), were sampled at most locations, and Leccino olives were sampled at one location because no suitable Manzanillo or Mission olives were available (table 3). One hundred olives were collected weekly from four trees at each location, June through December 2004, and May through December 2005. Sample size was decreased to 52 olives per tree when fruit infestation reached 50%.

Olives were dissected under a stereomicroscope, and oviposition scars (stings), live larvae, and pupae or larval/adult exit holes were counted. Olives bearing stings were considered infested, as table olive producers have a zero tolerance policy for olive fruit fly infestation. Prior to dissection, each olive was measured to compare fruit size across locations, because olive fruit fly adults exhibit a preference for large fruit under field conditions (Burrack and Zalom 2008; Yokoyama et al. 2006). The longest point on the olive (l), the widest point (w) and 90° from the widest dimension (h) were measured and used to calculate fruit volume ($V = (4/3\pi)(h/2)(w/2)(l/2)$). Fly populations were monitored at each location using four plastic McPhail traps, as described previously. Data from 2004 and 2005 was similar for all locations, therefore data from 2005 is presented.

Infestation levels in 2005 reached 100% in Butte and Ventura counties. Infestations grew slowly at the Amador and Sonoma sites but were high by the end of the season (fig. 4A). Fly trap captures mirrored the delayed infestation pattern at Amador and Sonoma (fig. 4B), and these two locations had the smallest olives throughout the season (fig. 4C). Smaller olives are typically less infested in the field (Burrack and Zalom 2008), and both fly population and olive size are affected by weather. Infestation levels and trap captures were low in Tulare County for the entire season, despite olive size and development comparable to the other monitoring locations (figs. 4A, 4B and 4C).

Previous monitoring efforts have also reported lower trap captures in San Joaquin Valley locations (Rice et al. 2003; Yokoyama et al. 2006). *B. oleae* populations in the Central Valley may be limited by high temperature and food resources (Wang et al. 2009) (see page 29). Solano County Mission olives were significantly less infested than

TABLE 2. Total olive fruit flies caught at monitoring locations during olive production season (May through November) in 2003, 2004 and 2005*

County	Site	No. of traps	2003	2004	2005
			number of flies		
Amador	1	4	—†	—	10,718
Butte	1	4	3,880	10,956	8,487
Calaveras	1	2	406	4,692	—
Marin	1	2	331	78	—
Napa	1	2	3,499	2,039	1,369
	2	2	1,459	2,459	—
	3	2	1,920	3,034	—
	4	2	1,001	3,397	—
Sacramento	1	2	—	6,988	—
	2	2	—	—	2,942
	3	2	—	6,838	—
San Diego	1	2	8,711	5,290	10,008
San Luis Obispo	1	2	—	1,227	1,191
	2	2	3,765	3,756	2,339
Santa Barbara	1	2	—	3,924	—
	2	2	—	3,979	—
Shasta	1	2	52	204	1,700
Sonoma	1	2	1,857	4,895	3,058
	2	2	602	1,207	1,288
Solano	1	2	8,216	11,667	—
	2	2	10,466	40,422	16,686
	3	2	4,051	9,490	—
	4	4	1,167	9,914	2,889
Tulare	1	4	—	—	287
Ventura	1	4	—	—	13,800
Yolo	1	4	2,454	7,521	5,269
Yuba	1	2	1,163	—	—

* Data from 2002 and 2006 not presented because data collection was not season-long.
† Winter dates and years with incomplete data for a location are omitted.

TABLE 3. Olive infestation data locations

County	Location	Trapping location	Varieties sampled
Amador	Abandoned orchard	Amador 1	Leccino
Butte	Commercial and fallow orchard	Butte 1	Manzanillo, Mission
Sonoma	Abandoned orchard	Sonoma 2	Mission
Solano	Wolfskill Experimental Orchard	Solano 4	Manzanillo, Mission
Tulare	Lincove Research Station	Tulare 1	Manzanillo
Ventura	Abandoned orchard	Ventura 1	Mission
Yolo	UC Davis campus farm	Yolo 1	Manzanillo, Mission

Manzanillo olives from the same location. Field observations from this site suggest that Manzanillo olives may be preferable to Mission for oviposition in the field when female flies have a choice (Burrack and Zalom 2008).

Reproductive biology

Examination of trap captures compared to ovarian development in the female indicated that the olive fruit fly has at least four generations per year in California, with a partial generation spanning the winter (Burrack 2007). An absence of mature eggs in fly ovaries during the spring and early summer has often been noted in European *B. oleae* populations (Delrio and Prota 1976; Economopoulos et al. 1982; Fletcher et al. 1978; Raspi et al. 2002; Tzanakakis 1986) and is referred to as a summer reproductive diapause. A similar absence of mature eggs can be induced in flies reared in the laboratory by exposing larvae to cool, short days and adults to hot, long days with no access to olives (Koveos and Tzanakakis 1990, 1993; Koveos et al. 1997; Raspi et al. 2002; Raspi et al. 2005).

In order to determine if this phenomenon occurs in California *B. oleae* populations as well as to determine when flies were capable of infesting olives, females flies collected from monitoring traps were dissected for five sites (Butte 1, Napa 1, San Diego 1, Solano 4 and Yolo 1). These locations were selected because trapping was conducted year-round, and they represented different California climates. Ten flies from each location and sampling date were dissected, and when fewer than 10 flies per week were collected, all flies were dissected. Ovarian development, egg load and mating status were observed for each of the dissected flies.

We determined whether the ovaries of female flies contained mature eggs and whether their spermathecae contained sperm. Mature eggs are easily distinguished from developing eggs by a distinctly darker micropile on the anterior end. Egg load, or the total number of mature eggs present in both ovaries, was also determined. Mating status was determined via staining with 4′, 6-diamidino-2-phenylidole dihydrocholride (DAPI) at 1 microgram per milliliter in phosphate buffered solution and observed with UV-flourescent microscopy as adapted from Fritz and Turner (2002). Flies were dissected in 70% ethyl alcohol, and spermathecae were removed, placed in a drop of DAPI on a microscope slide and crushed with a cover slip.

The morphology of the olive fruit fly spermatheca and ethanol preservation made quantification of sperm difficult. Therefore, flies were classified as mated or unmated. An overall classification of reproductive biology was assigned to each fly by combining ovarian development rankings and mating status. These categories were: (1) unmated (sperm absent), immature (immature ovaries); (2) unmated, mature (mature ovaries); (3) mated (sperm present; mature eggs in ovaries [gravid]), immature; and (4) mated, mature. Only flies in category 4 would be capable of infesting olives.

All statistical analyses were conducted using SAS version 9.1 (SAS Institute, Cary, N.C.). Analysis of variance was conducted with Proc GLM, and means were separated via LSD. Nonparametric rank tests were conducted using the Kruskal-Wallis test via Proc Npar1way in SAS.

There were significant differences between months in the proportion of unmated flies with immature ovaries and mated flies with mature ovaries observed (unmated/immature: $F_{8,20}$ = 5.16, P = 0.0014; mated/mature: $F_{8,20}$ = 4.94, P = 0.0018), but there was also a significant site/month interaction for

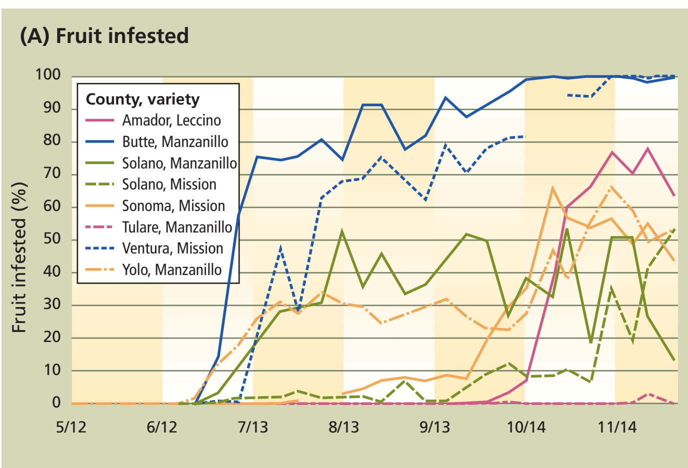
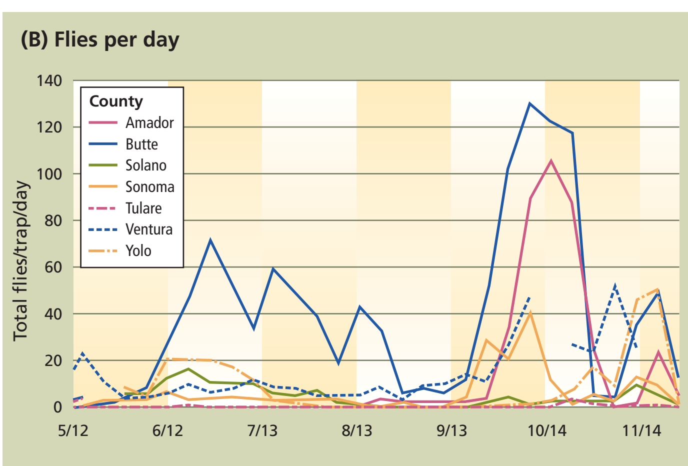
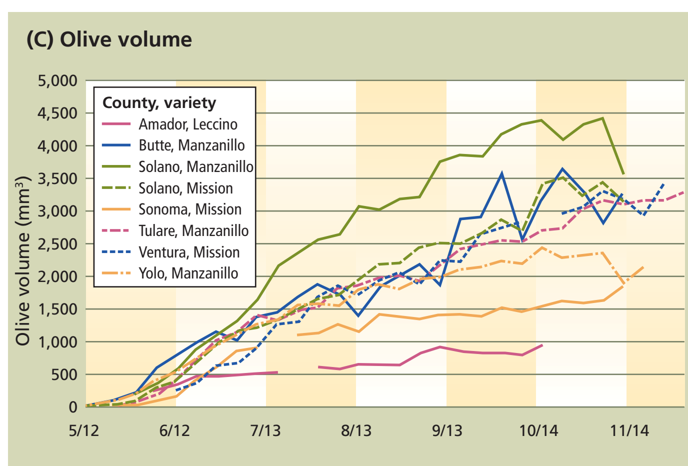


Fig. 4. (A) Percentage of fruit infested, sampled weekly, (B) flies caught per trap per day and (C) olive development at fruit infestation locations in 2005. Gaps in lines signify dates for which olive data was not collected.





both categories (unmated/immature: $F_{32,20} = 4.01$, $P = 0.0009$; mated/mature: $F_{32,20} = 5.17$, $P = 0.0001$). The differences among years for both rankings were nonsignificant (unmated/immature: $F_{2,20} = 2.36$, $P = 0.1205$; mated/mature: $F_{2,20} = 1.18$, $P = 0.3267$), and therefore, yearly data was pooled by month.

Because of the significant interaction effect between site and month, the data for individual sites is presented. The greatest proportion of mated, mature flies was observed in March or April and October through November, for the Yolo, Solano and Butte county sites (figs. 5A, 5B and 5C). High proportions of potentially destructive flies (mated, mature) were observed in April, August and September in Napa County (fig. 5D). The greatest proportion of unmated, reproductively immature flies throughout the year was observed at San Diego, where the highest percentage of mated, gravid flies was present in June, July and August (fig. 5E).

The proportion of reproductively immature flies increased in spring or early summer at all locations, a period during which the European literature suggests that a reproductive diapause may occur. However, reproductively mature flies were also present at this time. A decrease in mean egg load was observed during the spring and fall (data not shown). At no point during the summer months were reproductively mature females completely absent.

Egg load was positively related to mating status ($F_{1,3049} = 160.20$, $P < 0.0001$) at all locations for all months. Mean egg load was larger in mated than unmated flies, regardless of month, and was greatest in March and May and least in September. On average, mated flies had 7.30 eggs in their ovaries, while unmated flies had 2.44 eggs present. Flies with mature eggs in their ovaries were more likely to be mated ($\chi^2 = 1228.4922$, df = 1, $P < 0.0001$).

Population densities as indicated by trap captures were high at both the Butte and San Diego sites (table 2) relative to the other sites. McPhail traps are thought to overestimate the proportion of gravid female flies in a population (Neuenschwander and Michelakis 1979), so the abundance of reproductively immature flies is likely not due to greater trap capture and it is possible that the proportion of immature flies may be even greater than that observed through trap captures. The climate at San Diego is characterized by moderate, coastal-influenced temperatures throughout the year, as opposed to hot summer and relatively cool winter temperatures that fall below

Fig. 5. Ovarian development and mating status for olive fruit fly at five locations. Flies were categorized as (1) unmated (sperm absent), immature ovaries, (2) unmated, mature ovaries, (3) mated (sperm present), immature ovaries and (4) mature, mature ovaries. Only flies in category (4) would be capable of infesting olives. Flies were collected weekly, and data pooled by month. Percentages of a given class (unmated/immature or mated/mature) indicated by the same letter for a single location were not significantly different ($\alpha = 0.05$) when adjusted means were compared via LSD; data from December, January and February was eliminated from analysis for all years due to insufficient sample sizes.

the fruit fly development thresholds. Therefore, more-extensive generational overlap might be expected at the San Diego site than at the Butte site, resulting in more young, reproductively immature females present in the population year-round.

Managing olive fruit fly

UC researchers have developed a greater understanding of the behavior and biology of the olive fruit fly in the 12 years since its initial detection, but there is still a great deal of work to be done to develop tools to apply this information in effectively managing this pest. Models determining when olives become susceptible to olive fruit fly attack and how fly populations respond to climatic conditions are being developed using the data described here. With a few exceptions, the olive fruit fly has not prevented commercial olive production in California for most growers, but it has significantly changed their insect management requirements.

Statewide surveys have gathered important information about the life cycle of the olive fruit fly, which will be used to improve pest management practices. *Above,* larvae infest olive fruit.

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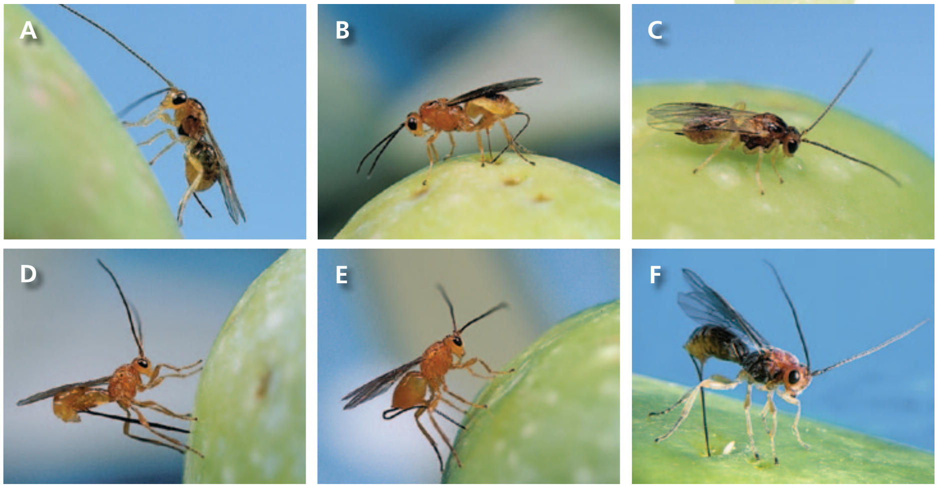
REVIEW ARTICLE

Biological controls investigated to aid management of olive fruit fly in California

by Kent M. Daane, Marshall W. Johnson, Charles H. Pickett, Karen R. Sime, Xin-Geng Wang, Hannah Nadel, John W. Andrews Jr. *and* Kim A. Hoelmer

The widespread and rapid establishment of the olive fruit fly in California required immediate changes in integrated pest management (IPM) programs for olives. After finding that resident natural enemies did not provide adequate control, researchers began a worldwide search for parasitoids, with exploration in the Republic of South Africa, Namibia, India, China and other countries. Parasitoids were shipped to California, and most were studied in quarantine to determine the best species for release. Two parasitoid species —* Psyttalia lounsburyi *and* Psyttalia humilis *— are now being released throughout the state's olive-growing regions, and researchers are studying their effectiveness.



Parasitoids imported into California for quarantine studies include braconid parasitoids reared from wild olive fruit fly, (A) *Psyttalia lounsburyi*, (B) *Bracon celer* and (C) *Utetes africanus*, as well as braconid parasitoids reared on other fruit fly species, including (D) *Diachasmimorpha longicaudata*, (E) *D. kraussii* and (F) *Fopius arisanus*.

The olive fruit fly was first found in Southern California in 1998 (Rice et al. 2003). Facilitated by longevity and the adults' ability to fly long distances, the fly dispersed rapidly throughout the state. There was little opportunity to attempt a statewide eradication program, so current research efforts emphasize long-term management practices. Biological control may be a part of this program (Daane and Johnson 2010).

How might natural enemies contribute to the control of olive fruit fly (*Bactrocera oleae* [Rossi])? Commercial orchards now rely upon a broad-spectrum insecticide combined with a highly attractive bait (Johnson et al. 2006). The effectiveness of insecticide-based programs is, however, limited by the abundance of roadside and residential olive trees in California, which serve as reservoirs and contribute to the fly's reinvasion of treated orchards (Collier and Van Steenwyk 2003). Classical biological control — the importation of natural enemies from the pest's home range — offers the best opportunity to economically suppress olive fruit fly populations in these situations. We review ongoing efforts in California to (1) document the natural enemies of olive fruit fly already present, (2) search for and import novel natural enemies from other countries and (3) determine the effectiveness and limitations of these natural enemy species. To date, California scientists have received approval from the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS) for the release of several parasitoid species, and permits are pending for two others (see page 26).

Natural enemies in California

Although the olive fruit fly is native to Africa and Asia (Nardi et al. 2005), some North American predators and parasitoids may attack it. Insect predators such as lady beetles and lacewings are found in olive orchards, but because the fly's eggs are embedded underneath the fruit's epidermis and the larvae feed deep inside the fruit (Tzanakakis 2006), the immature stages are protected from most generalist predators.

Before the larva pupates, it creates a thin window on the fruit surface through which it may be exposed to predators. If the fruit is still firm, the larva will often pupate inside. However, upon fruit maturation most fly larvae leave the older fruit, especially in the late summer and fall, and drop to the ground to pupate in the soil beneath the tree (Tzanakakis 2006). Orsini et al. (2007) placed fly puparia (which enclose the fly pupa) on the ground in olive orchards and used different barriers around each to distinguish mortality levels due to abiotic (e.g., climate) and biotic (e.g., predators) factors. In an August trial, olive fruit fly exposed to predators was reduced by about 60% compared to other treatments (fig. 1). Ants (e.g., *Formica* species) were the most abundant predators on the ground and were observed carrying and killing olive fruit fly pupae. Predation rates vary among orchards, depending on factors such as the species and densities of predators present and the soil depth at which fly pupae are located. European studies similarly indicate that arthropods can inflict substantial mortality on olive fruit fly pupae (Daane and Johnson 2010; Tzanakakis 2006).

A California-resident parasitoid has also been found attacking olive fruit fly. The parasitoid is similar to the European *Pteromalus myopitae* (Graham) (Hymenoptera: Pteromalidae), hence it is currently referred to as *Pteromalus* species near *myopitae (P.* sp. nr. *myopitae).* It has been reared from olive fruit fly collected primarily in coastal counties from San Luis Obispo to San Diego, although it has also been collected in Alameda, Butte, Fresno, Solano and Yolo counties. This parasitoid is solitary (one per fly larva) and feeds externally on third-instar olive fruit fly. An olive fruit fly survey in San Luis Obispo County reported an average parasitism level of 2.98% by *P.* sp. nr. *myopitae* (Kapaun et al. 2010). Parasitism levels varied considerably, ranging from 0% to 33% (based on collections of 100 infested fruit per week) with activity highest in August and September. Because *P.* sp. nr. *myopitae* has never been reported elsewhere, it is likely a North American parasitoid of native fruit flies; it opportunistically parasitizes olive fruit fly but has never been collected on any native fruit fly species despite numerous surveys.

***Pteromalus* species near *myopitae* is resident to California and has been reared from olive fruit fly collected primarily in coastal counties. The adult (A) oviposits onto second- or third-instar fly larvae, placing an egg (B) on the outside of the larva, where the parasitoid larva (C) develops as a solitary, external parasitoid.**

Foreign exploration

Imported material. Resident natural enemies do not adequately suppress olive fruit fly populations below damaging levels. For this reason, California researchers began seeking natural enemies abroad in 2003. The search started in Africa, where olive fruit fly probably originated and there is a rich diversity of fruit fly parasitoids. Olive fruit fly parasitoids were reported in Africa as early as 1912 by the renowned Italian entomologist Filippo Silvestri during surveys for parasitoids of Mediterranean fruit fly (Medfly) (*Ceratitis capitata* [Wiedemann]) (Wharton 1989).

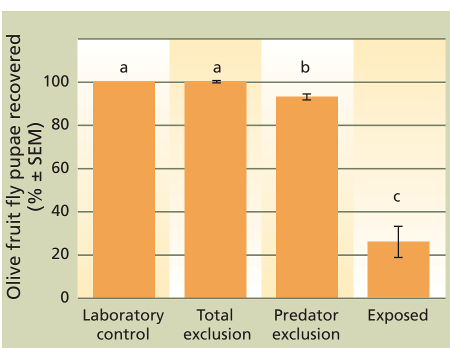


Fig. 1. Mean percentage (± SEM) of olive fruit fly pupae recovered after 4 days (August 2005) when held in laboratory control, and placed in an olive orchard where treatments were "total exclusion" of all natural enemies; "predator exclusion," preventing walking predators from reaching pupae; and "exposed," allowing both flying and walking natural enemies access to pupae. Different letters above each bar indicate significant differences (Tukey's HSD test, $P < 0.05$) (Orsini et al. 2007).

Members of the USDA Agricultural Research Service's European Biological Control Laboratory, the California Department of Food and Agriculture, UC researchers and cooperators explored the Republic of South Africa, Namibia, Kenya, La Réunion (an island east of Madagascar), the Canary Islands, Morocco, Pakistan, India and China. Collections for "specialists" (i.e., natural enemies that primarily attack one species) were made from wild olive fruit (*Olea europaea* ssp. *cuspidata*) from south to northeast Africa, and from southwest Asia to central China. The parasitoids reared from olive fruit fly included *Psyttalia lounsburyi* (Silvestri), *Psyttalia concolor* (Szépligeti), *Psyttalia humilis* (Szépligeti), *Psyttalia ponerophaga* (Silvestri), *Utetes africanus* (Silvestri) and *Bracon celer* Szépligeti.

The greatest yield of parasitoids came from collections made in South Africa, Namibia and Kenya (table 1). The most common species were *U. africanus*, *P. lounsburyi* and *P. humilis* (table 1). The highest levels of parasitism were found in Kenya collections where *P. lounsburyi* and *U. africanus* together parasitized more than 57% of collected flies. The next highest parasitism levels were in collections from Pakistan (27.7% parasitism by *P. ponerophaga*) and Republic of South Africa (27.8% to 68.0% parasitism by *P. humilis, P. lounsburyi*, *B. celer* and *U. africanus* during 3 years of collections). Although *P. concolor* was the only olive fruit fly parasitoid found in Morocco and the Canary Islands, parasitism rates were limited to 14.6% and 2.3%, respectively. Similarly, in the Republic of South Africa, *P. humilis* accounted for less than 4% of parasitism. However, in Namibia *P. humilis* was the dominant parasitoid and attained parasitism levels from 18.1% to 35.1%. In China, few olive fruit flies were collected, although one (unidentified) *Diachasmimorpha* species was obtained, and in India no olive fruit were found on wild olive trees during the 2006 and 2007 explorations (Alan Kirk, personal communication).

Numerous fruit fly parasitoids are known to attack other flies in the genus *Bactrocera.* A few of these more "generalist" parasitoids (i.e., natural enemies that attack numerous species) were also imported to California. These were *Fopius arisanus* (Sonan), *Diachasmimorpha kraussii* (Fullaway) and *D. longicaudata* (Ashmead). All were supplied by Russell Messing at University of Hawaii, where they had been reared on Medfly. Similarly, colonies of *P. humilis* maintained on Medfly in Guatemala were sent to California, supplied by Pedro Rendon of the USDA APHIS Plant Protection and Quarantine program (Yokoyama et al. 2008, 2010).

Reported efforts. A parasitoid's performance in other regions provides insights for researchers when determining which natural enemy species should be released. *P. lounsburyi* was identified nearly 100 years ago as an olive fruit fly parasitoid and is often reported as the most effective natural enemy in wild olives of southern Africa (Copeland et al. 2004). *P. ponerophaga* has a similar long association with olive fruit fly and is the only olive fruit fly specialist known from Pakistan (Wharton 1989). However, no systematic effort has been made to include these parasitoids in European biological control (Wharton 1989), presumably because they have been difficult to import and rear.

We found no reports of concerted efforts to import or manipulate *U. africanus* for biological control, although in some South African surveys it is an abundant olive fruit fly parasitoid in wild olives (Hancock 1989). Similarly, *B. celer* is often the most commonly reported parasitoid attacking olive fruit fly in commercial and wild olives in South Africa (Neuenschwander 1982), where it achieved parasitism rates as high as 87%. However, small-scale attempts to rear and/or release *B. celer* in Europe have been unsuccessful (Wharton 1989).

Instead, biological control of olive fruit fly has focused on members of the *P. concolor* species complex, which includes *P. concolor* from northern Africa and *P. humilis* from sub-Saharan Africa, especially after an efficient mass-rearing method was developed in the 1950s using Medfly reared on an artificial diet (Daane and Johnson 2010). However, *P. concolor* has not provided adequate or consistent olive fruit fly control in Europe and, where it has established, repeated mass releases are required to boost parasitism rates (Copeland et al. 2004). Nonetheless, we consider *P. concolor* and *P. humilis* to be important to screen for use in California biological control. Their native range spans much of northern and eastern Africa (Wharton and Gilstrap 1983) and, given the diversity of habitats and climates encompassed, they likely comprise several biotypes, or even new species or genetically differentiated populations (Rugman-Jones et al. 2009), some of which may be better suited to control olive fruit fly in California (Yokoyama et al. 2010).

F. arisanus is well known as a generalist parasitoid of fruit-infesting tephritids. Native to Southeast Asia, it was introduced to the Hawaiian Islands in the 1940s and provided excellent control of Oriental fruit fly (*Bactrocera dorsalis* [Hendel]). It now also contributes to Medfly control (Wang, Messing, Bautista, et al. 2003). Following the success in Hawaii, *F. arisanus* was introduced widely to control these and other tephritid pests in Australia, Central America, various Pacific and Indian Ocean islands, and the Mediterranean Basin, though not all of these introductions have been as effective. The few attempts to establish *F. arisanus* on olive fruit fly in Europe were unsuccessful. One study reported that *F. arisanus* failed to reproduce on olive fruit fly in field cages (Neuenschwander et al. 1983); however, more recent laboratory work has confirmed that *F. arisanus* can reproduce on olive fruit fly (Calvitti et al. 2002; Sime et al. 2008).

D. longicaudata, a native of Southeast Asia (Wharton 1989), attacks a relatively wide range of tephritid flies, including Medfly, Oriental fruit fly, Caribbean fruit fly (*Anastrepha suspensa* [Loew]) and Mexican fruit fly (*A. ludens* [Loew]) (Wang and Messing 2004). It has been used widely for biological control. One attempt was made to rear and release it against olive fruit fly in Greece, but it did not become established (Daane and Johnson 2010). *Diachasmimorpha kraussii* is native to Australia, attacks a range of *Bactrocera* species and has been released in Hawaii to control Medfly (Bokonon-Ganta et al. 2007); we have found no reports of its use against olive fruit fly, but it has been reported attacking olive fruit fly in Israel (C.H. Pickett, personal communication).

Quarantine nontarget studies

Before exotic natural enemies are released in California, quarantine studies are conducted to determine whether or not they will attack insect species other than the intended target (Hoelmer and Kirk 2005). There are more than 140 tephritids in California (Foote et al. 1993), including some endemic species and others that were brought into the state for the biological control of weeds. Rather than test all of these species, researchers assess parasitoid responses to fruit fly species found in the three common habitats of fruit fly larvae — fruits, flower heads and stem galls — to explore their tendency to specialize on certain host habitats. Tested species are selected to maximize both practicality (ease of locating and/or rearing hosts) and potential for host acceptance (resemblance of infested plant structure to olives in shape or size). Therefore, most

TABLE 1. Fruit fly and parasitoids reared from field-collected wild olives for importation into California, 2003–2007

			Species reared*							
Country	Year	Insects reared	*Bactrocera* spp.	*Psyttalia humilis*	*Psyttalia concolor*	*Psyttalia lounsburyi*	*Psyttalia ponerophaga*	*Utetes africanus*	*Bracon celer*	*Diachasmimorpha* spp.
		n	%							
Morocco	2004	318	85.4	0.0	14.6	0.0	0.0	0.0	0.0	0.0
Canary Islands	2004	965	97.7	0.0	2.3	0.0	0.0	0.0	0.0	0.0
Pakistan	2005	636	72.3	0.0	0.0	0.0	27.7	0.0	0.0	0.0
La Réunion	2004	700	86.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0
Namibia	2004	597	69.2	18.1	0.0	0.0	0.0	3.7	9.0	0.0
	2007	874	58.1	31.3	0.0	9.0	0.0	1.6	0.0	0.0
	2008	3,077	50.0	35.1	0.0	11.0	0.0	3.3	0.6	0.0
South Africa	2003	2,218	49.5	3.2	0.0	14.9	0.0	22.8	9.6	0.0
	2004	794	32.2	2.2	0.0	14.3	0.0	46.1	5.2	0.0
	2005	377	72.2	0.0	0.0	15.1	0.0	12.7	0.0	0.0
Kenya	2005	3,647	42.5	0.0	0.0	35.6	0.0	21.9	0.0	0.0
China	2007	438	97.5	0.0	0.0	0.0	0.0	0.0	0.0	2.5
India	2006	0	—	—	—	—	—	—	—	—
	2007	0	—	—	—	—	—	—	—	—

* Percentages of adult olive fruit fly and parasitoids reared are shown; does not include gall-formers or "unknown" parasitoid species that may have been reared from galls, from other fruit fly species or as hyperparasitoids on primary parasitoids of olive fruit fly.

of the imported parasitoids were either sent directly to the UC Berkeley quarantine facility, or to the collaborating laboratory in France and then to the UC Berkeley facility.

Olive fruit fly belongs to the tephritid subfamily Dacinae, which is not native to North America. California's native and introduced fruit fly species fall into two other subfamilies, Trypetinae and Tephritinae (Foote et al. 1993). For a nontarget, fruit-feeding Trypetinae, researchers selected the native black cherry fly (*Rhagoletis fausta* [Osten Sacken]), which infests fruit of bitter cherry. For a flower-head feeder, they selected *Chaetorellia succinea* (Costa), an imported Tephritinae used to control yellow starthistle (*Centaurea soltitialis* L.). For a gall-former, researchers selected another Tephritinae biological control agent, *Parafreutreta regalis* (Munro), which forms stem galls in Cape ivy. The testing of *C. succinea* and *P. regalis* addressed the risk posed to beneficial species by the candidate parasitoids. Unless stated otherwise, these three species were common to all UC Berkeley quarantine studies; other nontarget fruit flies were tested when available.

There was some variation in the materials and methods used to test the different species, but procedures were generally as described by Daane et al. (2008). Briefly, researchers used small cages (about 12 square inches) to isolate female parasitoids with either target (olive fruit fly) or nontarget hosts for 48 hours in a no-choice test. Target and individual nontarget species were then placed together for a choice test for the next 48 hours. The number of searching events (i.e., parasitoids on the host plant) and probing events (i.e., parasitoids inserting their ovipositor to place an egg into the fruit, flower head or gall) were recorded during discrete observation periods. Afterward, the host material was isolated and held for parasitoid or fly emergence.

Parasitoids and olive fruit fly

P. lounsburyi. *P. lounsburyi* was the only parasitoid tested that probed only into infested olives and reproduced solely on olive fruit fly (table 2). That *P. lounsburyi* is relatively specialized on olive fruit fly is supported by the fact that it had been reared only from olive fruit fly in decades of field collections of African fruit flies (Copeland et al. 2004; Wharton et al. 2000). In addition, its geographic range is entirely contained within that of olive fruit fly.

P. ponerophaga. It has been suggested that *P. ponerophaga* specializes on olive fruit fly because the parasitoid has only been reported from this species (Sime et al. 2007). Quarantine-screening studies of nontarget impacts were limited to the weed biological-control agents — *C. succinea* (yellow starthistle fly) and *P. regalis* (Cape ivy fly) — and no fruit-infesting fly species were tested. In no-choice tests, *P. ponerophaga* adults probed into galls on Cape ivy and produced parasitoid offspring from this nontarget host, but did not probe or reproduce in yellow starthistle (table 2).

P. concolor* and *P. humilis. *P. concolor* should be viewed as a "species complex," as previously mentioned. While similar, there may be biological differences that influence their affectiveness in California. For example, researchers found that even *P. humilis* colonies from different locations had slightly different levels of host specificity (table 2). However, *P. concolor* and *P. humilis* populations tested were able to reproduce on nontarget Cape ivy fly. In other laboratory studies, *P. concolor* was similarly reared from numerous fruit fly species (Wharton and Gilstrap 1983). However, small-cage trials are artificial, and olive fruit fly and Medfly are the primary hosts of *P. concolor* and *P. humilis* in their native African range (Copeland et al. 2004; Wharton et al. 2000).

B. celer. *B. celer* also attacked and reproduced on Cape ivy fly, but surprisingly did not reproduce on the black cherry fly, the fruit-infesting fly tested with this species (table 2). However, *B. celer* did probe on host materials for all fruit flies presented except currant fly. To date, *B. celer* has been reported only as a parasitoid of olive fruit fly and Medfly in field surveys (Wharton et al. 2000), with an additional, unconfirmed record on *Ceratitis nigra* Graham.

U. africanus. One of the most commonly recovered species in the South African collections, *U. africanus* was difficult to rear in quarantine. It reproduced on olive fruit fly, as expected, but this parasitoid was never observed to show any interest (by searching or probing) in either the target or nontarget host plants during tests (table 2). The literature indicates that *U. africanus* has been reared from olive fruit fly, Medfly, Oriental fruit fly, coffee fruit fly (*Trirhithrum coffeae* Bezzi) and natal fly (*Ceratitis rosa* Karsch) (Wharton and Gilstrap 1983).

TABLE 2. Host-specificity trials — searching, probing and reproduction by imported parasitoids on olive fruit fly and nontarget fruit fly species

Parasitoids*	Olive fruit fly	Cherry fly	Apple maggot	Cape ivy fly	Yellow starthistle fly	Currant fly	Reference
Psyttalia concolor (Italy)	S/P/R†	S/P	S/P	S/P/R	S/P	NI	Unpublished data
Psyttalia humilis (Kenya)	S/P/R	S/P	S/P	S/P/R	NI	S	Unpublished data
Psyttalia humilis (Namibia)	S/P/R	—	—	S/P/R	NI	—	Unpublished data
Psyttalia "unknown sp. A"	S/P/R	S/R	NI	S/P/R	NI	NI	Unpublished data
Psyttalia ponerophaga	S/P/R	—	—	S/P/R	NI	—	Unpublished data
Psyttalia lounsburyi	S/P/R	NI	NI	S	NI	NI	Daane et al. 2008
Diachasmimorpha longicaudata	S/P/R	S/P/R	S/P	S/P/R	NI	NI	Unpublished data
Diachasmimorpha kraussii	S/P/R	S/P/R	S	S/P/R	S/P/R	S/P	Unpublished data
Bracon celer	S/P/R	S/P	NI	S/P/R	S/P	NI	Nadel et al. 2009
Utetes africanus	R	NI	—	NI	NI	—	Unpublished data
Fopius arisanus	S/P/R	—	—	NI	NI	—	Sime et al. 2008

* Target host was olive fruit fly; nontarget hosts were cherry fly (*Rhagoletis fausta* [Osten Sacken]), apple maggot (*Rhagoletis pomonella* [Walsh]), Cape ivy fly (*Parafreutreta regalis* [Munro]), yellow starthistle fly (*Chaetorellia succinea* [Costa]) and currant fly (*Euphranta canadensis* [Loew]).

† S = host plant searched by parasitoid; P = host plant probed by parasitoid; R = parasitoid successfully reproduced in host; NI = parasitoid showed no interest in host plant or host during observation period; — = not tested.

***Diachasmimorpha* species.** *D. longicaudata* and *D. krausii* were the most aggressive of the quarantine-screened parasitoids, probing nearly all host material presented and producing offspring from nontarget, fruit-infesting species as well as the beneficial species (table 2). This result was not surprising because in total they have been reared from more than 20 fruit fly species (Wharton and Gilstrap 1983).

F. arisanus. While *F. arisanus* is considered more of a generalist, it is not attracted to either *C. succinea* eggs on yellow starthistle buds, or *P. regalis* eggs in Cape ivy stems or the associated galls (table 2). These results are consistent with studies in Hawaii that show *F. arisanus* only attacking fruit-feeding tephritids (Wang, Bokonon-Ganta, et al. 2004). The host range in *F. arisanus* is probably constrained by its host-searching behavior: females are generally stimulated to search for host eggs by fruit odors; smooth, round fruit surfaces; and oviposition punctures left by flies (Wang and Messing 2003). Introducing *F. arisanus* to California still requires evidence that native, fruit-feeding Tephritidae are unlikely to be attacked. Sixteen tephritid species native to California feed in fruit (Foote et al. 1993), but at least eight are found at higher elevations where *F. arisanus*, a tropical species, is unlikely to flourish.

Parasitoid biology studies

Researchers studied the biology of imported natural enemies to help determine the best combination of species for release in California's climatically varied olive-growing regions. Parasitoid host-stage preference, development time, adult longevity and fecundity (offspring per female) were determined when colony numbers permitted these additional quarantine studies (table 3).

Host-stage preference. Newly infested olives were held for different lengths of time to create fruit with various olive fruit fly host "age categories" (i.e., different immature fly stages). These infested olives were placed with mated female parasitoids, and the amount of time the parasitoids searched and probed on the different age categories was recorded. After the exposure period, the olives were held to rear either adult parasitoids or flies. These experiments established that *P. lounsburyi*, *P. ponerophaga*, *P. concolor*, *P. humilis, D. longicaudata* and *D. kraussii* were internal parasitoids that preferred to oviposit into second- or third-instar olive fruit fly (table 3). *B. celer* is an external-feeding parasitoid that prefers late third-instar maggots. *F. arisanus* is an egg-larval parasitoid that inserts its eggs into olive fruit fly eggs, and the parasitoid completes its life cycle in the larval olive fruit fly. *F. arisanus* females may sometimes lay their eggs in first-instar olive fruit fly.

Host-stage preference did not always correlate with reproductive success. This was most clearly seen in trials with *P. lounsburyi*, where adults spent more time probing olives with larger third-instar maggots (fig. 2A), but more offspring were produced from olives containing smaller second- and third-instar maggots (fig. 2B). Many parasitoids locate hidden hosts by detecting substrate vibrations. For example, adult *P. concolor* are thought to respond more

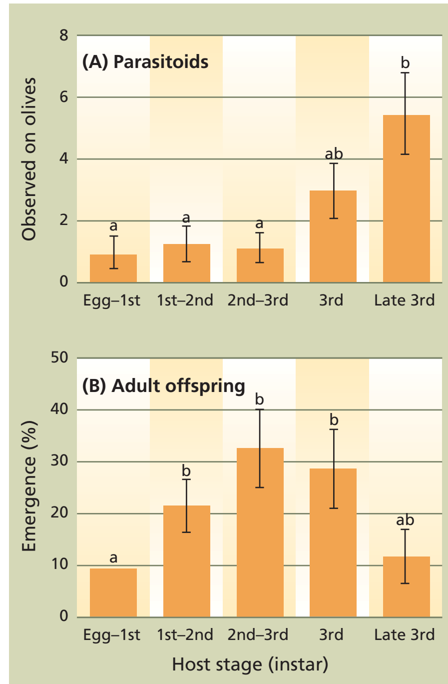


Fig. 2. Host-stage preference as mean percentage (± SEM) of (A) adult female *Psyttalia lounsburyi* on olives containing hosts of a given age category during timed observations and (B) *P. lounsburyi* offspring that emerged from different host-stage categories. Different letters above each bar indicate significant differences (one-way ANOVA, $P < 0.05$) (Daane et al. 2008).

TABLE 3. Key biological parameters for parasitoids of olive fruit fly studied in UC Berkeley quarantine facility

Parasitoid species tested	Host-stage preference	Development time (egg to adult)	Adult longevity	Offspring per female	Reference
		. . . . days	. . . .	*n*	
P. lounsburyi	Second to third instar	22.8 ± 0.8 (75°F)	61.8 ± 8.2	10.2 ± 2.6	Daane et al. 2008
P. ponerophaga	Second to third instar	20.5 ± 1.5 (77°F)	36.2 ± 4.9	18.7 ± 2.9	Sime et al. 2007
P. concolor (Italy)	Second to third instar	—	68.8 ± 16.4	22.5 ± 5.1	Sime, Daane, Messing, et al. 2006
P. humilis (Kenya)	Second to third instar	—	77.6 ± 15.3	28.7 ± 4.1	Sime, Daane, Messing, et al. 2006
P. humilis (Namibia)	Second to third instar	16.4 ± 0.6 (77°F)	36.0 ± 7.3	35.2 ± 4.1	Daane/Sime, unpublished data
P. concolor (South Africa)	Second to third instar	18.1 ± 0.4 (77°F)	53.2 ± 6.6	48.8 ± 8.5	Daane/Sime, unpublished data
B. celer	Third instar	35.5 ± 0.8 (72°F)	51.0 ± 11.7	9.7 ± 7.2	Sime, Daane, Andrews et al. 2006
U. africanus	Second to third instar*	20.5 ± 1.0 (75°F)	—	—	Daane/Sime, unpublished data
D. longicaudata	Second to third instar	20.8 ± 0.9 (77°F)	59.2 ± 5.0	23.6 ± 5.3	Sime, Daane, Nadel, et al. 2006
D. kraussii	Second to third instar	21.6 ± 1.7 (77°F)	64.1 ± 7.8	22.7 ± 5.5	Sime, Daane, Nadel, et al. 2006
F. arisanus	Egg	—	—	4.4 ± 0.8	Sime et al. 2008

*Few replicates were completed with *U. africanus*, and only 10 adults were reared from olive fruit fly during the trial.

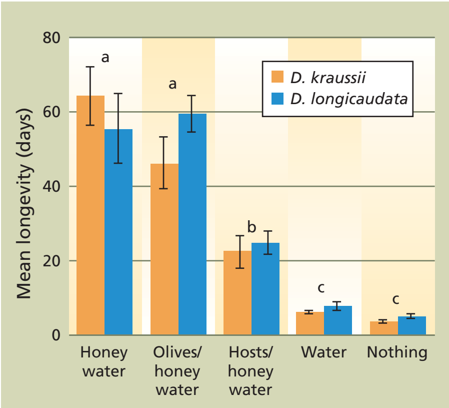


Fig. 3. Adult female *Dichasmimorpha kraussii* and *D. longicaudata* longevity given different food provisions. Different letters above each bar indicate significant treatment differences (Tukey's HSD test, $P < 0.05$) (Sime, Daane, Nadel, et al. 2006).

strongly to the third than the second instar because the larger instar produces stronger or more frequent vibrations while feeding (Canale and Loni 2006). However, the third-instar olive fruit fly maggots feed deeper in olives and may be beyond the reach of the short *P. lounsburyi* ovipositor (less than 2 millimeters).

Development time. The egg-to-adult developmental rates of *P. lounsburyi*, *P. ponerophaga*, *P. concolor*, *D. kraussii* and *D. longicaudata* were relatively similar, about 22 days at constant temperatures near 77°F (25°C), while *B. celer* required nearly 40% more time (table 3). Olive fruit fly requires about 23 days at 77°F (25°C), suggesting that (except for *B. celer*) these parasitoids could have generation times similar to olive fruit fly.

Adult longevity. When provisioned with water and honey, examined adult parasitoid species lived 36 to 78 days at temperatures around 77°F (25°C) (table 3). For all tested species, adults lived for less than 5 days without food, as shown for *D. longicaudata* and *D. kraussii* (fig. 3). For most species studied, there was also a reduction in longevity when adults were provided hosts in infested olives, suggesting that the parasitoids expended energy while handling hosts and that the parasitoids were able to distinguish host-infested olives from those lacking hosts.

Tolerances for high and low temperatures may be critical for parasitoid establishment in California because olive fruit fly infestations are found in both relatively cool coastal and hot inland areas, resulting in different seasonal development of the fly (Yokoyama et al. 2006). Overall patterns of adult longevity for all parasitoids tested showed a negative correlation with temperature, as shown for the Kenya and Italy colonies of *P. humilis* (fig. 4).

Lifetime fecundity. Researchers studied the parasitoids' reproductive potential by providing newly emerged and mated adult females with an overabundance of infested olives every 2 days (table 3). All species tested deposited most of their eggs during the first third or half of their life span (fig. 5). Surprisingly, the two specialists (*P. lounsburyi* and *P. ponerophaga*) had the lowest lifetime fecundity of the larval endoparasitoids, which develop inside the host (table 3). One hypothesis to explain these low fecundity rates concerns the relative lengths of their ovipositors (see below). Another explanation concerns the chemical cues used to orient to and identify host larvae and the host/plant complex. Domestic olives differ chemically from wild olives. These differences could disrupt the parasitoid's host-searching, host-identification or ovipositional behaviors, or impede larval development.

Quarantine studies also reported low lifetime fecundity for *B. celer*, the external parasitoid, and *F. arisanus*, the egg-larval parasitoid (table 3), although in each case researchers suggest that experimental conditions may have negatively influenced natural egg deposition. In the UC Berkeley quarantine studies, researchers found up to 80% mortality of olive fruit fly eggs exposed to *F. arisanus* (Sime et al. 2008). Similar findings have previously been reported on olive fruit fly (Calvitti et al. 2002) and other hosts (Moretti and Calvitti 2003). Most likely this direct mortality results from the egg being repeatedly probed (i.e., stabbed) by the *F. arisanus* ovipositor. Olive fruit fly lays a single egg per fruit puncture, whereas the typical host of *F. arisanus*, the Oriental fruit fly, deposits up to 100 eggs per puncture (Ramadan et al. 1992). The tendency of *F. arisanus* to probe repeatedly within an oviposition puncture may be an evolutionary consequence of its use of this host. By comparison, more than 100 progeny can be obtained per female *F. arisanus* when reared on the Oriental fruit fly (Ramadan et al. 1992).

Releasing natural enemies

California researchers received USDA-APHIS approval for the release of *P. lounsburyi* and limited release of *P. humilis*; approval is pending for *P. ponerophaga*; and permits for the limited release of *F. arisanus* are being prepared. To date, *P. lounsburyi* has been released and recovered in field-cage studies, but has not yet been shown to overwinter. More work has been done with *P. humilis*, which is easier to rear, and levels of up to 60% parasitism have been reported from cage studies (Wang, Johnson, Daane, Yokoyama 2009; Yokoyama et al. 2008, 2010). However, as with *P. lounsburyi*, there is no clear evidence to date that *P. humilis* can

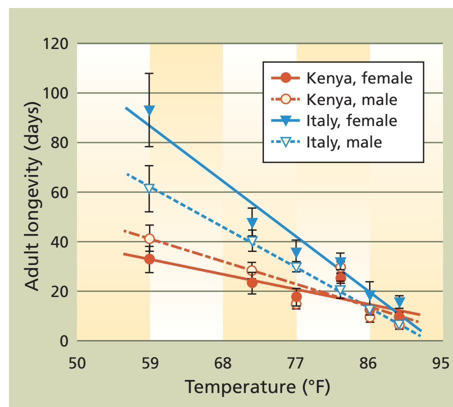


Fig. 4. Adult *P. humilis* longevity declined with increasing constant temperature for each gender and culture. Within each culture, no significant differences were found between female and male longevity at any temperature tested (Sime, Daane, Messing, et al. 2006).

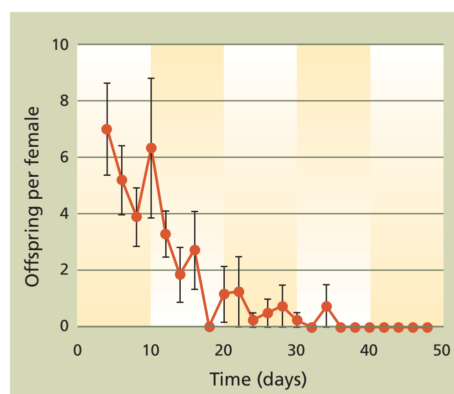


Fig. 5. Mean lifetime production of offspring (± SEM) produced by *P. humilis* from a Kenyan culture (Sime, Daane, Messing, et al. 2006).

establish and thrive without repeated augmentation.

There is a risk with the release of each natural enemy species that some nontarget species will be attacked, but the benefits often outweigh the risks (Hoddle 2004). Also, not all pest species are prime targets for classical biological control — there are potential problems with olive fruit fly and natural enemy biology that may limit the levels of control achieved.

Seasonal host availability. The olive fruit fly's survival is limited in regions with high or low temperature extremes (Wang, Johnson, Daane, Opp 2009). The fruit also may not be developed enough for olive fruit fly to survive early in the summer; young, hard fruit are not preferred for oviposition (Burrack and Zalom 2008). Moreover, olive fruit fly populations are scarce in some interior valley regions with high summer temperatures (Wang, Johnson, Daane, Nadel 2009) (see page 29). These facts suggest that parasitoid survival might also be difficult in some regions where their host, the olive fruit fly larvae, is scarce during some seasonal periods.

Wild versus domestic olives. The domestic olive is a distinct subspecies of wild olive, which has smaller fruit than most cultivated olives. As a result, fly maggots tunnel deeper inside the larger domestic olive. The ovipositors of specialized parasitoids (*P. lounsburyi* and *P. ponerophaga*) are too short to reach fly maggots feeding deep within the larger olives (Sime et al. 2007; Wang, Johnson, Daane, Yokoyama 2009; Wang, Nadel, Johnson, et al. 2009). The length of the ovipositor relative to the depth of the maggot within the fruit apparently limits the biocontrol agent's ability to successfully parasitize certain hosts, a problem that has been well documented for other fruit fly parasitoids (Sivinski et al. 2001). Therefore, African parasitoids of olive fruit fly may fail to successfully establish on fruit flies in fleshier European cultivars, because their short ovipositors are adapted for foraging in small, wild, African olives.

Surveys in wild and cultivated African olives provide support for this hypothesis. *P. lounsburyi*, *U. africanus* and *B. celer* are most commonly reared from wild olives (Copeland et al. 2004; Neuenschwander 1982), whereas in cultivated olives, *B. celer.* with its much longer ovipositor, predominates, and the other species tend to be rare (Neuenschwander 1982). In the UC Berkeley quarantine studies, both *D. longicaudata* and *D. kraussii* reproduced well on cultivated olives, and these more generalist parasitoids have very long ovipositors (Sime, Daane, Messing, et al. 2006). Among the favorable characteristics of *F. arisanus* as a parasitoid of *B. oleae* are its relatively long ovipositor and the fact that it usually oviposits into eggs. Both features may help it circumvent the difficulties encountered by some larval parasitoids attacking *B. oleae* in larger olive cultivars.

Ripe wild olives, *left*, collected in Africa, where olive fruit fly is considered to be native, are much smaller than the cultivated European varieties used throughout the world. *Right*, springbok and kudu graze among wild olive trees on a South Africa hillside. The African parasitoids that specialize on olive fruit fly found in small wild olives tend to have relatively short ovipositors that may not reach fly maggots deeper in the pulp of cultivated olives.

Natural enemy interactions. For best results natural enemies should coexist, but sometimes they interfere with each other. For example, the unexpected appearance of *P.* sp. nr. *myopitae* could potentially create a conflict with classical biological control efforts. Parasitoids that immobilize the host, including *P.* sp. nr. *myopitae* and *B. celer*, may have a competitive advantage over larval parasitoids that allow the host to continue to develop and grow after parasitoid oviposition, such as *Psyttalia* species. In quarantine experiments, researchers found that the egg-larval parasitoid *F. arisanus* prevailed in competition against two species of larval-pupal parasitoids, *D. kraussii* and *P. concolor* (Sime et al. 2008). The intrinsic competitive superiority of *F. arisanus* over larval-pupal parasitoids must be taken into consideration for its use in California.

Insecticides and biological control. Insecticide use affects biological control programs (Mills and Daane 2005). Repeated sprays of GF-120 Naturalyte NF Fruit Fly Bait (Dow AgroSciences, Indianapolis, Ind.) are used to control olive fruit fly. Although this spinosad bait is classified as a reduced-risk material, its frequent use may disrupt biological control. Nadel et al. (2007) investigated the impact of GF-120 on a green lacewing (*Chrysoperla carnea* [Stephens]), and showed that ingestion clearly poses some risk to lacewing populations due to adult mortality and reduced fecundity. Laboratory studies indicated that several important braconid parasitoids of fruit flies — *F. arisanus*, *Diachasmimorpha tryoni* (Cameron) and *Psyttalia fletcheri* (Silvestri) — would not feed on fresh GF-120 residues, but when the insecticide was directly applied there were high mortality rates (Wang et al. 2005).

Expectations in California

Biological control can be a practical, safe and economically effective means of fruit fly control, and its importance continues to grow in regions where pesticide use is less desirable (e.g., sustainable agriculture) or more restricted (e.g., urban trees). The research programs that we describe provide background information on natural enemy biology, and identify specific natural enemies for importation and evaluation, and for possible release into California. Over the coming years, researchers will better understand the level of controls expected from imported natural enemies, and will improve IPM programs to integrate biological controls with the insecticides currently used in olive management.

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REVIEW ARTICLE

High temperature affects olive fruit fly populations in California's Central Valley

by Marshall W. Johnson, Xin-Geng Wang, Hannah Nadel, Susan B. Opp, Kris Lynn-Patterson, Judy Stewart-Leslie *and* Kent M. Daane

Olive fruit fly commonly infests olives in California's Central Valley. Field studies indicate that trap counts for olive fruit fly adults in pesticide-free sites decrease in mid- and late summer and then rebound from September to November. Part of this decline is associated with heat stress that the flies experience in mid-July and August. Studies have shown that adult flies will die within a few days if they cannot access adequate amounts of water and carbohydrates. Flight ability is dramatically reduced when resources are unavailable. Olive fruit fly adults may use black scale honeydew as a carbohydrate source to help them survive hot periods. Heat also affects the fly's reproduction and immature stages within olive fruit. Geographic information system (GIS) maps may be useful for predicting the risk of olive fruit fly infestation.

Marshall W. Johnson

An adult female olive fruit fly deposits an egg into olive fruit.

The discovery in 1998 and subsequent spread of the olive fruit fly throughout the major olive-producing areas of California dramatically affected the pest management activities practiced by growers. Prior to its introduction, the major arthropod pests targeted for control in California olives were olive scale (*Parlatoria oleae* Colvée) (Hempitera: Diaspididae) and black scale (*Saissetia oleae* [Olivier]) (Hempitera: Coccidae) (Daane et al. 2005). Olive scale is well managed with biological control due to the introduction and establishment of the parasitoids *Aphytis paramaculicornis* DeBach and Rosen, and *Coccophagoides utilis* Doutt (Daane et al. 2005). Black scale is mainly controlled in the Central Valley by pruning infested trees to facilitate greater air movement in the summer, which results in significant desiccation of first-instar crawlers (Daane and Caltagirone 1989).

However, the establishment of olive fruit fly (*Bactrocera oleae* [Rossi]) (Diptera: Tephritidae) forced many growers onto a weekly treatment regime that runs from mid-June through harvest (September to December), using the spinosad product GF-120 NF Naturalyte Fruit Fly Bait (Dow AgroSciences) (Johnson et al. 2006). This management protocol enables growers to deliver fruit with near-zero infestation levels to the table olive processors. Olives destined for oil pressing may have significant levels of infestation without an appreciable decline in quality, as long as the time between harvest and pressing is minimal (Pereira et al. 2004; Torres-Villa et al. 2003).

As temperatures surpass 84°F, adult flies become increasingly agitated and egg laying is halted, and above 95°F they are motionless.

Adult behavior and survival

Olive fruit fly adults may be monitored with flat-panel sticky traps or McPhail traps (Johnson et al. 2006). The numbers of adults captured in the Central Valley decline during the hottest periods of July and August and increase in September as temperatures decrease (Rice et al. 2003; Yokoyama et al. 2006) (fig. 1). For most insect species, a decline in trap counts suggests a reduction in adult densities in an area. This is not initially the case with olive fruit fly, whose behavior changes as daily temperatures rise.

Avidov (1954) reported that below 62°F the adults are inactive. As temperatures increase above the threshold temperature, adult activity increases. Normal activity, flight and egg laying occur between 73°F and 84°F. As temperatures surpass 84°F, adult flies become increasingly agitated and egg laying is halted, and above 95°F they are motionless. Laboratory observations (M.W. Johnson, unpublished) also suggest that adults seek and remain near moisture sources as temperatures approach and surpass 95°F.

Reduced adult fly activity can result in lower trap counts in the field while maximum daily temperatures remain around 95°F to 99°F and the flies have access to adequate water and carbohydrate sources (Wang et al. 2009a). However, as the frequency at which daily maximum temperatures equal or surpass 100°F increases, greater numbers of adults will die due to heat stress, especially when they cannot access adequate quantities of water and food (Wang et al. 2009a, b) (fig. 2). Although adult females may ingest liquid from punctures they make in olive fruit, this secretion does not provide the needed carbohydrates to help them survive heat-induced stress (Johnson and Nadel, unpublished data).

One might assume that acquisition of adequate amounts of food and water would be easy for olive fruit fly adults, which are strong flyers. Using a custom-designed flight mill, Wang et al. (2009b) reported that adults of both sexes held for 7 days at 75°F (constant temperature) and provided with ample food (honey and hydrolyzed yeast) and water, were able to fly uninterrupted for an average of 2,164.8 ± 228.8 yards during a mean period of 1.54 ± 0.16 hours (fig. 3).

Nonetheless, heat stress and lack of water and food can affect flight ability. Olive fruit fly adults that were subject to the same conditions as described for 7 days and then to water only or no food and water in diurnal temperature regimes (65°F at night; 95°F or 100°F during the day) for 24 hours before the flight test did not perform as well as the control group (fig. 3). All stressed groups of tested flies flew significantly shorter distances (≥ 42%) than the control ($F_{6,252}$ = 62.7, P < 0.01). Additionally, individual flies that were denied food and water from the time that they emerged as adults and were held at either 65°F at night and 95°F, or 100°F, during the day for 1 to 2 days, flew significantly shorter distances (≥ 92%) than the flies provided no food and water for 24 hours after having access to food and water for 7 days (fig. 3).

In a worst-case scenario, an adult fly that emerges in mid-August in the Central Valley may commonly experience maximum daily temperatures over 100°F for 3 consecutive days (Lynn-Patterson 2006). Without food or water immediately available, an adult will only be able to fly an average of 16.4 ± 4.4 yards to locate these resources in a dry and unexplored landscape.

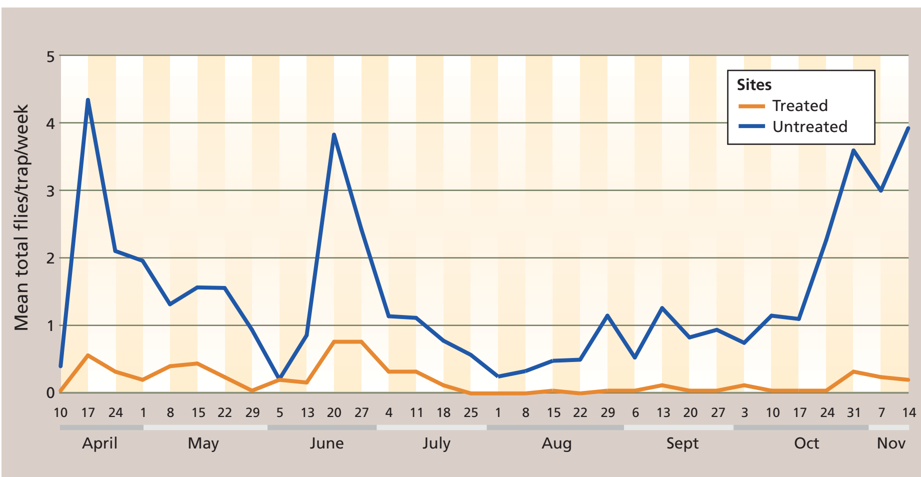


Fig. 1. Average olive fruit fly populations at nine untreated sites (e.g., urban, landscape and abandoned commercial plantings) and five treated (with GF-120) commercial sites in Fresno and Tulare counties during the 2003 growing season (Johnson, Nadel and Stewart-Leslie, unpublished data).

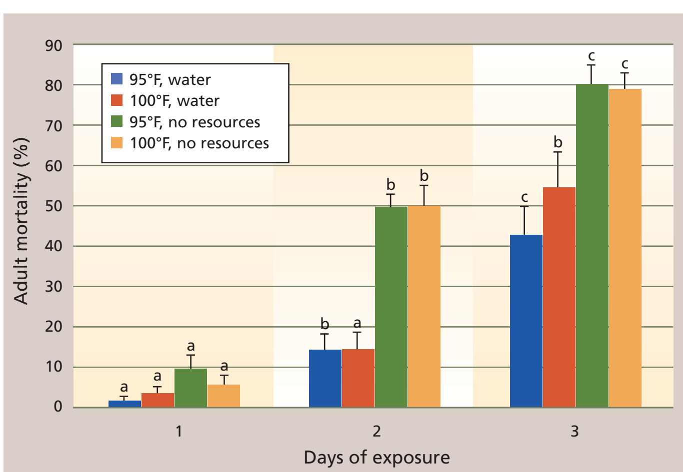


Fig. 2. Mortality of olive fruit fly adults subjected to 1 to 3 days exposure to 95°F and 100°F, in the absence of food and with and without access to water (Wang et al. 2009b). Different letters above columns representing the same temperature/resource treatment indicate significant differences (*P* < 0.05; Tukey's HSD test) within the exposure duration.

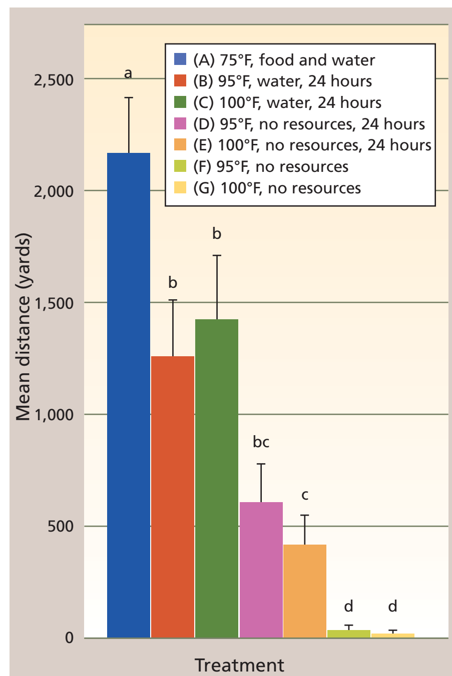
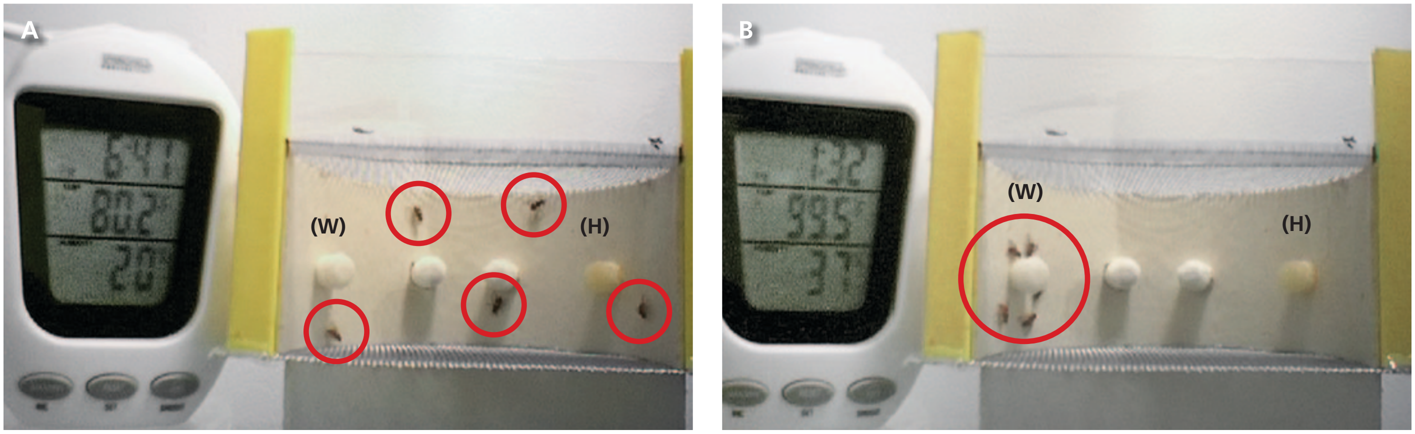


Fig. 3. Mean distances flown by olive fruit fly adults exposed to various temperatures and resources. Flies (A-E) were preconditioned for 7 days at 75°F with ample food and water prior to treatment. Treatments were: (A) no treatment (control); (B) preconditioned at 95°F, then 24 hours of water only; (C) preconditioned at 100°F, then 24 hours of water only; (D) preconditioned at 95°F, then 24 hours with no resources; (E) preconditioned at 100°F, then 24 hours with no resources; (F) no preconditioning, held from 1 to 2 days at 95°F with no resources; and (G) no preconditioning, held from 1 to 2 days at 100°F with no resources (Wang et al. 2009b). Different letters above columns indicate significant differences (*P* < 0.05; Tukey's HSD test).



Experimental setup shows (A) the typical distribution of five olive fruit fly adults (circled) within an observation chamber, with cotton wicks and water (W) and honey (H) at a cool temperature (80°F) and 20% relative humidity, and (B) the congregation of olive fruit fly adults (circled) around a water wick (W) when the temperature is hot (99.5°F) and 37% relative humidity.

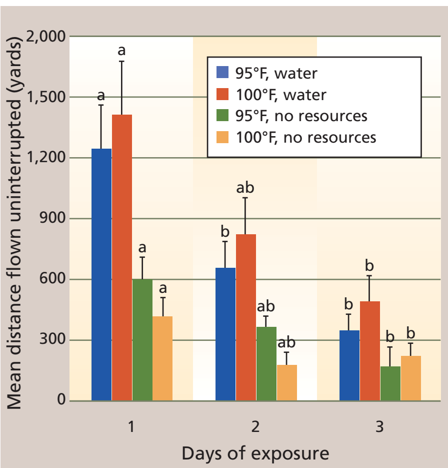
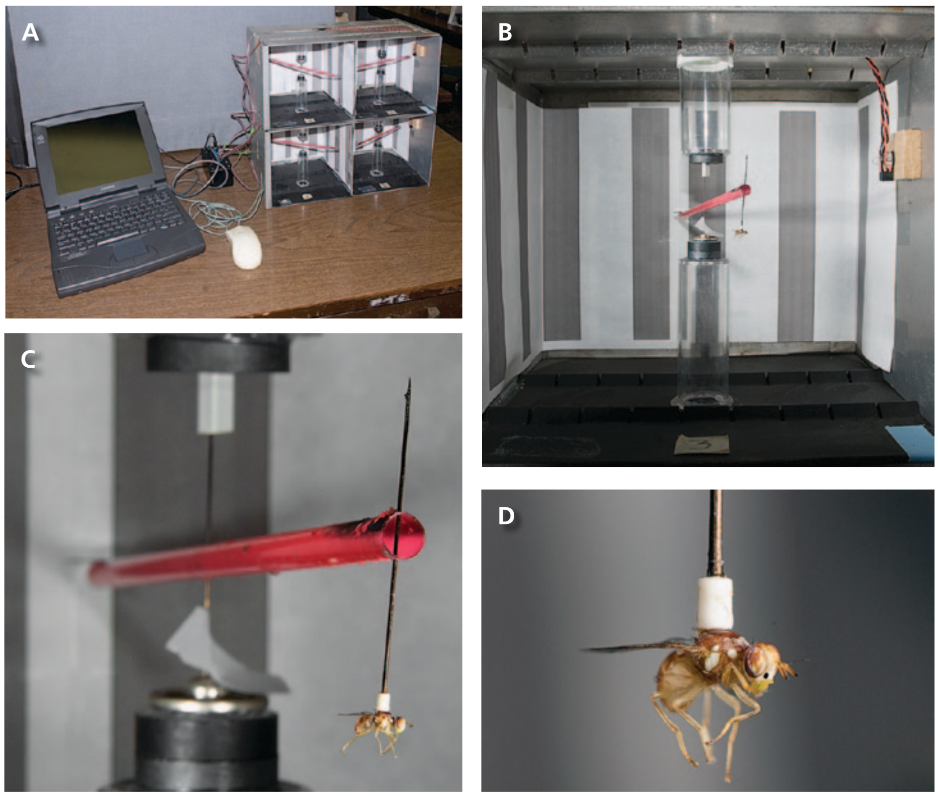


Fig. 4. Mean distances flown by olive fruit fly adults subjected to 1 to 3 days exposure to 95°F and 100°F, in the absence of food and with and without access to water (Wang et al. 2009b). Different letters above columns representing the same temperature/resource treatment indicate significant differences (*P* < 0.05; Tukey's HSD test) within the exposure duration.



Fly flight is measured using (A) a custom-designed flight mill setup with computer; (B) an individual flight mill unit; (C) a beam that rotates during insect flight; and (D) a tethered fly fastened to a rotating beam.

Such a fly would have an 84% chance of dying in the first 24 hours, and of those that did survive only about 25% would be able to fly (Wang et al. 2009b). Additionally, when olive fruit fly adults were held at 65°F at night and 95°F or 100°F during the day over a 3-day period with either water alone or no food or water, those flies that survived one day could fly significantly farther than those that survived 3 days ($F_{2,407} = 18.7$, $P < 0.01$) (fig. 4).

Egg and larval survival

Reproductive dormancy in olive fruit fly subsides as greater numbers of mature fruit appear within the orchard, commonly in late July and early August in California (Burrack and Zalom 2008; Wang et al. 2009a). During periods of high maximum daily temperatures (3 consecutive days at 100°F or above in July and August) (Lynn-Patterson 2006), mated adult females may lay their eggs in developing olives prior to morning temperatures reaching 95°F. No eggs are deposited during the night, even when temperatures are cool enough for normal activity (Avidov 1954; Wang et al. 2009a). Eggs are deposited just beneath the fruit epidermis and may be exposed to high temperatures, depending on where an individual fruit is located on the tree (Wang et al. 2009a).

Laboratory studies showed that adult females held under different diurnal temperature regimes (65°F at night and 75°F, 95°F or 100°F during the day) laid similar numbers of eggs when the temperature was 65°F and the experimental chamber was illuminated ($F_{2,55} = 0.2$,

P = 0.852). However, under illumination and higher temperatures, females laid significantly fewer eggs at 95°F (about four per female) than at 75°F (about 12 per female) ($F_{1,38}$ = 8.4, P = 0.006), and no eggs were laid at 100°F (Wang et al. 2009a).

Even after eggs are deposited within olive fruit, they are still susceptible to the high temperatures common in Central Valley orchards. Eggs within fruit held at 65°F (night) and 75°F (day) developed into first-instar larvae after 6 days (Wang et al. 2009a). In contrast, eggs within fruit subjected to 65°F (night) and 95°F (day) had a 49% mortality rate, and of the first-instar larvae that did develop, none became second instars. When subjected to 65°F (night) and 100°F (day), no eggs hatched after 10 days exposure and all died. The overall finding was that egg ($F_{3,57}$ = 2472, P < 0.001) and first-instar ($F_{3,57}$ = 2472, P < 0.001) mortality increased as exposure time increased (Wang et al. 2009a).

Later field studies showed that maximum daily temperatures in olive trees in the Central Valley (Parlier) varied depending on whether measurements were taken within the canopy interior or the east or west perimeter. Mean temperatures recorded on the west side of the tree canopy in August 2007 were 108°F (and over 104°F for 26 days) compared to 101°F (and over 104°F for 13 days) on the east side, and 96°F (and never over 104°F) within the canopy interior ($F_{2,90}$ = 52.7, P < 0.001). All of these temperatures are high enough to impose some level of mortality on olive fruit fly eggs and larvae. Field studies in the same locality in mid- and late summer 2007 and 2008 showed that less than 2% of offspring from eggs laid in olives completed development to the adult stage (Wang et al. 2009a).

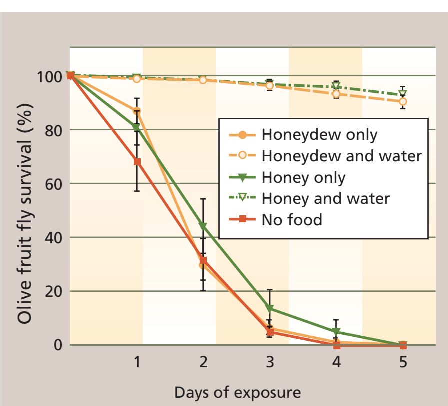


Fig. 5. Survival of olive fruit fly adults when held at 65°F (night) and 97.5°F (day) with access to various combinations of water, honey and black scale honeydew, or no food or water.

Scale honeydew and heat stress

This information suggests that it is difficult for olive fruit fly adults to survive the high summer temperatures in the Central Valley. Water may commonly be found within or near most orchards from a variety of sources, such as morning dew, creeks, ponds, irrigation water (ditches and canals), sprinklers, drip tape and fan jets. However, fly adults also need carbohydrates to survive heat stress. Honeydew (fresh or dry) produced by black scale is a common carbohydrate source in olive orchards. Our laboratory tests have shown that fly adults provided with honey and water, or black scale honeydew and water, survive temperatures of 65°F (night) and 97.5°F (day) with minimal mortality compared to adults only provided honey alone, honeydew alone, or no food and water over 5 days ($F_{4,36}$ = 189.9, P < 0.0001) (fig. 5) (M.W. Johnson and H. Nadel, unpublished data).

The carbohydrate source alone did not reduce the impact of heat on survival. Flies that had food resources (honeydew or pure honey) but no water suffered mortality similar to those flies without food or water. There was a significant interaction between carbohydrate source and days of exposure ($F_{20,180}$ = 33.3, P < 0.0001). These results are similar to what we have observed in our laboratory and field studies on olive fruit fly when 50% honey water was used as a carbohydrate source. These findings are significant because they suggest that olive fruit fly adults could use black scale honeydew to help them survive periods of high temperature in the Central Valley. The management of black scale populations via cultural controls such as the pruning of interior canopies may also contribute to the management of olive fruit fly adults.

Temperature maps and fly activity

Geographic information systems (GIS) enable the examination of temperature trends over specific areas based on defined criteria, such as temperature levels for specific time intervals. The examination of temperature trends in olive-producing areas in the Central Valley over 10 years (1992–2001) revealed that it was quite common for temperatures to be greater than 100°F for 3 consecutive days during mid-July and August (fig. 6) (Lynn-Patterson 2006). On the California coast, these trends were rarely observed. Over this time period, temperatures greater than 100°F for 3 consecutive days were more common in the southern (San Joaquin Valley) than the northern (Sacramento Valley) Central Valley (see http://arcims.gis.uckac.edu/CIMIS). By September, most of the Central Valley rarely had 3 consecutive days greater than 100°F (fig. 6).; in 2003, olive fruit fly surpassed one adult per trap per week at the end of August and continued to increase into November (fig. 1).

Growers and consultants may wish to use these maps to determine if they can temporarily halt insecticide treatments for olive fruit fly adults during July and August. However, there are many factors other than temperature that influence whether olive fruit fly will be a problem in a particular olive orchard. Olive fruit fly adults with access to adequate sources of water and carbohydrates can survive heat stress in large numbers and will be able to fly long distances (more than 1,000 yards) even when stressed. Growers who consider halting their control programs, especially in the San Joaquin Valley, should take under consideration the irrigation schedules and infestation levels of black scale and other insects that might produce honeydew within their own and neighboring orchards. Also important is the proximity of irrigation canals, creeks, ponds and rivers, as well as abandoned orchards or untreated olives trees used for landscaping, which can serve as an infestation source of olive fruit fly. Morning dew in the orchard may provide a moisture source for flies, and weedy undergrowth in the orchard or neighboring crops can afford some relief from the heat.

Perhaps the most useful information that one can obtain from the GIS maps is knowing when temperatures historically have dropped to low levels that would be conducive to olive fruit fly activity and survival in a particular area. As temperatures decline at the end

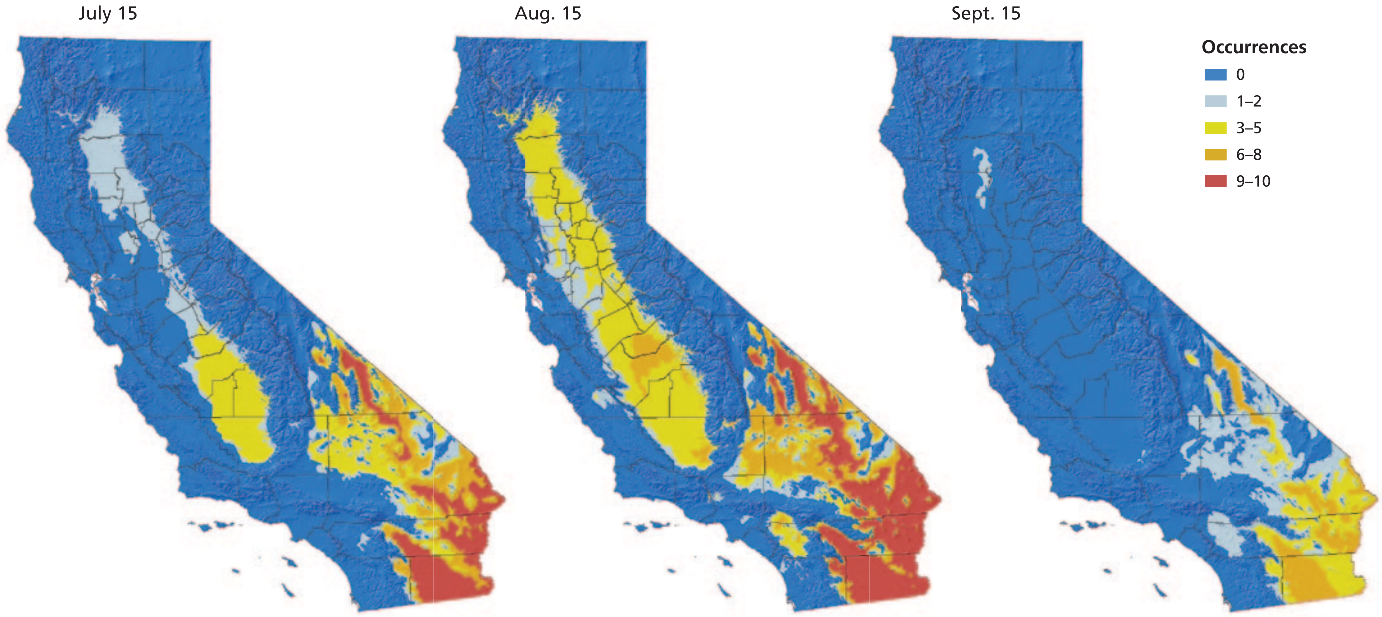


Fig. 6. Mean temperature patterns in California over 10 years (1992–2001), showing number of years (occurrences) with maximum temperatures greater than or equal to 100°F for 3 consecutive days ending on July 15, Aug. 15 and Sept. 15 (Lynn-Patterson 2006).

of August, olive fruit are increasing in size and maturing (Martin and Sibbett 2005). Olive fruit fly adults prefer to lay their eggs in the largest olives available (Neuenschwander et al. 1985). As flies return to normal activity in late summer, the olives remaining on the trees are at greater risk of infestation than at anytime during the summer, and protecting the fruit then is of prime consideration.

Future directions

Research on the ecology and management of olive fruit fly is continuing. A better understanding of the abilities of olive fruit fly adults to disperse among orchards in the summer would be helpful. Given that olive fruit fly adults need carbohydrate sources to survive heat stress, it may be best to continue treating with GF-120 in July and August. The adults are attracted to the sweet fruit fly bait in the GF-120. If stressed flies seek a carbohydrate source in summer, it may be assumed that they would then seek out available bait residues in GF-120. If this is true, the GF-120 may be having a greater impact than realized. This needs to be determined. Also of importance is the impact of summer heat either directly or indirectly on parasitoid natural enemies that are now being released as part of a classical biological control program for olive fruit fly control (see page 21).

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RESEARCH ARTICLE

Mediterranean clonal selections evaluated for modern hedgerow olive oil production in Spain

by Joan Tous, Agusti Romero, Juan Francisco Hermoso *and* Antonia Ninot

Traditional olive oil production is limited by its high cost, mainly due to labor expenses for harvesting and pruning. A new olive planting system based on hedgerows and harvesting machines could decrease production costs while maintaining high quality. To improve the efficiency of the continuous-straddle mechanical harvesters, vigor must be managed to limit tree size. However, few cultivars are adapted to this system. Selections from three cultivars are typically used in these super-high-density orchards. We field-tested 'Arbequina i-18', 'Arbosana i-43' and 'Koroneiki i-38' in an irrigated, super-high-density planting system in Catalonia (northeast Spain). We present a review of 6 years of horticultural data and summarize sensory characteristics and other properties of the resulting olive oils.

Paul M. Vossen

Olive trees have been cultivated for centuries in Mediterranean climates, including California's Central Valley (shown). New super-high-density hedgerow systems allow for mechanical harvesting, greatly reducing labor costs.

The olive tree, olive fruit and olive oil have been at the core of Mediterranean agriculture and trade since early cultivation times, providing sustenance to various cultures and civilizations of the Mediterranean Basin. Over the last few decades, olive (*Olea europaea*) cultivation has undergone important technological changes, which have involved a reduction in the number of olive oil varieties used, and an increase in the density of new plantations that is linked to improvements in harvesting machinery and irrigation systems.

In the early 1990s, a new design and management strategy for olive orchards, the super-high-density hedgerow system, appeared in Catalonia (northeast Spain). Later it was introduced into other Spanish regions and other countries. Clonal selections of local varieties were planted in new olive orchards with tree densities ranging from 600 to 1,000 trees per acre (1,500 to 2,500 per hectare) to test the suitability of the plants to mechanization and the production of high-quality, extra-virgin olive oil. Traditional olive orchards have 80 to 200 trees per acre (200 to 500 per hectare).

Just a few olive varieties have been compared for their adaptability to high-density plantings and continuous mechanical harvest. Our program at the Institut de Recerca i Tecnologia Agroalimentaria (IRTA) screened three old Mediterranean olive varieties — 'Arbequina' and 'Arbosana' from Catalonia and 'Koroneiki' from Crete (Greece) — to identify those with outstanding characteristics such as compact growth habits, low-medium vigor, early maturity and excellent oil quality (Tous et al. 2003). Agronomical evaluations in Spain and other countries have shown that these IRTA clones are precocious (bearing their first crop at an earlier age than standard cultivars), achieve higher yields earlier after planting and produce extra-virgin oil of excellent quality.

Editor's note: More than 12,000 acres of olives have been planted in California using the super-high-density system. Research in California is inconclusive about the long-term viability of super-high-density olive culture under California growing conditions; further field studies based in the state can address these questions.

California olive orchards

Olives were introduced in California by the Catalan Franciscan fathers, who planted olive trees in gardens adjacent to their missions. Their olives and oil were appreciated not only as food but also as an element in liturgical celebrations.

Today, the predominant table olive industry in California is supported by classic cultivars introduced for their suitability to traditional and intensive table olive orchard systems (Tous and Ferguson 1997; Vossen 2007). In California, the industry generally plants five cultivars (Mission, Manzanillo, Sevillano, Ascolano and Barouni) to produce black-ripe olives (Connell 2005). 'Mission' trees were likely introduced to California during Franciscan times, via Mexico in 1769 (Sutter 2005).

Olive planting for oil production, by contrast, has grown from negligible acreage in 1996 to approximately 16,000 acres (6,400 hectares) by 2008. Most of this acreage, 12,000 acres (4,800 hectares), is planted in super-high-density orchards with 560 to 870 trees per acre (1,400 to 2,175 per hectare) (UC Davis Olive Center 2009).

Most high-density California olive plantings are three releases of IRTA's clonal plant material from the Mas de Bover research station in Catalonia, Spain, the initial selections from their olive improvement program started in the mid-1980s. The IRTA clonal varieties currently available are 'Arbequina i-18', 'Arbosana i-43' and 'Koroneiki i-38', propagated in California by a few authorized nurseries. The success of these early clonal selections and the super-high-density system is also evidenced by their early adoption in traditional olive oil–producing countries, such as Spain, Portugal, Tunisia and Morocco, as well as diverse, nontraditional olive-growing regions that are beginning to produce extra-virgin olive oils of remarkable quality such as California, Chile and Australia.

TABLE 1. Horticultural characteristics of three olive tree clones tested in a super-high-density planting system in Catalonia, Spain

Characteristics	Arbequina i-18	Arbosana i-43	Koroneiki i-38
Vigor	Low	Very low	Medium
Growth habit	Semi-erect	Open	Open
Canopy density	Compact	Compact	Compact
Precocity of bearing	Early	Early	Early
Productivity	Very high and regular	Very high and regular	High
Fructification	In clusters	In clusters	In clusters
Harvest season	Early, midseason*	Late†	Midseason

* Maturation occurs in Catalonia from about mid-November to mid-December.
† Matures about 3 weeks later than 'Arbequina'.

We describe the performance and limitations of these olive oil clones in comparative field trials performed in an irrigated, super-high-density system in Catalonia, which supports their adoption in modern orchards. We also contribute additional information to help define the suitable orchard design and management of super-high-density plantings in California.

Horticultural characteristics

The clone 'Arquebina i-18' was obtained in 1997 in a program to identify and select outstanding individuals of 'Arbequina', the most important cultivar in Catalonia (160,000 acres [65,000 hectares]) from traditional orchards located in the PDOs (protected designations of origin) of Les Garrigues and Siurana in northeast Spain. 'Arbosana i-43' was selected in 1987 from surveys of the 'Arbosana' cultivar in the Alt Penedès region in Catalonia. The clone 'Koroneiki i-38' was selected in 1990 from trees of this Greek variety at the Mas de Bover research station. Morphological descriptions of the tree, leaf, fruit and endocarp for these cultivar clones have been published (Tous et al. 1999; Tous and Romero 2000, 2002).

Crop performance

The first comparative field trial with these clones in super-high-density hedgerow orchards was planted in

The growth habit of 11-year-old trees is shown for the IRTA clones (A) 'Arbequina i-18' (B) 'Arbosana i-43' and (C) 'Koroneiki i-38', in a hedgerow, super-high-density planting system in 2009, in Spain.

As the newly planted super-high-density orchards in California enter their optimal olive oil production phase, it will be interesting to compare and follow experiences and observations with other regions.

Tarragona in 1998 (Tous et al. 2003, 2008) (table 1).

Yields. Differences between varietals in cumulative fruit yield became evident during early years of the trial (table 2). In Tarragona, the highest cumulative yields were measured for 'Arbequina i-18' (31,875 pounds per acre) followed by 'Arbosana i-43' (26,470 pounds per acre) and 'Koroneiki i-38' (22,361 pounds per acre). In a similar trial in Cordoba (Andalusia, southern Spain), 'Arbequina i-18', 'Arbosana i-43' and 'Koroneiki i-38' showed higher mean harvest yields (3 to 6 years after planting) than other varieties tested (data not shown) (León et al. 2006); in this southern location 'Koroneiki i-38' was the most precocious (table 2). During the first years of both trials, the influence of environment on precocity and average crops achieved was larger in Cordoba due to the higher vegetative tree growth in this province.

The mean harvest of super-high-density cultivars in Tarragona was 4,397 pounds per acre (3rd year), 4,205 pounds per acre (4th year; frost on trees affected productivity), 10,344 pounds per acre (5th year) and 7,291 pounds per acre (6th year), all similar to harvests obtained in other high-density orchards in Spain. The high yields observed in early years of the Spanish trials and commercial orchards are not sustainable. Under the favorable growing conditions that foster vigorous tree growth, a reduction in potential production occurs in the 6th to 8th years, with averages of 7,138 to 8,030 pounds per acre, usually due to shade and limited ventilation in the tree canopies (Tous et al. 2010). The yields of 7- to 10-year-old orchards are more variable and depend on management of the canopy volume, which should not exceed 143,000 to 171,500 cubic feet per acre to facilitate movement of the over-the-row harvesters.

Vigor. We observed the lowest tree vigor (trunk cross-section, canopy volume and sucker emission) in 'Arbosana i-43' and 'Arbequina i-18' (table 3). 'Koroneiki i-38' is notorious for being more vigorous and producing more suckers than the other cultivars. The yield efficiency of each varietal clone was measured to determine the balance between productive and vegetative activity during the early bearing phase. The highest index scores were observed in 'Arbequina i-18' and 'Arbosana i-43' (0.12 pound per cubic foot), followed by 'Koroneiki i-38' (0.07 pound per cubic foot). 'Koroneiki i-38' showed a higher tendency to vegetative growth, and the crop was irregular among trees during the first years of the trial.

Mechanical harvest. Several intrinsic varietal characteristics, such as growth habit and canopy width, influence the efficiency of fruit removal during mechanical harvest. Our selections display two growth habit categories: semi-erect ('Arbequina i-18') and open canopy ('Arbosana i-43' and 'Koroneiki i-38'). Straddle machines or grape harvesters perform better than trunk shakers for these cultivars. More than 90% of the fruit was removed in all cultivars, independent of their size, position in the canopy and maturation index. By contrast, the efficiency of trunk-shaking harvesters is clearly influenced by growth habit (Pastor et al. 1998), and yield is improved with an erect or semi-erect tree shape, large fruits and low fruit removal force.

Disease. 'Arbequina i-18' is more sensitive than the other selections to olive leaf spot (*Spilocaea oleagina*) when planted in coastal environments and humid valleys. 'Arbequina i-18' is more tolerant than the other two cultivars to frost, while 'Koroneiki i-38' is the most sensitive.

TABLE 2. Annual and cumulative yields of IRTA olive clones planted in 1998 (Tarragona, Catalonia) and 2000 (Cordoba, Andalusia), Spain, in a super-high-density planting system 2 and 6 years after planting, respectively

	Arbequina i-18		Arbosana i-43		Koroneiki i-38	
Year	Tarragona	Cordoba	Tarragona	Cordoba	Tarragona	Cordoba
	lb/acre*					
Second	1,102	0	803	273	0	3,213
Third	6,002	13,203	4,771	15,305	2,416	18,502
Fourth†	4,428	12,527	2,833	7,990	5,356	5,440
Fifth	12,038	17,957	12,173	17,279	6,822	11,170
Sixth	8,305	5,519	5,890	6,583	7,678	4,027
Average (3th–6th)	7,693	12,302	6,537	11,790	5,568	9,786
Cumulative yield (lb/acre)	31,875	49,207	26,470	47,431	22,361	42,354

* 1 lb/acre = 1.1209 kg/ha.
† In the 4th year (2002), crop yield was slightly lower due to frost problems in Tarragona (December 2001).
Source: Tous et al. 2003, 2008; León et al 2006.

TABLE 3. Vegetative and productive characteristics of three olive cultivars growing in a 5-year-old, super-high-density orchard in Catalonia, Spain, 2000–2003 (2nd–5th year after planting)

Cultivar	Suckers (4th year)	TCSA* (5th year)	Canopy volume (5th year)	Cumulative yield (2nd-5th year)	Yield efficiency
		in^2†	$ft^3/acre$	lb/acre	$\sum lb/ft^3$‡
Arbequina i-18	0.4c§	5.54c	192.389ab	23.539a	0.12a
Arbosana i-43	1.4b	5.85bc	168.795b	21.330ab	0.12a
Koroneiki i-38	5.2a	7.67a	189.674ab	14.594c	0.07bc

* Trunk cross-sectional area.
† 1 $inch^2$ = 6.4516 cm^2; 1 $ft^3/acre$ = 0.0700 m^3/ha; 1 lb/acre = 1.1209 kg/ha; 1 lb/ft^3 = 16.0185 kg/m^3.
‡ Sum of first yields (2nd to 5th year) per cubic foot of canopy volume at 5th year (2003).
§ Mean separation within columns by Duncan's multiple range test, $P < 0.05$.

Harvest time. Gradual fruit ripening and maturation is commonly observed in the three cultivars, although this parameter is highly influenced by tree fruit load and seasonal conditions as well as geographical location. Optimal harvest time is different for each of the cultivars: 'Arbequina i-18' is optimal in Catalonia from mid-November to mid-December, 'Koroneiki i-38' matures in late December and 'Arbosana i-43' in mid-January.

Fruit and oil characteristics. 'Arbequina i-18' produced larger fruits than the other two cultivars (table 4). The pulp/stone ratio was higher for 'Arbosana i-43' and 'Arbequina i-18', followed by 'Koroneiki i-38'. Fruit water content ranged between 56.0% in 'Koroneiki i-38' and 61.1% in 'Arbosana i-43'. Oil content expressed as percentage of dry weight was higher in 'Arbequina i-18' (54.4%), followed by 'Koroneiki i-38' (52.4%) and 'Arbosana i-43' (50.7%).

The three clonal selections produced extra-virgin olive oil of excellent quality. The fatty acid composition of 'Arbequina i-18' and 'Arbosana i-43' oils was similar (table 5). 'Koroneiki i-38' oil is characterized by a higher content of oleic acid (more than 76%) at the expense of palmitic and linoleic acid, which contribute to longer shelf life. 'Arbosana i-43' and 'Koroneiki i-38' oils were consistently richer in polyphenols than 'Arbequina i-18'. When compared at the organoleptic sensory level (fig. 1), 'Arbequina i-18' oil was the most balanced of the three, with a medium fruity intensity, balanced in the palate and an outstanding sweetness. 'Koroneiki i-38' produced the most fruity, green, bitter and pungent oil of the three, and 'Arbosana i-43' oils had an intermediate palate profile. Oil composition and flavor change as the olive fruit develops. The distinctive and contrasting sensory attributes of the extra-virgin oils from each varietal allows for unique blends with a wide range of interesting sensory characteristics.

TABLE 4. Fruit characteristics of three IRTA clones tested in an irrigated, super-high-density planting system in Catalonia, Spain, from trees 3 to 7 years old, 2001–2005

Cultivar	Fruit weight	Pulp/stone ratio	Oil content	Moisture	Oil content
	g		*% fresh weight*	*%*	*% dry weight*
Arbequina i-18	1.72 ± 0.18*	4.31 ± 0.59	21.9 ± 1.0	60.1 ± 3.0	54.4 ± 2.5
Arbosana i-43	1.59 ± 0.37	4.69 ± 0.54	19.8 ± 0.8	61.1 ± 2.2	50.7 ± 2.8
Koroneiki i-38	0.90 ± 0.14	3.44 ± 0.84	22.9 ± 0.8	56.0 ± 2.3	52.4 ± 3.4

* Mean values ± standard error (SE).

TABLE 5. Olive oil characteristics* of three IRTA clones tested in an irrigated, super-high-density planting system in Catalonia, Spain, from trees 5 to 6 years old, 2003 and 2004

Cultivar	Palmitic acid, C16:0	Oleic acid, C18:1	Linoleic acid, C18:2	Linolenic acid, C18:3	Total polyphenols	Bitterness	Oil stability
	. . . .	. . . . %	. . . .		*ppm cafeic acid*	K_{225}	*hours* †
Arbequina i-18	14.5a‡	69.4c	11.1a	0.72b	234b	0.2a	9.10b
Arbosana i-43	13.6a	73.0b	7.9b	0.9a	343a	0.30a	12.8ab
Koroneiki i-38	11.4b	76.6a	6.89c	0.93a	400a	0.45b	15.23a

* Oil characteristics: main fatty acid composition (%), total polyphenols (ppm cafeic acid), bitterness (K_{225}) and oil stability.
† Oil stability against oxidation, applying Rancimat method (hours at 120°C).
‡ Mean separation within columns by Duncan's multiple range test, $P < 0.05$.

Field observations

Initial observations from the Mas de Bover cultivar trials and orchard design evaluations, initiated in the 1980s, have been validated by the worldwide adoption of IRTA's clonal selections. The three initial selections described here have been planted in new high-density (121 to 242 trees per acre) and super-high-density (over 600 trees per acre) olive tree orchards around the world, and most recently California.

The most consistent plant characteristics and performance, as observed in super-high-density orchards around the world, can be summarized as follows:

'Arbequina i-18'. This highly productive variety is early bearing with little alternating bearing. It is considered frost resistant and adaptable to different climatic and soil conditions, and is adaptable to high-density and super-high-density hedgerow orchards. Its semi-erect growth habit facilitates its training on a central leader. It produces medium-fruited extra-virgin oil that is balanced in the mouth; the sweet attribute is outstanding and easily appreciated by new consumers. Its commercialization can be monovarietal or blended with other oils.

'Arbosana i-43'. This is an early-bearing cultivar with high productivity.

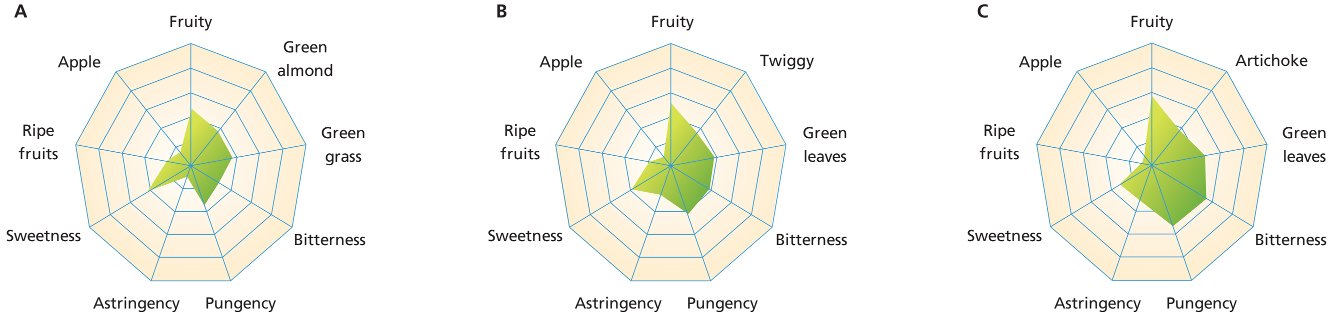

Fig. 1. Sensorial profiles of olive oils from three IRTA clones: (A) 'Arbequina i-18', (B) 'Arbosana i-43' and (C) 'Koroneiki i-38'. The green polygon represents the intensity of each taste attribute scored on a 10-point scale.

Fruit of three clones used in super-high-density planting systems. 'Arbequina i-18' and 'Arbosana i-43' are native to Catalonia, Spain, and 'Koroneiki i-38' is native to Greece.

Due to its low vigor, it adapts well to hedgerow systems for olive growing. Sensitive to frost, its fruit is small and ripens several weeks later than 'Arbequina'. It produces intense, green-fruited virgin oil with high levels of bitterness, spiciness and astringency. Due to its higher polyphenol content, it is particularly interesting for blending and to stabilize and prolong the shelf life (time to rancidity) of the milder 'Arbequina' oil.

'Koroneiki i-38'. This is a productive and early-bearing cultivar. It is considered drought resistant but frost sensitive, and well suited to hot growing areas. It is tolerant to olive leaf spot and has very small fruit, which ripen after 'Arbequina' but before 'Arbosana'. It produces quite-stable extra-virgin oils, rich in oleic acid and polyphenols, with intense green color and bitterness, and a long shelf-life.

Olive tree breeding program

Scientists at IRTA's Mas de Bover research station are evaluating additional clonal materials and old orchards of olive varieties, and prioritizing the search for varietal characteristics that can improve productivity, a low vigor/compact growth habit, disease resistance and extra-virgin olive oil with high levels of antioxidants. IRTA recently initiated a project to catalogue a collection of ancient trees (estimated 500 to 700 years old) in local orchards around northeast Spain that contain individual trees of unclear varietal origin, as potential sources of novel germplasm to produce olives of improved agronomic performance and desirable olive oil sensory attributes.

As the newly planted super-high-density orchards in California enter their optimal olive oil production phase, it will be interesting to compare experiences and observations with other regions in terms of economic viability, orchard management and sustainability, natural resource utilization and extra-virgin oil qualities.

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Olive cultivars field-tested in super-high-density system in southern Italy

by Angelo Godini, Gaetano Alessandro Vivaldi, *and* Salvatore Camposeo

According to the International Olive Oil Council, world olive oil consumption has risen from 2.8 million tons (1991-1992) to 3.5 million tons (2005-2006), due to increases in the consumption of healthier foods in many countries, including the United States. The market outlook for extra-virgin olive oil is very good, and many countries are actively increasing their olive acreages, particularly in North Africa, the Middle East, South America, Australia and the United States (Godini 2010).

The Mediterranean's traditional olive industry is based on production systems that are hundreds of years old and characterized by low yields and high production costs. The European Union subsidy system, which has helped European olive farmers to stay in business, will end in 2014. Moreover, the application of a "free exchange" area in 2010 will legalize the importation of lower-cost extra-virgin olive oils from the southern Mediterranean Basin into Europe (Godini 2010). Year after year, the profitability of Italy's traditional olive culture becomes increasingly doubtful, notwithstanding the worldwide renown of so-called "Made in Italy" extra-virgin olive oil (Godini and Bellomo 2002).

Paul M. Vossen

Super-high-density hedgerow planting systems for olives employ over-the-row harvesters (shown, in California).

California production of extra-virgin olive oil is reportedly about 2% of total U.S. consumption, with the rest imported mainly from Italy and Spain. In recent years, California has started increasing its oil olive acreage. California olive growers have planted more than 22,000 acres since 1999, about 12,000 acres of which is in the super-high-density olive system, with tree densities of 676 per acre or more. This system allows for mechanical planting and harvesting of olives, reducing labor costs.

We believe that super-high-density olive culture can help to assure profitability for both European and U.S. olive growers in the coming decades. This model, born in Spain at the end of the 20th century, has resulted in noticeable increases in yield per acre. Up until now, super-high-density olive culture has utilized a limited number of cultivars, primarily 'Arbequina', 'Arbosana' and 'Koroneiki', which possess suitable features such as a semi-dwarf habit, early bearing (first production at the second-to-third year after planting), consistent initial crops (more than 2.2 pounds per plant), crop stabilization between 5 and 6 years, and fruit that is impact-resistant and has good oil quality (Godini and Bellomo 2002).

The results that we present here are preliminary. Considering that Italy's Mediterranean climate is similar to California's, we believe that soil and climate differences should have little influence on the applicability of these findings to California.

Experimental orchard

In summer 2006, we established a new experimental orchard at Valenzano, near Bari, in the experimental farm of the Dipartimento di Scienze delle Produzioni Vegetali at University Aldo Moro of Bari, Italy. In addition to standard clones of 'Arbequina', 'Arbosana' and 'Koroneiki', two additional cultivars were introduced: 'Coratina', the most popular Apulian olive oil cultivar, and 'Urano', a new Italian cultivar considered by our research group to be well-suited for super-high-density olive culture.

The olive trees were propagated in commercial nurseries by softwood cutting, and the experimental orchard was established according to the super-high-density planting scheme (676 plant per acre, with a tree spacing of 157.5 inches by 59 inches) and a north-south row orientation. The trees were trained to central leaders. Drip irrigation was supplied to each tree every 3 days between late spring and late summer, increasing from 423 cubic yards per acre annually in 2006, to 476 in 2007, to 794 in 2008 and 2009. Harvesting was performed on Nov. 20 in 2008 and 2009, in the third and fourth years after planting, respectively, using the Pellenc Activ' 4560 harvesting machine.

Cultivar performance

Vegetation. In December 2009, the average tree height had reached 107 inches, 5.3 times the initial growth of the previous year, with a maximum of 7.6 times more growth for 'Arbequina' and a minimum of 2.2 times more for 'Urano' (table 1). Only the crown width of 'Coratina' exceeded 79 inches by

TABLE 1. Tree height at planting (June-July 2006) and December 2009, crown width in December 2009

Cultivar	Tree height		Crown width
	Planting	December 2009	December 2009
		inches	
Arbequina	14.1b*	107.3b	77.5b
Arbosana	13.0b	97.0c	77.7b
Coratina	16.9b	120.9a	96.5a
Koroneiki	16.0b	117.6a	78.4b
Urano	41.1a	92.7c	74.5b
Mean	20.2	107.1	80.9

* Within the same column and for a single parameter, different letters mark values significantly different at $P = 0.01$ (SNK test).

December 2009, exceeding the harvester tunnel size and requiring pruning intervention to control its transverse canopy growth.

Annual yields. The average annual yield in the third year was 7.7 pounds per tree, equivalent to 2.3 tons per acre; only 'Urano' exhibited a surprisingly high yield of 3.7 tons per acre (table 2). In the fourth year, the average crop yield was 11 pounds per tree or 3.3 tons per acre (up 40% from 2008), and it was more variable among cultivars. 'Koroneiki', 'Arbosana' and 'Arbequina' followed by 'Coratina' gave satisfactory yield (between 13.7 and 11.3 pounds per tree or 4.1 and 3.4 tons per acre). The yield for 'Urano' dropped to 4.9 pounds per tree or 1.5 tons per acre, perhaps due to heavy cropping in the previous year.

Cumulative yields and oil. We also compared cumulative yields over the first 4 years of the trial. 'Koroneiki' showed the highest cumulative yield (41.3 tons per acre), and 'Urano' was relatively less productive (31.6 tons per acre) (table 2). The peculiar behavior of 'Urano' requires further investigation. Considering its average overall oil content of about 17.0%, 'Koroneiki' was the most productive cultivar with 6.9 tons per acre of oil over 4 years. The other cultivars exhibited similar cumulative oil production.

Harvesting efficiency, fruit and shoot damage. Harvesting efficiency was satisfactory on the whole (93.1%), notwithstanding differences among cultivars (table 3). 'Arbequina', 'Coratina' and 'Urano' had the highest harvest efficiency; 'Arbosana' and 'Koroneiki' were less satisfactory. But these differences were due to the fruit-ripening stages reached by each cultivar at the harvesting date: mature for 'Arbequina', 'Coratina' and 'Urano', but immature 'Arbosana' and 'Koroneiki'.

No damaged fruits were reported for 'Arbequina', 'Arbosana' and 'Koroneiki', whereas 'Coratina' and 'Urano' exhibited very low percentages of damaged fruit.

The average percentage of shoots damaged per tree by the harvesting machine beaters was insignificant at less than 1.0%. Of these damaged shoots, young and thin current-year shoots incurred the most damage (80.0%), perhaps because they were more exposed. The percentage of damaged shoots up to 1 inch in diameter was 14.3%, and to shoots thicker than 1 inch was 5.7%. Only 'Coratina' and 'Urano' exhibited a significant percentage of broken shoots or branches thicker than 1 inch: 'Coratina' because of its spreading habit between rows, and 'Urano' because of its spreading habit and thick, bending branches.

TABLE 2. Fruit production per year, cumulative yield at the third (2008) and fourth (2009) year after planting, and mean oil output and cumulative production

Cultivar	Fruit production: 3rd year	Fruit production: 4th year	Cumulative yield*	Mean oil output	Cumulative oil production
	pounds/tree†	*pounds/tree†*	*tons/acre*	*%*	*tons/acre*
Arbequina	5.5b‡	12.4ab	33.4b	17.7	5.68b
Arbosana	6.2b	12.6ab	35.1ab	17.5	5.83b
Coratina	7.1b	11.3b	34.1b	17.3	5.86b
Koroneiki	8.4b	13.7a	41.3a	15.0	6.89a
Urano	12.1a	4.9c	31.6c	16.8	5.26b
Mean	7.7	11.0	35.1	16.9	5.91

* Over four years of the trial.
† 7.73 pounds per tree = 2.3 tons per acre.
‡ Within the same column and for a single parameter, different letters mark values significantly different at $P = 0.01$ (SNK test).

TABLE 3. Harvesting efficiency, damaged fruits and damaged shoots per tree, as mean of the third and fourth year after planting

Cultivar	Harvesting efficiency	Fruit damaged	Shoots damaged
	%	*%*	*n/tree*
Arbequina	97.2a*	0.0c	0.4b
Arbosana	87.1b	0.0c	0.5ab
Coratina	97.3a	1.5a	0.2c
Koroneiki	87.6b	0.0c	0.6a
Urano	96.0a	0.4b	0.2c
Mean	93.1	0.4	0.4

*Within the same column and for a single parameter, different letters mark values significantly different at $P = 0.01$ (SNK test).

High density, high yields

The present data confirms and improves upon results obtained in previous experimental trials (Camposeo and Godini 2010). In terms of early bearing and yield consistency, all the tested cultivars performed satisfactorily. And in sensory evaluations, the resulting extra-virgin oils had sweet typology and were well-balanced, highly fruity and ready to use (Camposeo et al. 2010).

We know that higher yields have been recorded elsewhere with super-high-density olive culture; however, we consider annual yields of about 17.5 tons per acre of fruit to be satisfactory. In fact, this value, equivalent to a yield of only about 9.4 pounds per tree, would be helpful in avoiding alternate bearing and subsequent problems that could cause conflicts between vegetative growth and cropping consistency. Tree size can be controlled by pruning when they grow larger than the size of the harvester head. Our data indicates that the noted yield limit was reached by at least four out of five cultivars in just the 4th year after planting.

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Methods evaluated to minimize emissions from preplant soil fumigation

by Suduan Gao, Bradley D. Hanson, Dong Wang, Gregory T. Browne, Ruijun Qin, Husein A. Ajwa *and* Scott R. Yates

Many commodities depend on preplant soil fumigation for pest control to achieve healthy crops and profitable yields. Under California regulations, minimizing emissions is essential to maintain the practical use of soil fumigants, and more stringent regulations are likely in the future. The phase-out of methyl bromide as a broad-spectrum soil fumigant has created formidable challenges. Most alternatives registered today are regulated as volatile organic compounds because of their toxicity and mobile nature. We review research on methods for minimizing emissions from soil fumigation, including the effectiveness of their emission reductions, impacts on pest control and cost. Low-permeability plastic mulches are highly effective but are generally affordable only in high-value cash crops such as strawberry. Crops with low profit margins such as stone-fruit orchards may require lower-cost methods such as water treatment or target-area fumigation.

Shank application of 1,3-D is followed by a disking/rolling operation, *inset*, to break the shank trace and compacted soil surface.

Soil fumigation with methyl bromide has been used for decades in California to control a variety of soil-borne agricultural pests, such as nematodes, diseases and weeds. Major, high-value cash crops that rely on soil fumigation include strawberries; some vegetables such as carrot, pepper and tomato; and nurseries and orchards for stone fruit, ornamentals and grapevines. In California, tree and grapevine field nurseries must meet requirements of the California Department of Food and Agriculture (CDFA) Nursery Nematode Control Program (CDFA 2008). Without fumigants, the productivity of these cropping systems would suffer from yield losses due to diseases, replant disorders or lack of phytosanitary certification.

Because of its role in depleting stratospheric ozone, methyl bromide was phased out in the United States and other developed countries as of January 2005, under provisions of the U.S. Clean Air Act and the Montreal Protocol (an international agreement). Some limited uses of methyl bromide are permitted under critical-use exemptions and quarantine/preshipment criteria, which are subject to application and approval annually.

Limited to a few registered compounds, growers have turned to alternative fumigants such as 1,3-dichloropropene (Telone or 1,3-D), chloropicrin (CP) and methyl isothiocyanate (MITC) generators (metam sodium or dazomet) (Trout 2006). In addition to direct toxicity, most of these alternative fumigants are also regulated as volatile organic compounds (VOCs). Some VOCs released into the atmosphere can react with nitrogen oxides under sunlight to form harmful ground-level ozone, an important air pollutant. Regulations such as use limits and buffer zones have been used to minimize emissions and protect public and environmental health. More-stringent regulations are being developed for fumigants to reduce air emissions, especially in ozone-nonattainment areas such as Ventura County and the San Joaquin Valley (CDPR 2008; Segawa 2008).

The UC Statewide Integrated Pest Management Program recently prepared a field fumigation guide for emission control, which is available on the California Department of Pesticide Regulation website (UC IPM 2009). This paper is not intended to represent or serve as a replacement for that guide, but rather to update findings on emission-reduction technologies, including projects under the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) Pacific Area-Wide Pest Management Program. We summarize extensive research on emission reduction from soil fumigation conducted over the last few years, and identify agricultural practices for minimizing fumigant emissions while achieving good efficacy. We also identify knowledge gaps and other research needs for the near future.

Factors affecting emissions

Soil fumigants are volatile chemical compounds. The purpose of fumigation is to achieve maximum control of soilborne pests, which requires an effective concentration or exposure duration and the uniform distribution of fumigants in soil. A number of processes affect the fate of fumigants after soil application (fig. 1). Fumigants are subject to partitioning into soil air, water and solid phases (most importantly, organic matter); volatilization (emission); degradation (chemical and microbial), movement in soil via diffusion; and potential leaching. Volatilization and leaching can potentially contaminate the air and water. Emission loss is a major air-quality concern. To minimize emissions as well as ensure efficacy, it is necessary to contain fumigants in the rhizosphere where plant roots are present and soilborne pests are dominant. Without proper containment, more than half of fumigants applied can be lost through emissions (fig. 2). Fumigant lost into the atmosphere not only contributes to air pollution, but also translates into wasted resources intended for soil pest control.

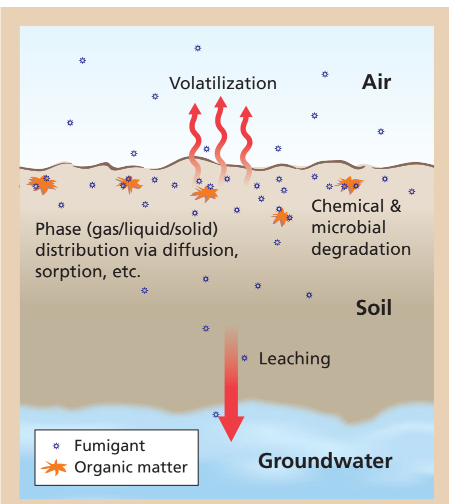

Fig. 1. Processes affecting the fate of fumigants in soil.

Fumigant lost to atmospheric emissions not only contributes to air pollution, but also translates into wasted resources intended for soil pest control.

Soil conditions (such as texture, moisture and organic matter content), weather and surface barriers, and the chemical properties of the fumigant can all affect emissions. Generally speaking, lower emissions are expected from soils with fine texture, high water content, high organic-matter content and low temperature compared to dry soils with coarse texture, low organic-matter content and high temperature. Approaches to reducing fumigant emissions include application methods such as equipment design (injection depth), physical barriers, irrigation, soil amendment with chemicals or organic materials and target-area treatment.

Current application techniques include broadcast fumigation and chemigation. With standard broadcast fumigation, fumigants are applied directly to the soil at a certain depth using conventional equipment or rigs (shanks). Chemigation is injecting fumigants into soil with irrigation water through sprinklers or drip tapes.

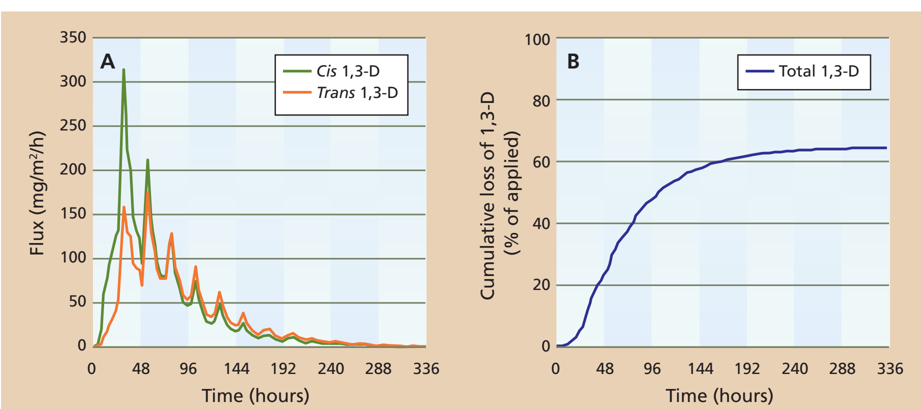

Fig. 2. Emission flux from a bare surface soil after shank injection of 1,3-dichloropropene (1,3-D) (with 2.5% inert ingredients) at an 18-inch depth into a sandy loam soil. The 1,3-D included *cis*- and *trans*-isomers; the sum of the isomers volatilized over time divided by the total applied gives the cumulative emission loss.

Applying fumigant deeper in the soil lowers emissions by increasing fumigant travel time to the surface and its interaction with soil. Increasing the shank-injection depth from 12 to 24 inches (30 to 60 centimeters) resulted in a 20% or greater reduction of methyl bromide emissions in bare soils (Yates et al. 2002).

The general consensus for bare-soil fumigation is that emissions from drip application, especially subsurface, are lower than broadcast-shank injections (Gao, Trout, Schneider 2008; Wang et al. 2009). This is attributable to two factors: (1) increasing soil water content decreases air pore volume (i.e., vapor diffusion) and increases the amount of fumigant partitioning in the aqueous phase and (2) there are no shank traces (i.e., soil fractures) that can serve as volatilization channels. The fumigant diffusion rate in the liquid phase is much slower than in the gas phase. Substantially higher soil water content would reduce the fumigant's distribution in soils by reducing vapor diffusion, reducing efficacy. Good efficacy can only be ensured when the fumigant moves with applied water for a relatively uniform distribution (Ajwa and Trout 2004). However, because fumigants are highly volatile, drip-applied fumigants near soil surfaces without any barriers may still result in high emission losses. Currently, about half of California's strawberry acreage, especially in the coastal areas, is fumigated using drip application.

Plastic films

Plastic tarping or "mulching" is the most commonly used practice to contain fumigants in soil and control emissions. The effectiveness of tarping on emission reduction depends largely on the chemical's characteristics and tarp permeability, and also to some extent on soil conditions. Tarping with polyethylene film was found to be ineffective

A company applies fumigant through drip irrigation in a strawberry field.

Plastic tarping minimizes emissions following fumigant application.

to control 1,3-D emissions, especially in relatively dry soils (Gao and Trout 2007; Papiernik and Yates 2002). However, high-density polyethylene (HDPE) tarp applied over irrigated soil can substantially lower 1,3-D emissions, due to both higher soil water content and water condensation under the film (Gao and Trout 2007). About 50% emission reduction was measured for an HDPE-tarped treatment in relatively cooler fall weather conditions, compared to bare soil (Gao, Hanson, et al. 2009). Tarped treatment in pre-irrigated soil in summer may also improve pest control due to elevated soil temperatures under the tarp. Shrestha et al. (2006) observed significant reductions in weed populations due to high temperatures up to 117°F under the tarp, which was partially attributed to the effect of solarization.

Virtually impermeable film. Low-permeability films, including virtually impermeable film (VIF), showed great potential in early laboratory or small-plot tests (Wang et al. 1997b). VIF has much lower permeability to most fumigants than HDPE films (Ajwa 2008).

VIF is generally a multilayered film composed of barrier polymers such as nylon or ethyl vinyl alcohol (EVOH) sandwiched between polyethylene polymer layers (Villahoz et al. 2008). A number of studies have shown that VIF can retain higher fumigant concentrations than HDPE film, reducing emissions while improving efficacy, especially for weed control (Hanson et al. 2008; Noling 2002). The effectiveness of VIF in large-field applications has been difficult to ascertain because it can be damaged during field installation, with potential changes in permeability.

Recent field data confirmed that this type of film can effectively reduce emissions more than 90% (Ajwa 2008; Gao, Qin, et al. 2009). The tarp permeability did increase after field installation but was still substantially lower than that of polyethylene films (Qin, Gao, Ajwa 2008; Yates 2008). There are also concerns about damage from field installation and improper gluing materials in the VIF tarp. These potential problems, however, were not observed in a recent field trial (Gao, Hanson, et al. 2009), when a Bromostop VIF (0.025-millimeter thickness) from Bruno Rimini Corp. (London, U.K.) was applied to a shank-injected 1,3-D (Telone II) field, achieving greater than 95% emission reduction.

Totally impermeable film. A new type of low-permeability film, so-called totally impermeable film (TIF), was reportedly easier to install and maintain in field applications (Chow 2008; Villahoz et al. 2008). This film has even lower permeability to fumigants than some other VIFs (Ajwa 2008). For example, the mass-transfer coefficient (indicating tarp permeability to fumigants) for TIF was 0.0004 inch (0.001 centimeter) per hour for *cis* 1,3-D compared to 0.028 inch (0.07 centimeter) per hour for Bromostop VIF before field application, and 0.008 inch (0.02 centimeter) versus 0.106 inch (0.27 centimeter) per hour, respectively, after installation over raised beds in the field.

TIF is a five-layer film incorporated with a middle layer of EVOH into a standard polyethylene-based film (Chow 2008). Information on field emission reductions is insufficient because this film has not been made available commercially. The most recently reported research data indicated that TIF can have similar effectiveness in reducing emissions as other VIFs; but these low-permeability films can cause emission surges when the tarp is cut and after about 1 week, due to the release of high amounts of retained fumigant (Gao et al. 2010). These emission surges would increase exposure risks to workers and bystanders. To reduce the risk, the waiting period between fumigation and tarp cutting or removal should be long enough for fumigants to degrade under the tarp. VIFs can retain fumigants under the tarp, making lower application rates possible, provided that satisfactory pest control can be achieved. The low-permeability films also showed the potential to improve the uniformity of fumigant distribution up to a certain depth in the soil profile, so lower application rates than are currently used for bare soil or underneath standard polyethylene film would be possible.

Water seals and pre-irrigation

With proper management, post-fumigation water seals (with sprinklers) and pre-irrigation can reduce emissions to some extent. The latter is used to achieve adequate soil moisture if the soil is dry, but not to a level that would inhibit fumigant movement/distribution in the soil profile. Water seals reduce fumigant emissions by forming a high-water-content layer at the soil surface, which serves as a barrier preventing the fumigant from diffusing into the air (Wang et al. 1997a).

Some earlier studies showed that high water content in the surface soil provided a more effective barrier to 1,3-D movement than HDPE tarping (Gan, Yates, Wang, et al. 1998). Intermittent water seals following soil fumigation have been effective in reducing emissions of methyl isothiocyanate (Sullivan et al. 2004; Wang et al. 2005) and 1,3-D or chloropicrin in the field (Gao and Trout 2007; Yates et al. 2008a). The effect is more pronounced in reducing emission peak flux, or volatilization rates from soil, by as much as 80% following fumigant application (Gao, Qin, et al. 2009). When irrigation stops, however, the emission flux tends to increase, depending on fumigant concentrations in the soil. As a result, cumulative or total emission losses may not be reduced as substantially as the peak flux. Reducing the peak flux is important because it lowers the potential exposure risk to workers and bystanders. Buffer zones are determined based on the peak emission flux.

When the proper amount of water is applied, water seals do not necessarily reduce fumigant concentration and distribution in the soil profile. This would hold true when only a relatively wet surface layer (up to 6 inches of soil) is maintained, and this layer should help retain fumigants in the soil. More frequent water applications appear to be more efficient in reducing emissions than fewer applications with large amounts of water. But the high water content in surface soil can reduce the efficacy of a fumigant to control nematodes and weeds at or near the soil surface (Hanson et al. 2008). Sequential treatment should be considered when surface pest control is a concern.

Irrigation with sprinklers forms a water seal, which minimizes emissions after fumigation.

Chemical treatments

Soil amendments with chemicals (such as ammonium or potassium thiosulfate [ATS or KTS], thiourea or polysulfides) sprayed over surface soil are extremely effective in reducing emissions. These chemicals can react with fumigants such as methyl bromide, 1,3-D, chloropicrin and iodomethane (methyl iodide) to form nonvolatile compounds by dehalogenation (Gan, Yates, Becker, et al. 1998; Wang et al. 2000). The practicality of using these chemicals on a large field scale to reduce fumigant emissions has yet to be determined. Considerations include cost factors when large quantities of thiosulfate are needed, and potentially undesirable soil-fumigant-thiosulfate reactions.

Field trials involving spraying KTS on the soil surface following fumigation revealed that this chemical can significantly reduce emissions of 1,3-D (by about 50%) and chloropicrin (by 85%) (Gao, Qin, et al. 2008). By destroying fumigant, this chemical treatment would potentially reduce the fumigant dosage at or near the soil surface, but studies showed either no effect or a limited impact on its efficacy for controlling nematodes and/or weeds (Gan et al. 2000; Gan, Yates, Becker, et al. 1998). However, strong reactions between KTS and the fumigant occurred, which resulted in a reddish-brown surface soil color and an unpleasant smell that lasted for several weeks. This reaction was not observed in a strawberry field when KTS was applied to the furrows of raised beds, most likely due to the low levels of fumigant emission measured from the furrows (Qin, Gao, Ajwa 2008; Qin, Gao, McDonald, et al. 2008). Zheng et al. (2007) indicated that the smell may have been derived from sulfur byproducts of the transformation of thiosulfate and fumigants in the soil.

Amendments and target treatments

Soil amendment with organic materials such as composted manure has been effective in degrading fumigants and also reducing emissions in the laboratory and some field studies. Because fumigants are readily incorporated into organic matter (Xu et al. 2003), soil with high organic-matter content was reported to produce lower emissions (Ashworth and Yates 2007). However, field data is inconclusive regarding the efficacy of adding organic amendments such as composted dairy manure right before fumigation to reduce fumigant emissions.

Yates et al. (2008b) reported that a field with organic matter (composted municipal green waste) incorporated in the previous year resulted in much lower emissions than a field without the amendment but with water seals. In a field trial with relatively high fumigant application rates, manure incorporation at 5 and 10 tons per acre (12.4 and 24.7 megagrams per hectare) did not reduce emissions (Gao, Qin, et al. 2009). Similarly, a recent trial using a higher amendment rate of 20 tons per acre (49.4 megagrams per hectare) also did not show emission reduction, possibly due to reduced bulk density from too much organic material (Gao, Hanson, et al. 2009). The quantity and quality of organic matter may also determine its effectiveness in reducing emissions. High manure application rates accompanied by irrigation and/or strong surface compaction may be needed to achieve emission reduction. However, increasing the incorporation rate may be too costly to be worthwhile.

The fumigation of targeted areas such as tree rows or tree sites may be applicable for orchards where replant disease is a major concern (Browne 2008). The shank application of fumigants in row-strip (shank-strip) or drip application of fumigant in tree sites (drip-spot) have been tested in fields for efficacy as well as emissions (Gao, Trout, Schneider 2008; Wang et al. 2009). These target-area treatments lower emissions by reducing the treated acreage to less than 50% (shank-strip) or 10% (drip-spot), automatically reducing the total amount of fumigants applied. Applying surface sealing or water treatment can achieve further emission reduction.

Cost estimates

Cost is important when evaluating the feasibility of emission-reduction

TABLE 1. Emission-reduction potential and cost estimates for surface sealing/treatments to reduce emissions from soil fumigation

Soil-surface treatment	Emission-reduction potential	Cost (excluding fumigant)	Other considerations
Bare soil	Reference level, often > 60% of total applied fumigant emissions	Not estimated for field preparations such as disking and compaction	
HDPE tarp	Up to 50%, depending on soil moisture and temperature	HDPE: $950–$1,100 per acre (materials, ~ $500; glue, $100; application, $350; cutting and removal, $100)	Effective in relatively moist soils
Low-permeability tarps (e.g., VIF)	> 90%, if tarp is installed successfully	VIF: $1,200–$1,600 per acre, assuming material cost is 1.5 to 2 times HDPE, and other costs similar to HDPE	Effective in almost all conditions; unclear time needed for safe tarp removal
Water treatment	20%–50%, depending on water amount and number of applications	< $300 per acre, depending on water price and whether grower owns or rents sprinkler system	May reduce efficacy at surface soil, requiring double treatments in sequence
Chemicals (e.g., thiosulfate)	> 50%	Fumigant-to-thiosulfate active ingredient ratio of 1:1 to 1:2, at $150–$300 per acre	Oversupply of nutrients to soil, post-treatment odor and potential soil-property changes
Composted manure	Inconclusive	Depends on application rate and material costs; commercial composted manure is $15–$30 per ton	Improves soil properties; consider when free or low-cost materials are available

techniques for different commodities (table 1). Field data from a number of trials showed that low-permeability plastic tarps are the most promising technique but also the most costly. The commonly used standard polyethylene tarp costs about $950 to $1,100 per acre depending on acreage, with higher costs for small acreage and lower costs for large acreage (personal communication, industry representatives). Costly plastic materials may not be affordable for commodities with low profit margins, such as stone fruit orchards and annual vegetables.

Low-permeability films such as VIF or TIF generally cost 1.5 to 2 times the cost of polyethylene films. In addition to the higher cost for VIF, high levels of fumigants may be released into the atmosphere upon removal or when planting holes are cut into the tarp. To reduce potential exposure risks, longer waiting periods between fumigation and tarp cutting/removal are necessary to allow fumigant degradation in soils. This issue requires further detailed investigation, as the fate of fumigants would vary depending on the soil and environmental conditions. If applicable, the injection of thiosulfate through drip irrigation under the tarp may effectively reduce this risk (Qin et al. 2007), although no field tests have been done.

Caution must be taken when considering a chemical treatment such as thiosulfate for reducing emissions. The cost of this chemical fertilizer is low, at less than $2 per gallon (about 11 pounds) of ammonium thiosulfate (Thio-Sul, containing 12% nitrogen and 26% sulfur). To meet crop sulfur requirements, ammonium thiosulfate is recommended at 6 to 12 gallons per acre for row and vegetable crops, and 5 to 10 gallons per acre for trees and vines using soil injection and surface banding, or 15 to 20 gallons per acre in a broadcast spray (www.tkinet.com/thiosul.html). However, fumigation rates are often much higher than fertilization rates. For example, 1,3-D can be applied at a maximum rate of 33.7 gallons (332 pounds active ingredient) per acre in California. Research showed that to significantly reduce emissions, thiosulfate and fumigant are needed at a ratio greater than one-to-one in molecular weight. For 1,3-D, a one-to-one ratio would require about 75 gallons of ammonium thiosulfate containing the active ingredient, at a cost of about $150 per acre. While this level of thiosulfate would likely reduce emissions, it could also introduce excessive nutrients or salts that cause other serious crop-production concerns. Thus, large-field applications of chemical treatment with thiosulfate are undesirable. Additional concerns with chemical treatment are the post-application odor and potential soil-property changes that have not been fully addressed.

Water seals, deep injection, drip application and the incorporation of high rates of organic materials are also low-cost options to control fumigant emissions. Using water costs much less than plastic tarps and offers some environmental benefits, because no materials must be disposed of. The cost for a 25-millimeter water application by sprinklers ranges from $100 to $300 per acre, depending on whether the grower owns or rents the sprinkler system. The overall cost of using water is currently substantially lower than plastic tarps, but this may change over time depending on water supplies in California.

Commercially available, clean, composted manure costs $15 to $30 per ton. The costs to apply higher rates than 25 tons per acre may not be feasible for commodities with low profit margins. In some situations, composted green waste from municipalities may be available at no cost; however, this material may also contain other undesirable waste products, such as plastic.

Research needs

Reducing emissions from soil fumigation is required to comply with environmental regulations. Low emissions can be achieved through the management of application methods such as deep injection and subsurface drip, physical barriers with plastic films, irrigation to form water seals or achieve relatively moist soil conditions, and the reduction of treatment areas to planting rows or sites. Soil chemical treatment (e.g., thiosulfate) can be effective in lowering emissions and may prove to be an effective strategy for extreme cases, such as fumigant spills. Although the incorporation of composted dairy manure to surface soil at or below 25 tons per acre did not reduce emissions in some field tests, the longer incorporation times and higher rates accompanied by certain soil preparations or more effective materials may have the potential to reduce emissions and improve soil physiochemical properties. Low-permeability plastic tarps such as VIF have shown the most promise in reducing emissions while improving efficacy. This type of film may also need lower application rates, which can help compensate for its high cost.

Research on the performance of the next generation of low-permeability films is needed for large-field applications. Any emission-reduction technology that enhances degradation or reduces fumigant concentration in soil or surface soil would have an undesirable impact on pest control because of the reduction in exposure dosage. This makes it more desirable to use low-permeability tarps, which unfortunately cost the most. Feasible techniques for different commodities depend on their availability to the production system, effectiveness in emission reduction, potential impact on pest control and cost.

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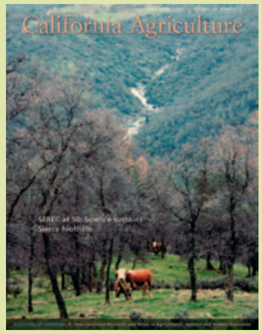

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FW = Farmworker health and safety
SF = Sierra Foothill Research and Extension Center

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The pressures of urbanization and shrinking profits have led California farmers to seek alternative approaches. Agritourism can provide growers with access to new customers as well as bolster income. More than 2.4 million visitors experienced agritourism at California farms and ranches in 2008. They stayed at guest ranches in the foothills, picked peaches in the Sacramento Valley, played in corn mazes up and down the state, shopped at on-farm stands, held weddings in fields and vineyards, and participated in myriad other agriculture-related tourism activities. In the next issue of *California Agriculture* journal, UC researchers present results of the first statewide economic survey of agritourism operators, to better understand the goals, needs and economic outlook for the state's agritourism community.