JANUARY–MARCH 2016 • VOLUME 70 NUMBER 1

California Agriculture

Climate smart agriculture for California

Also:

Pest monitoring and management:
Spotted wing drosophila, navel orangeworm, brown marmorated stink bug

Managing eucalyptus

University of California | Peer-reviewed Research and News in Agricultural, Natural and Human Resources

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University *of* California
Agriculture and Natural Resources

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Orders and Subscriptions:
1301 S. 46th St., Bldg. 478, Richmond, CA 94804-4600
Phone: (510) 665-2163; Fax: (510) 665-3427; calag@ucanr.edu

Editorial:
2801 Second Street, Room 184; Davis, CA 95618-7779
(530) 750-1223; calag@ucanr.edu
californiaagriculture.ucanr.edu

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COVER: Fruit and nut trees, like these in a Yolo County walnut orchard, need a certain amount of cold weather each year for proper foliage and flower development. As the climate warms, declining annual chill hours — the total number of hours when the temperature falls between 32°F and 45°F — may change where crops are grown (page 9). *Photo by Will Suckow.*

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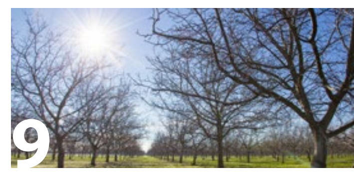

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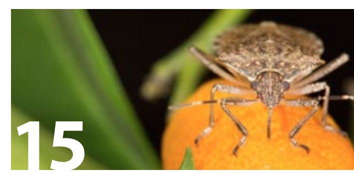

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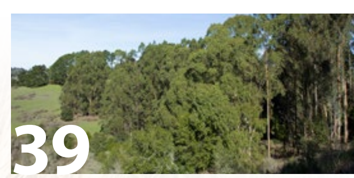

Will Suckow

Preparing for an uncertain future with climate smart agriculture

by Karen Ross, Secretary, California Department of Food and Agriculture

California is the nation's leading agricultural state, with 76,400 farms producing more than 400 commodities with a farm-gate value of $54 billion. The mission of the California Department of Food and Agriculture (CDFA) is to promote and protect agriculture. It's a complex job — and one that is getting more complex as the climate changes.

With the current drought in its fourth year, California has already started to experience some of the anticipated impacts of climate change. With drought, we have seen economic losses including job losses, fallowed land, and greater demand for a limited amount of water. A concerted approach is urgently needed to prepare California agriculture for future climate change impacts. One essential approach is embracing and implementing the concept of climate smart agriculture.

Karen Ross

Practicing climate smart agriculture means following three principles: developing agricultural systems that are resilient to climate change; reducing greenhouse gas emissions from agriculture; and preparing for climate change in a way that keeps farms productive and profitable.

I heard a lot about climate smart agriculture during a recent visit to the Netherlands with a delegation of agricultural leaders from California. The Netherlands is a leading agriculture distributor in Europe and the world's second largest (after the United States) agricultural exporter. Climate smart agriculture is already strongly integrated into Dutch economic and food security strategies. Our delegation not only heard about the threats from higher precipitation, but also about how overly dry conditions in the summer threaten the stability of peat dikes, which dry up to the point that they may simply float away, compromising the levee structure in a region where most of the land is below sea level.

In California we can prepare for such multi-faceted impacts through our own climate smart agriculture initiatives. At CDFA, we have a variety of programs and efforts underway to support agricultural sustainability, build resilience to climate change and reduce greenhouse gas emissions:

The *State Water Efficiency and Enhancement Program (SWEEP)* is an emergency drought program implemented at the direction of Gov. Jerry Brown to assist farmers in moving to efficient water irrigation systems that save water, conserve energy and reduce greenhouse gas emissions. To date, SWEEP has funded 233 projects totaling almost $18 million with $10.5 million in matching grower funds. The program is built on a strong scientific foundation and supported by a collaborative partnership involving other agencies, resource conservation districts, the California State University (CSU) system and UC ANR Cooperative Extension (UCCE). The academic institutions play a key role in providing technical evaluations of applications for water savings and reductions in energy consumption.

The *Dairy Digester Research and Development Program,* launched in 2014, provides incentives for dairy operations to install manure digesters. Digesters capture methane from dairy lagoons, allowing the gas to be used to generate electricity. Methane is a short-lived climate pollutant that is 28 times more potent as a greenhouse gas than carbon dioxide. In 2015, CDFA awarded $11.1 million for the development of five digesters at California dairies. Matching funds by developers totaling $19 million were allocated to these projects. The digester program is supported by several scientific experts from the University of California as well as a technical advisory sub-committee. The program highlights the many opportunities to use agricultural byproducts for multiple benefits, including the generation of electricity.

Evett Kilmartin

More-efficient irrigation technologies — like this drip system in an almond orchard in Yolo County — save water, conserve energy and reduce greenhouse gas emissions.

Elëna Zhukova

Manure from dairy cows — like these in Fresno County — is typically collected in lagoons, which generate the potent greenhouse gas methane. Dairy digesters capture the methane produced by microbial manure decomposition so that it does not escape to the atmosphere and can be used as a source of renewable energy.

The *Fertilizer Research and Education Program* has a long-standing collaboration with UCCE to provide growers with cost-effective practices to improve the efficient use of fertilizer and minimize environmental impacts. Improving the timing and rate of nitrogen fertilizer application can help to prevent leaching and runoff as well as emissions of nitrous oxide (N_2O), another potent greenhouse gas. Efficient use of fertilizer also reduces the amount applied, saving money for the grower.

Under the *Healthy Soils Initiative*, Gov. Brown has directed CDFA to lead an interagency collaboration to promote the development of healthy soils that sequester carbon on working lands. The health of agricultural soil influences its ability to build and retain adequate organic matter via the activity of plants and soil organisms. Adequate organic matter helps to enable the soil to function as a vital living ecosystem and provide the foundation for sustainable agricultural productivity. Carbon sequestration has been difficult to quantify in soils given the long time period for the accumulation of stable soil carbon pools. However, recent work by the Natural Resources Conservation Service (NRCS) has yielded results that allow for the scientific estimation of greenhouse gas reductions associated with several soil management practices (comet-planner.com/). These management practices can be implemented on a wide range of croplands and rangelands. We are eager to collaborate with UCCE, NRCS, resource conservation districts and other researchers to advance this important work as part of climate smart agriculture.

These are a few examples of practices that can reduce greenhouse gases and increase climate resilience on our farms and ranches. Gov. Brown's 2016-2017 proposed budget signals California's ongoing support for these initiatives, including $20 million for SWEEP, $35 million for the dairy digester program and $20 million for the Healthy Soils Initiative. In addition, the proposed budget includes $40 million for the Sustainable Agricultural Lands Conservation Program, overseen by the Strategic Growth Council (sgc.ca.gov/s_salcprogram.php) and administered by the Department of Conservation, and which supports the protection and sustainable management of California's agricultural lands through planning and conservation via agricultural easements.

Going forward, CDFA's climate smart agriculture initiatives will be coordinated through the newly created Office of Environmental Farming and Innovation (cdfa.ca.gov/EnvironmentalStewardship/).

There is no doubt we can do more in the climate smart agriculture arena. As we continue to expand our work in this area, CDFA will continue to work closely with our partners, including the scientific and technical experts at the CSU and UC systems. We are fortunate in California to have such expertise available to support our food production system with sound research, an extensive technical support infrastructure and an enormously accomplished agricultural extension service. CA

No-till and cover cropping strategies help to build soil organic matter and sequester carbon, while also improving soil quality and retaining soil moisture. *Below*, in a no-till field that will soon be planted to processing tomatoes, Fresno County UCCE advisor Dan Munk uncovers the residue from a winter cover crop of triticale.

Elëna Zhukova

South Coast REC: Linking urban landscapes, water conservation and water quality

Darren Haver, director of South Coast Research and Extension Center (REC), arrives at work without leaving the Irvine suburbs. Passing block after block of housing, old developments and new, he sees irrigation water sheeting off concrete driveways into drains. Reaching the 200-acre REC, which soon will have housing developments right up to the fences, he hears the water running off the driveways of the realistically landscaped housing sites he's had built at the center.

Here, Haver, who also serves as county director and water resources/quality advisor for UC ANR Cooperative Extension (UCCE) in Orange County, is studying two major aspects of residential water use: how much is used in different landscapes, and how much pollution occurs in any runoff from those landscapes.

From 50% to 70% of residential water use is applied to landscaping. Typically the landscaping is over-irrigated, producing runoff that enters storm drains and creeks and eventually the ocean. The runoff may contain pesticides, most commonly pyrethroids found in lawn insecticides and ant sprays, which are entering urban watersheds at levels toxic to aquatic invertebrates.

The landscaped housing sites at South Coast REC are testing best management practices (BMPs) for residential water conservation and environmental protection. They serve as demonstration gardens for local homeowners and are inspiring new partnerships beyond UC — with pesticide manufacturers, for example, and even big-box stores.

The residential-use water study began here in this uniquely urban REC in 2005. With environmental chemist Jay Gan, at UC Riverside's (UCR) Department of Environmental Sciences, and entomologists Les Greenberg and Michael Rust, in the UCR Department of Entomology, Haver was investigating how insecticides were reaching local creeks. Haver became interested in the very high use of ant sprays and lawn insecticides around homes. "Nobody at that time had a clue about what happens when you apply those sprays to concrete or bricks," recalls Haver — or how much of the chemicals runs off-site.

Three home sites were built at South Coast REC in 2006 to develop, test and implement BMPs for residential landscaping. Each is 40 feet wide by 100 feet long, with a 24-by-24-foot structure, to simulate a home, and a landscaped yard with a standard 2% slope to the curb.

Site A, the typical landscape site, includes cool-season turf and big-box store plants such as white birch; it has a poorly installed sprinkler irrigation system, and the controller is set to the default position, providing water regularly regardless of weather conditions. A solid concrete driveway funnels roof water and landscape runoff away from the house.

Site B has a low-impact design, sometimes called Mediterranean, used in new housing developments. It has less lawn area, warm-season grass, plants that have some drought tolerance, a better irrigation design with soil moisture sensors, and some permeable flagstone walkway paving and slot drains in the driveway to divert water to planting beds.

Site C is a model of sustainability and water conservation. It has native landscaping, with native Southern California plants, a native sedge lawn, permeable paving and a smart drip irrigation controller that uses weather data from the previous day.

Multiple studies by UC researchers — at the South Coast REC test home sites and elsewhere — have helped to establish the significance of home landscapes as a source of environmental contaminants.

Research undertaken with scientists at the UCR Department of Environmental Sciences (Jiang et al. 2010) showed that pyrethroid insecticides and fipronil (common in ant sprays) are persistent in home landscapes. They were still present in wash-off water 112 days after application to concrete, and for more than 42 days after 14 washing-drying cycles.

At the American Chemical Society National Meeting in 2010, Haver presented, with fellow researchers Tamara Majcherek, from the UC Davis Department of Plant Sciences, and Jay Gan and Sveta Bondarenko, from the UCR Department of Environmental Sciences, the results from an experiment that involved washing down the

Researchers at South Coast REC use these three landscaped home sites to study water use and pesticide runoff. From left: Site A, Site B and Site C.

Darren L. Haver

Home site A, *left*, represents a typical California yard. By contrast, Site C, *right*, incorporates a variety of features that save water and reduce runoff: native Southern California plants (including the lawn), permeable paving and a smart irrigation controller that responds to weather conditions.

hardscapes after applying common pesticides on the three landscaped sites at South Coast REC (Haver et al. 2010). "People around here don't like their driveways dirty," says Haver, about the frequent hosing of hardscapes in the suburbs. Washing off the hardscape within 24 hours of the applications resulted in a significant amount of bifenthrin and fipronil running off from all three sites. But the fipronil load was 32 times greater from Site A, the typical site with concrete hardscaping, than from Site C, and the bifenthrin load was five times greater from Site A.

Haver works at UCCE because he's a problem solver. "I like to help homeowners sort out water quality issues," he says. The challenge in the residential water-use project is how to best effect change among homeowners, how to get the BMPs adopted in residential communities.

The answer may be a matter of regulation or urban planning. Haver collaborated with Lorence Oki at the UC Davis Department of Plant Sciences on a multiyear study of residential runoff in Sacramento and Orange counties, and the water flow data they collected is helping UC Davis Department of Environmental Design scientists perform pollutant load modeling for urban areas before and after implementing BMPs. The modeling will be useful for policymakers and planners.

In the absence of regulation, changing homeowners' behavior is a formidable challenge. Science has provided the data, but few homeowners are switching to warm-season turfgrass or smart irrigation controllers, two of the simplest, least expensive BMPs. So Haver has expanded the project to look at people's behavior.

Thousands of local homeowners have visited the three landscaped sites at the REC's public events. In 2012, Haver, in collaboration with Lillian Hayden, Mary Cadenasso and Lorence Oki in the Department of Plant Sciences at UC Davis, surveyed the visitors regarding their preferences at an event focused on water conservation BMPs.

The surveys revealed an aesthetic preference (60% of respondents) for Site B, the low-impact, or Mediterranean, landscape (Hayden et al. 2015) even while the respondents recognized that Site C was the least expensive to maintain and the most conserving of water. The researchers concluded that landscaping practices might not be the best area in which to try to achieve residential water conservation, unless homeowners' aesthetics could be changed or the water-conserving landscapes be made more appealing to homeowners.

Outreach materials like this door hanger help garden maintenance and pesticide application companies to communicate with residents about pesticide runoff.

In terms of changing homeowners' landscape choices and practices, Haver says "we have a long ways to go." Fewer than 7% of visitors completing a survey at the fall 2015 open house reported they had implemented a BMP. Public education will continue to be a major part of the project at the REC; Haver hopes the sites will be made open year-round to the public, so people are inspired by the professionally designed but "very doable" water-friendly landscaping and can learn how easy the BMPs are to implement.

There's strong interest in shaping new consumer practices among the change agents and tastemakers Haver has gathered around this project to improve residential water use. Outreach to and partnerships with garden maintenance companies, pesticide application companies, landscape architects, irrigation supply companies, housing contractors and developers and even pesticide manufacturers have been established. Many of those partners have their own data on consumer preferences. Since aesthetics may be the main factor behind landscape choices, Haver will this year also reach out to big-box stores, with the aim of further understanding plant shopping habits and influencing the selection of water-conserving plants the stores sell. CA

—Hazel White

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California gets global water conservation perspectives

A 10-year drought in Australia and perpetual water scarcity in Israel have driven agricultural irrigation scientists in those countries to new levels of innovation.

At a January 12-13 conference in Modesto, organized jointly by UC Agriculture and Natural Resources (ANR) and USDA Agriculture Research Service (ARS), California water managers and growers had an opportunity to glean ideas from the scientists working with agricultural industries in situations even more extreme than California's periodic droughts.

During the conference, the water outlook for California was improving with several wet storms pouring water into reservoirs and snow falling on the Sierra Nevada. However, UC ANR water experts cautioned against complacency.

"We're still in a drought," said Doug Parker, director of UC ANR's California Institute for Water Resources. "If it continues to rain and this drought comes to an end, we'll still be working on drought. Droughts are not new to California and will always be a part of our climate."

Australia was gripped from 2000 to 2010 by what has been termed the "Millennium Drought", said Ian Goodwin, the research manager of horticulture production sciences in the Department of Economic Development, Jobs, Transport and Resources in the state of Victoria. In the Murray-Darling Basin, an agricultural area twice the size of the state of Georgia, reservoirs fell to 8.5% of capacity. In one large irrigation district in the basin, the Australian government spent $1.5 billion (U.S. dollars) on new water infrastructure — lining ditches and adding valves and pressurized irrigation systems — to conserve water.

Australia has an established water trading program that permits growers to sell single-year water rights. However, during the height of the drought, the price of water rose so high that purchasing it became uneconomical for most growers, Goodwin said. Growers implemented a range of on-farm water conservation strategies to get through the drought — among them pulling out orchards, debranching and hedging trees, conversion to microirrigation, regulated deficit irrigation and improved irrigation system maintenance, Goodwin said.

In Israel, the limited availability of fresh water has driven the development of a number of pioneering water technologies.

Half of the country's drinking water is desalinated at five energy-intense coastal plants. "We have enough water," said Uri Yermiyahu, senior research scientist in the Institute of Soil, Water and Environmental Sciences at the Gilat Research Center in Israel. "The question now is how much does it cost."

Israel also considers treated wastewater and brackish groundwater valuable resources for irrigation. The effluent from domestic treatment plants is subjected to a number of processes to limit the presence of pathogens and organic and inorganic contaminants. In research, scientists have found that brackish water isn't appropriate for all crops, but high-quality olives and dates can be produced with the high-saline water.

"Beggars can't be choosers," said Guy Levy, senior soil scientist with the Ministry of Agriculture and Rural Development in Israel. "This is the water we have."

Levy said it is fairly safe to use the effluent and brackish groundwater, but the chemical balance in the soil must be carefully monitored and managed.

The use of screen covers is another water conservation tool being used in Israel. Growers of crops from fresh herbs to pomegranates and bananas are building inexpensive structures to modify the climate. These covers cost roughly $15,000 per acre, about one-tenth the cost of greenhouses, and reduce solar radiation, daytime air temperature and wind, while increasing humidity and nighttime temperature. The reduced solar radiation and wind lead to reduced crop water use, said Shabtai Cohen, director of the Israel Ministry of Agriculture's Volcani Center.

The screen also protects crops from hail.

"One (nectarine) farmer earned back the cost of the screen cover in one season," after a hailstorm damaged the fruit in many other orchards, Cohen said. "He was the only farmer with first quality nectarines."

The Israeli measures were to an extent partial to the country's unique agricultural situation. The industry is highly subsidized by the government and less focused on producing crops that can be competitive in international food markets.

"We might not see how these practices can work for us right now, but these are water management ideas farmers can think about," said Jim Ayars, USDA-ARS agricultural engineer. "Compared to Israel, California water is cheap. But with new regulations, such as the California Sustainable Groundwater Management Act, these could be critical tools."

The conference featured presentations on a variety of precision crop water management tools being developed by California scientists, such as soil water monitoring; precise, on-farm weather monitoring; irrigation system evaluation; deficit irrigation; and salinity mapping.

California farmers shared their drought experiences growing a diversity of crops in California, including citrus, avocado, grapes and tree nuts. They also outlined the types of research support they seek from UC ANR and USDA-ARS. Daniele Zaccaria, UC ANR Cooperative Extension agricultural water management specialist, said there was almost universal interest in drought research that isn't prompted by rapid response to a drought emergency.

"They believe that drought research and planning should be done in normal years, when we are free of emergency decision making," Zaccaria said. "To be progressive, we need to get away from year to year planning and enlarge planning activities to 6 or 7 years to address water banking, drip irrigation, salinity buildup and how sustainable production over the years might be impacted by new irrigation technologies."

—Jeannette Warnert

Modeling the effects of local climate change on crop acreage

by Hyunok Lee *and* Daniel A. Sumner

The impacts of climate change on agriculture depend on local conditions and crops grown. For instance, warmer winter temperatures in a given area would reduce chill hours, potentially cutting yields for some crops but extending the growing season for others. Using a century of climate data and six decades of acreage data, we established quantitative economic relationships between the evolution of local climate and acreage of 12 important crops in Yolo County. We then used the historical trend in climate change to project future crop acreages in the county. Only marginal changes in acreage in 2050 were projected for tree and vine crops there, in part because chill hours, although lower, remained above critical values. Walnuts were the most vulnerable tree crop, and the projections indicated some cultivars might be marginal in years with particularly warm winters. Processing tomato acreage might increase, due to a longer growing season, and also alfalfa acreage, if water availability and other factors remain constant.

Climate change is a global phenomenon, with global-scale market impacts. However, the impacts of climate change on agriculture in a given region are also determined by local climate parameters such as temperature and precipitation, as well as by the local geography and mix of crops.

In this study, using 105 years of local climate data and 60 years of local crop acreage information, we investigated, in the context of underlying economic forces, how growers in Yolo County have responded to past climate change. Our goal was to uncover statistical relationships between climate change and changes in crop acreage patterns (based on historical data) that will in turn help us to understand how growers may respond to climate change in the future.

Crop agriculture in Yolo County

Yolo County is in the northern Central Valley. The county has small urban areas, but agriculture, with its 368,000 acres of farmland, is significant to the county economy. Agriculture generated farm revenue of $721 million in 2013, with crops accounting for 95% of that amount (fig. 1).

The cropland, almost all irrigated, is devoted to a wide variety of crops, including tree and vine crops such as almonds, grapes and walnuts, annual crops such as processing tomatoes, and field crops with differing seasonal cycles such as alfalfa, rice and winter wheat. Although total crop acreage is dominated by field crops, revenue shares are more evenly distributed among field crops, tree and vine crops, and vegetables (fig. 1). The distribution of acreage within these categories has shifted over time; for example, apricots and plums, which were important in Yolo County in the past, have been replaced by wine grapes, almonds and walnuts; and barley, once a major field crop, has virtually

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v070n01p9&fulltext=yes

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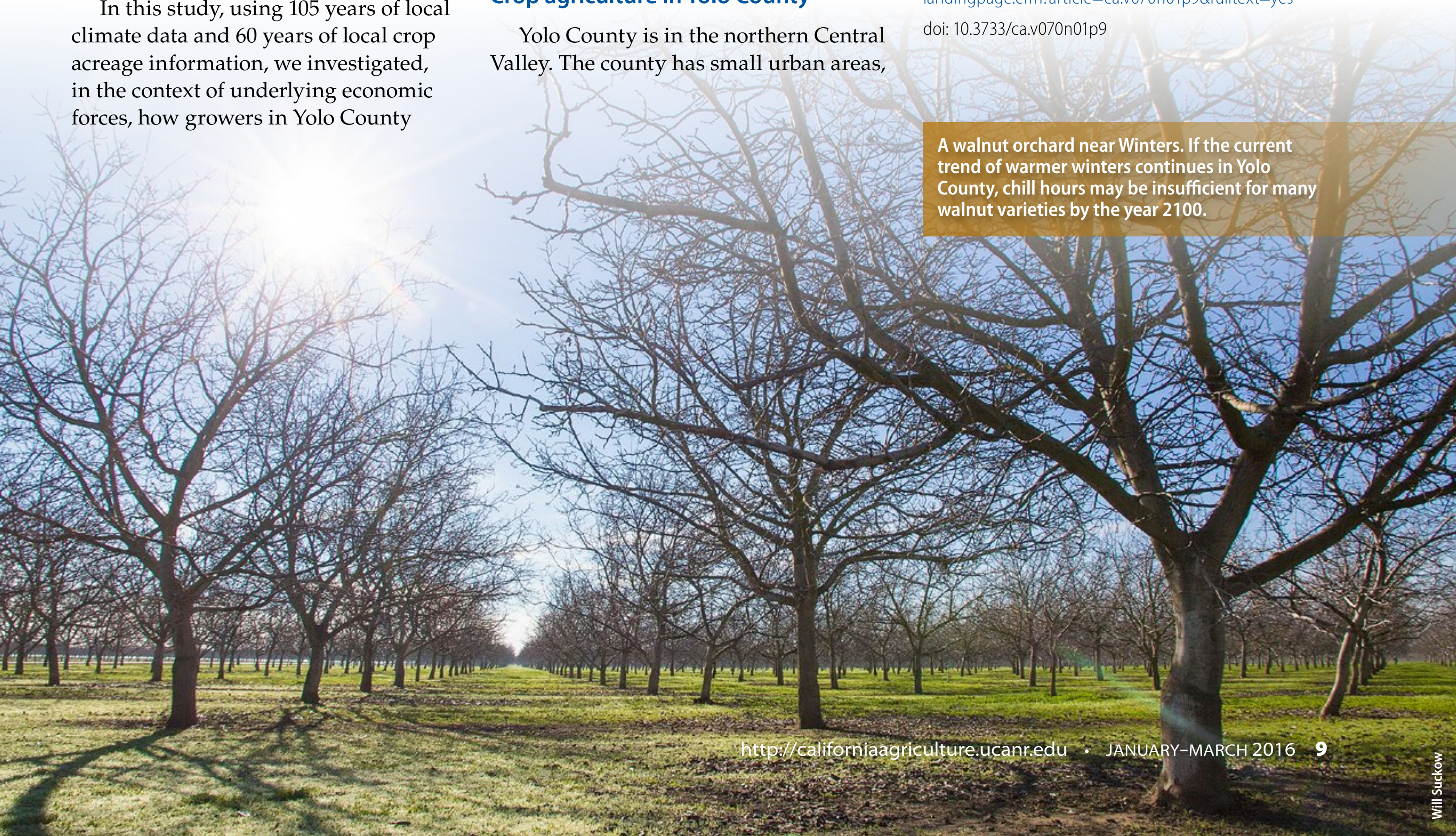

A walnut orchard near Winters. If the current trend of warmer winters continues in Yolo County, chill hours may be insufficient for many walnut varieties by the year 2100.

Will Suckow

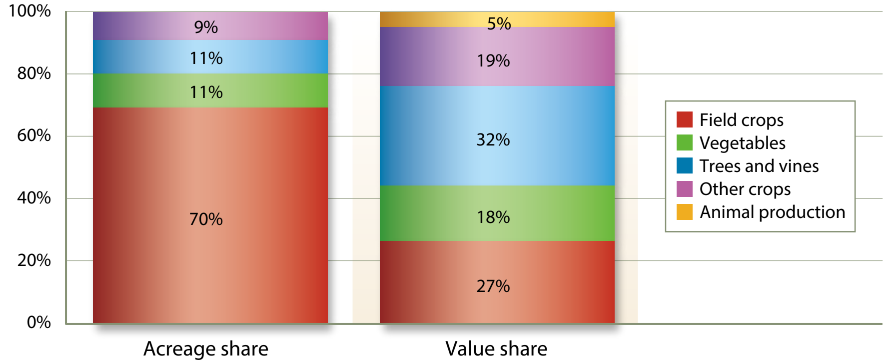

Fig. 1. Yolo County agriculture in 2013, showing acreage share and value share by commodity category. Shares are calculated based on total areage, 368,000 acres, and total value, $721 million. Field crop acreage does not include nonirrigated (dry) pasture land. "Other crops" includes organic crops, nursery products and seed crops. Source: 2013 Yolo County Agricultural Crop Report.

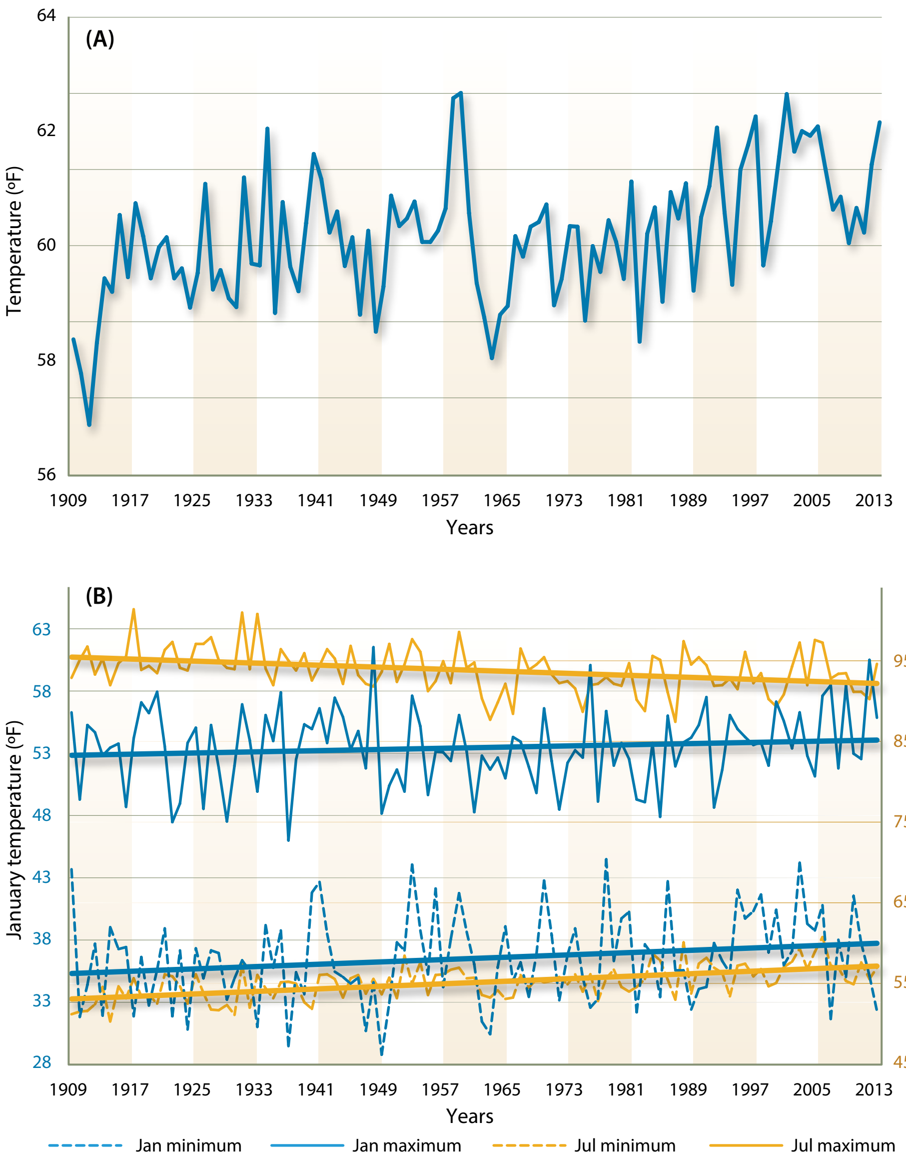

Fig. 2. Historical temperatures in Yolo County, California, 1909 to 2013, showing (A) annual average temperatures and (B) monthly average minimum and maximum temperatures for January and July. Both are derived from daily minimum and maximum temperatures.

disappeared. Wheat acreage has also declined. Processing tomatoes acreage continues to be significant, accounting for 90% of vegetable acreage.

Climate history in Yolo County

Figure 2 shows the climate trends for Yolo County from 1909 to 2013, based on daily minimum and maximum temperatures at the Davis weather station available from the National Oceanic and Atmospheric Administration (NOAA 2014). Annual average temperatures document an unmistakable long-term warming trend (fig. 2A). Monthly average minimum temperatures are unambiguously increasing for both January and July (fig. 2B), with January temperatures increasing at more than double the rate of July temperatures. Perhaps surprisingly, monthly average maximum temperatures are declining for July and roughly constant for January. That is, overall climate warming is evidenced by rising minimum temperatures, with a marked increase in winter. Similar findings are reported for California more broadly by Bar-Am (2009), who found winter average minimum temperatures increasing in wine grape regions.

Calculating climate indexes

The climate indexes we use in this study are growing degree days and chill hours, which are commonly used as measures of accumulation for heat and chill, respectively. Two immediate implications of the observed pattern of climate warming for crop agriculture are a decline in chill hours, which are crucial for deciduous trees and vines, and longer growing seasons for many annual crops. Changes in the duration of a growing season can be quantified by growing degree-days (GDD), which measures heat accumulation based on daily air temperature. Chill hours are the number of hours below a certain temperature in wintertime. Insufficient winter chill provides inadequate physiological stimulation to renew growth, causing a delay in the opening of leaf and flower buds. This leads to excessive shedding of flower buds or smaller blossoms, resulting in reduced fruit yield.

As convenient summary measures, annual GDD and chill hours were used to characterize agriculturally relevant climate warming changes in the Yolo County temperature data. Other climate measures such as occurrence and duration of extreme events like periods of heavy rainfall or extreme heat may also be important to crop viability, but were left for further research.

GDD is calculated as the difference, for a given day, between the daily average temperature and a lower-bound temperature below which plant growth is impaired. The daily average is also bounded by a temperature above which photosynthetic function is reduced. This study sets these two bounding temperatures at 46.4°F and 89.6°F, following Deschenes and Greenstone (2007). Thus, a daily mean temperature below 46.4°F or above 89.6°F registers as zero GDD. Annual GDD is the sum of daily GDD for the relevant growth period.

Chill hours are the number of hours below a critical temperature — most commonly 45°F (Aron 1983). A chill hours calculation requires data on hourly temperatures, but hourly temperature data was unavailable, so we approximated chill hours as a function of daily minimum and maximum temperatures, following Baldocchi and Wong (2008). Their approach assumes that temperature changes over a 24-hour period are gradual, and bounded by the daily maximum and minimum temperatures, with a linear process in which the daily temperature declines to the minimum, rises to the maximum and declines again to the minimum the next day. Assuming this process of daily temperature change, we estimated the daily chill hours. We calculated annual chill hours as the sum of chill hours during November through February, which is the usual dormant season for California's tree and vine crops.

In this study, we calculated two different GDDs, each representing a different growth period. The first growth period was from April 1 to August 31, for summer-harvested (or spring-planted) crops, denoted as GDD_{summer}. The second growth period was from November 1 to May 31 for spring-harvested (or late fall– or winter-planted) crops such as fall-sown hard red wheat, denoted as GDD_{winter}. Both summer and winter GDDs have increased over the last century, from 3,233 to 3,509 for GDD_{summer} and from 1,383 to 1,754 for GDD_{winter}, measured on the linear trend lines (fig. 3A). GDD_{winter} increased by about 0.26% per year, more than three times the rate (0.08%) observed for GDD_{summer}. Our finding of the more rapid increase in GDD_{winter} is especially noteworthy. In California, the amount of warmth measured by GDD is rarely a limiting factor for summer crops. However, an increase in GDD_{winter} likely results in positive winter growth.

Estimated chill hours have fallen by about 2 hours per year over the last 105 years (fig. 3B). Though varying in magnitude, the declining trend in chill hours is also found in other studies (Luedeling et al. 2009). The importance of chill hour declines depends on the chill requirements of the crops grown (see table 1). The current trend of chill hours reduction does not indicate major concerns for grapes or almonds, but chill hours could become binding for walnuts — these three crops account for more than 90% of tree and vine acreage in Yolo County.

If the present trend continues, chill hours would fall from the current trend value of 882 hours to a trend value of 712 hours by the end of the present century.

If the present trend continues, chill hours would fall from the current trend value of 882 hours to a trend value of 712 hours by the end of the present century. Thus, by 2100 many varieties of walnuts would have insufficient chill hours in years with average weather, and severely insufficient chill hours in some years with usually warm winters, which would

TABLE 1. Winter chill hours required for selected tree and vine crops

Crop	Chill hours*
Grape	100–500
Peach	200–1,200
Apricot	350–1,000
Kiwi	400–800
Almond	400–700
Walnut	400–1,500
Sweet cherry	600–1,400
European pear	600–1,500
European plum	700–1,800
Pistachio	800–1,000

* A wide range in chill hours reflects differences across varieties.
Source: Baldocchi and Wong (2008); the original source is Australasian Tree Crops Source Book.

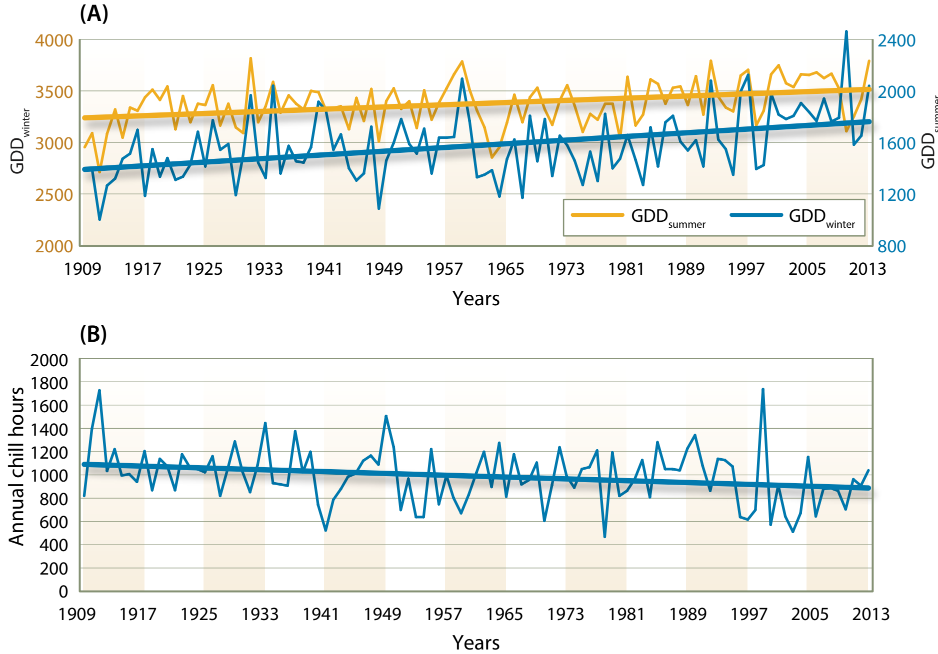

Fig. 3. Historical growing degree-days (GDD) (A) and chill hours (B) in Yolo County, 1909 to 2013. In (A) the GDD_{summer} period is April through August and the GDD_{winter} period is November through May. In (B) the annual chill hours were accumulated during November–February. Note that GDD_{winter} and chill hours span two consecutive calendar years: for example, for chill hours, the total for a winter includes the chill hours in November and December of one year and the chill hours in January and February of the following year. We report the total for each winter under the year that begins with January of that winter.

Insufficient chill hours can cause a delay in the opening of leaf and flower buds in crops such as walnuts, which may result in reduced fruit yield.

mean lower yields. Likely responses by growers would be either to shift away from walnuts, or to shift to walnut cultivars that require fewer chill hours.

The Chandler walnut cultivar, for example, which is common in Yolo County (UCCE 2012), requires a chilling portion of 45 to 50 (UCD 2015), which converts to 549 to 690 chill hours, using a conversion rate of 13 ± 0.8 (Luedeling and Brown 2011). In years in which chill hours fall below the current trend of decline (due to climate variability), or if the reduction in chill hours occurs at an accelerated rate, even Chandler walnuts could have insufficient chill hours.

Climate–acreage relationships

The economic reasoning relating climate to growers' acreage decisions is straightforward. Change in climate affects expected crop productivity and profit and therefore growers' choices about allocating crop acreage. For annual crops, current climate is most relevant. For tree and vine crops, the climate prospects over longer decision horizons are relevant. To quantitatively investigate climate–acreage relationships, we developed statistical models that specify crop acreages as functions of many economically relevant variables, including climate variables. The models allow us to isolate the effects of climate change on acreage, while statistically controlling for other relevant factors.

Equations. We specified an equation to characterize the planting for each of the 12 crops that have significant acreage in Yolo County currently (see table 2). Each of the 12 equations describes acreage of a specific crop as a linear function of variables relevant to the acreage decision of that crop. We assume that acreage decisions are guided by variables representing four broad categories: market conditions, water availability, agronomic practices (such as crop rotations) and climate. General description of the variables in each category is provided below. Detailed information about the specification of our regression equations can be found in Jackson et al. (2012) and Lee and Sumner (2015); this study uses improved and updated time series of the relevant data but the same equation specifications reported there.

Explanatory variables and data. Market conditions are represented by the expected product price for each crop and prices of crops that are considered substitutes in the planting decision. To represent current price expectations, we used one-period lagged prices for most field crops and other annual crops. For tree and vine crops, we used moving averages of multiple lagged prices.

Irrigation water supply is represented by previous years' precipitation, because replenishing sources of irrigation water often takes multiple years. We did not directly incorporate non-surface water such as groundwater or water transfers, but note that water transfers and groundwater access in Yolo County are influenced by availability of surface water.

Crop rotation often constrains acreage decisions. To reflect its effects on crop acreage decisions, we included the one-period lagged acreage of rotation crops where relevant.

Climate variables represent expected outcomes of temperature, not year-to-year short-term fluctuations in weather. To smooth out short-term fluctuations, we adopted 10-year moving averages of annual climate variables in the acreage estimation equations. Because GDD and chill hours are highly correlated, we used one or the other of the variables (that is, not both) in each equation. We used the 10-year moving average of chill hours for tree and vine crops, the 10-year moving average of GDD_{winter} for wheat, tomatoes and alfalfa, and the 10-year moving average of GDD_{summer} for the rest of the annual crops. Even though tomatoes and alfalfa are harvested mostly in the summer, tomatoes intended for early harvest are planted as early as February and the first cut of alfalfa occurs in April. Thus for these crops as well as wheat, warm temperatures during the winter growth period are particularly relevant.

We used crop acreage data spanning more than 60 years from the early 1950s to 2013, which are available from the

TABLE 2. Model results: Yolo County crop acreage response to changes in crop price (implied price elasticity) and climate indices

Crop	Rice	Alfalfa	Wheat	Corn	Safflower	Pasture	Tomato	Prune	Grape	Almond	Walnut	Other fruit
Own price variable†	626.18***	7.51	71.38***	348.74	2.73	0.53	125.70**	0.40**	11.42**	244.63	0.12	0.03*
	(3.94)	(0.37)	(3.03)	(0.51)	(0.58)	(0.38)	(1.93)	(1.93)	(2.33)	(0.48)	(0.53)	(1.78)
	Implied price elasticity											
	0.39	0.03	0.38	0.14	0.05	0.00	0.33	0.26	1.55	0.06	0.03	0.15
Climate index‡	$MGDD_s$	$MGDD_w$	$MGDD_w$	$MGDD_s$	$MGDD_s$	$MGDD_s$	$MGDD_w$	Mchill	Mchill	Mchill	Mchill	Mchill
	−7.75	40.30**	−100.35**	−13.46	21.36	6.38	32.27	1.49*	1.12	−2.87	4.83**	1.87**
	(−0.29)	(1.96)	(−2.66)	(−0.43)	(0.76)	(0.96)	(1.17)	(1.85)	(0.77)	(−0.48)	(1.95)	(2.39)

† Asterisks indicate different levels of significance: *** ($P \le 0.01$), ** ($P \le 0.05$) and * ($P \le 0.1$); numbers inside parentheses are t-values.

‡ $MGDD_s$ = 10-year moving average of GDD_{summer}, $MGDD_w$ = 10-year moving average of GDD_{winter}, and Mchill = 10-year moving average of chill hours.

The table shows the estimated change in the countywide acreage of a given crop in response to a one-unit increase in the crop price ("Own price variable") or a one-unit increase in one of three climate indices. We developed the model using California real prices from the U.S. Department of Agriculture (USDA) and acreage data from Yolo County Crop Reports. To meet the time series properties of constant mean and variance (stationarity), we transformed all variables in a first difference form, that is, year-to-year changes, and estimated each linear acreage equation separately using the ARIMA routine in Stata.

If current climate trends continue and all other variables such as wheat price hold steady, there could be a 45% decline in Yolo County wheat acreage by 2050.

Yolo County Crop Reports (Yolo County Agricultural Department 2014). The first available data year for analysis varied by crop between 1952 and 1954. The price data was collected from USDA sources over the same time periods. (The prices used in the acreage regressions are at the California state level, to reflect markets for Yolo County crops.)

Estimation results. Each of the 12 acreage equations was estimated separately. For each equation, crop acreage was regressed against explanatory variables discussed above. We found that crop prices and climate variables were more significant than other explanatory variables. Crop rotation was rarely statistically significant. Annual current water availability was relevant for a few annual crops, especially alfalfa, safflower and corn. Increased water availability tended to increase acreage of alfalfa and corn, but it reduced acreage of safflower. Water availability was less significant in explaining the variation in tree and vine acreage, which might be expected, because current water availability would be more important in year-to-year crop acreage decisions for annuals than for perennials. Likewise, it is expected that no one starts an orchard without already securing access to water given the long-term nature of orchard farming.

Crop prices affected acreage of rice and wheat with very strong significance ($P < 0.01$) and affected acreage of tomatoes, prunes and grapes with less, but still strong, significance ($P < 0.05$) (table 2). The implied price elasticities on acreage, calculated at the data means, were moderate for rice, wheat, tomatoes and prunes, and highest for grapes, about 1.6 (table 2), indicating that a 10% change in the expected grape price induces a 16% change in grape acreage. Such a strong price effect for grapes is consistent with the rapid emergence of grapes as the fruit crop with the largest acreage in Yolo County.

Climate variables were important for several crops. Moving averages of GDD_{winter} ($MGDD_w$) showed strong statistical significance for alfalfa and wheat acreages, but with different signs, positive for alfalfa and negative for wheat (table 2). A warmer winter provides favorable conditions for alfalfa production, given alfalfa is harvested six or seven times a year starting in the spring. The negative effect on wheat is less clear, but it might be due to the fact that many old wheat varieties (important in the earlier years of our data period) required a period of cool growing conditions known as vernalization.

None of the moving average variables measuring GDD_{summer} ($MGDD_s$) were statistically significant (table 2). GDD_{summer} is hardly a binding factor in most of California, but higher average temperatures may increase the frequency of extreme heat events. Our initial investigation of the incidence of consecutive days of extreme heat did not show any systematic patterns. Extreme climate events are important in agriculture and deserve more investigation in California research.

Models predict that processing tomato acreage, which accounts for 90% of vegetable acreage in Yolo County at present, could increase by 14% by 2050 if current climate trends persist with all other variables held constant.

Moving averages of winter chill hours were statistically significant for walnuts and other fruit at 5%, and for prunes at 10% (table 2), indicating that continuing warming in winter (or reduction in chill hours) would reduce the acreage for these crops. Walnuts and prunes are among the crops that require relatively high chill hours (table 1).

Climate change and future acreage

The statistical relationships between climate variables and the local pattern of crops planted over the past six decades in Yolo County may provide insight about future acreage there, if the current patterns of climate change continue. We projected changes in future acreage in 2050 relative to acreage in 2013, assuming determinants of acreage other than climate variables remained constant (we did not project changes in prices, technology or any other relevant drivers such as water availability). In other words, we assumed each climate variable will change each year along the estimated trend for the past century — +2.66 for GDD_{summer}, +3.57 for GDD_{winter}, and −1.96 for chill hours.

A permanent increase in GDD_{winter} by 3.57 units per year through 2050 increases alfalfa acreage by 6,036 acres, which represents a 15% increase over the 2013 acreage (table 3). The largest effect is on wheat acreage, which falls by 45%. The effects on tree and vine acreage are modest. Acreages for prunes, grapes, walnuts and other fruit decline due to fewer chill hours, whereas almond acreage expands slightly.

TABLE 3. Projected changes in Yolo County crop acreage in actual acres and percentage, 2013–2050*

	Rice	Alfalfa	Wheat	Corn	Safflower	Pasture	Tomato	Prune	Grape	Almond	Walnut	Other fruit
Annual change in climate index	2.66	3.57	3.57	2.66	2.66	2.66	3.57	−1.96	−1.96	−1.96	−1.96	−1.96
Acreage in 2013 (acres)	38,432	41,030	33,276	19,368	7,808	11,500	34,558	1,746	13,030	17,737	14,400	1,699
Change, 2013–2050 (acres)	−866	6,036	−15,029	−1,504	2,386	7,130	4,833	−123	−92	237	−398	−154
Change, 2013–2050 (%)	−2%	15%	−45%	−8%	3%	6%	14%	−7%	−1%	1%	−3%	−9%

* Projections assume the long-term historical trend of local climate change continues, holding everything else constant. The climate index for each crop is the same as in table 2.

TABLE 4. Summary of projected changes in Yolo County crop acreage, 2013–2050*

	All crops	Field crops	Vegetables	Tree and vine crops
Change, 2013–2050 (acres)	−3,962	−8,264	4,833	−531
Change, 2013–2050 (%)	−1.69%	−5.46%	13.98%	−1.09%

* Projections assume the long-term trend of local climate change continues, holding everything else constant.

Almond acreage in Yolo County is projected to increase by 1% by 2050 if the current warming trend continues and all other variables remain constant.

The increase in alfalfa acreage relative to wheat presents interesting implications for irrigation water demand. Wheat is one of the least irrigation-intensive crops per acre, partly because much of its growing season coincides with the rainy season in Yolo County. Alfalfa is one of the heavy irrigation water users. Thus, a significant shift of acreage from wheat to alfalfa would increase irrigation water demand.

The acreage changes by crop category (table 4) indicate a modest reduction in field crop acreage (about −5.5%), an important increase in vegetable (processing tomato) acreage (14%) and a small decline in tree and vine crop acreage (−1.1%). These calculations indicate that under century-long climate trends, overall crop acreage changes induced solely by climate change would be modest, amounting to less than 2% by 2050.

Interpreting the results

It is important to recognize the following caveats when interpreting the results of this study. Our acreage projections were based on climate change that follows the simple linear trends of climate change for the past 105 years. We did not incorporate climate variability, extreme events or accelerated warming. More importantly, other climate-related factors that occur outside of Yolo County, such as irrigation water impacts caused by lower snowpack, were not incorporated directly. Moreover, our projections did not incorporate market impacts caused by climate change in other regions. Our projections also did not incorporate changes in policy, technology, agricultural practices or growers' behavior that may be driven in part by climatic change. That is, we did not build in exogenous or endogenous adaptation, such as expanded federal crop insurance or shifts in cultivars that require fewer chill hours. For example, across the three walnut cultivars planted in California, winter chill requirements differ by 40% (UCD 2015) and cultivars requiring less winter chill may be on the horizon.

H. Lee is Research Economist in the Department of Agricultural and Resource Economics at UC Davis, and D.A. Sumner is Director of the UC Agricultural Issues Center and Frank H. Buck, Jr. Professor in the Department of Agricultural and Resource Economics at UC Davis.

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Review Article

Biological control program is being developed for brown marmorated stink bug

by Jesus Lara, Charlie Pickett, Chuck Ingels, David R. Haviland, Elizabeth Grafton-Cardwell, David Doll, James Bethke, Ben Faber, Surendra K. Dara *and* Mark Hoddle

Brown marmorated stink bug (BMSB) is an invasive, polyphagous pest that has been detected in 42 U.S. states. In 2010, it caused millions of dollars in crop damages to apple growers on the East Coast, where it arrived from Asia during the 1990s. In 2002, BMSB was reported in California; since then, it has been detected in 28 counties and is established in at least nine counties. Although this pest has not yet been found on commercial crops in the state, detections of BMSB in commercial orchards have been documented in Oregon and Washington. Proactive research in California has joined national efforts led by U.S. Department of Agriculture researchers to develop a classical biological control program for BMSB. A study is under way to determine potential non-target effects of a specialist egg parasitoid,* Trissolcus japonicus *(Hymenoptera: Platygastridae), imported from Beijing, China, part of the home range of BMSB. In addition, the role of BMSB natural enemies residing in California is being assessed. A review of the recent research outlines the possible opportunities for reducing the threat BMSB poses to California.

Brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), has a native range that includes China, Japan, Korea and Taiwan. Its host plant range extends to more than 170 species, among which are valuable ornamentals and agricultural fruit, nut and vegetable crops (Lee et al. 2013; Rice et al. 2014). BMSB can cause direct injury to crops while using its piercing-sucking mouthparts to feed. Characterization of feeding injury to marketable crops such as surface discoloration, depressed areas, deformation or abortion of fruit bodies and internal tissue damage can vary by crop (Rice et al. 2014). BMSB was first detected in the United States in 1996 in Allentown, Pennsylvania. Since then, BMSB has been detected in 42 U.S. states, with establishment (reproduction) confirmed in at least 26 states where nuisance and/or agricultural problems associated with its presence and ensuing economic losses to crops have been reported (NIPMC 2015).

Crop losses from BMSB and aggregations in human-made structures have been significant in the eastern United States, where BMSB first established (Rice et al. 2014). The establishment of BMSB in this region confirms its tolerance to climates outside of its home range. Field and laboratory research is needed to characterize the degree to which BMSB can tolerate temperature stresses (i.e., winter cold and summer heat) and how this may influence population dynamics in other geographic locations within the United States (Cira et al. 2016). In addition, the invasion process of BMSB in the United

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v070n01p15&fulltext=yes

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BMSB adult feeding on kumquat fruit. In California, BMSB populations are found mainly in urban locales, but there is risk they will move into agricultural areas.

Mike Lewis

States may have been facilitated by the lack of effective natural enemies and the availability of host plants. Therefore, the influence of abiotic and biotic factors may play a significant role in determining BMSB establishment in regions where this pest has arrived.

The first BMSB detection in California was recorded in 2002, and populations are now established in at least nine counties. Although current BMSB populations are largely confined to urban areas, there is risk of their movement into agricultural areas. Considering the evidence of BMSB damage from the East Coast, researchers in California recognized a need to proactively develop management strategies for BMSB in advance of potential infestations in crop production areas. Seasonal monitoring for BMSB is essential in each detection area to confirm whether populations are established, characterize their yearly phenology and update statewide distribution maps (fig. 1), all of which are needed to facilitate the development of strategic BMSB management guidelines.

Fig. 1. Known distribution of BMSB in California, as of December 2015.

Origin and distribution

Initial genetic comparisons detected low diversity among BMSB populations in the United States (i.e., representative insect specimens from 10 states, including California) compared to BMSB populations in Asia and identified Beijing, China, as the likely origin of BMSB populations in the United States (Xu et al. 2014). Follow-up molecular work being led by U.S. Department of Agriculture (USDA) researchers is adding further resolution to the invasion origins of BMSB in the United States. Preliminary results suggest that there could have been multiple BMSB introductions into the West Coast compared to the East Coast. Including more BMSB samples from California as part of these analyses would help clarify whether the presence of BMSB in California could have resulted from accidental translocations from infested areas on the East Coast and introductions from Asia as part of commerce and private activities.

All life stages (eggs, nymphs and adults) of BMSB.

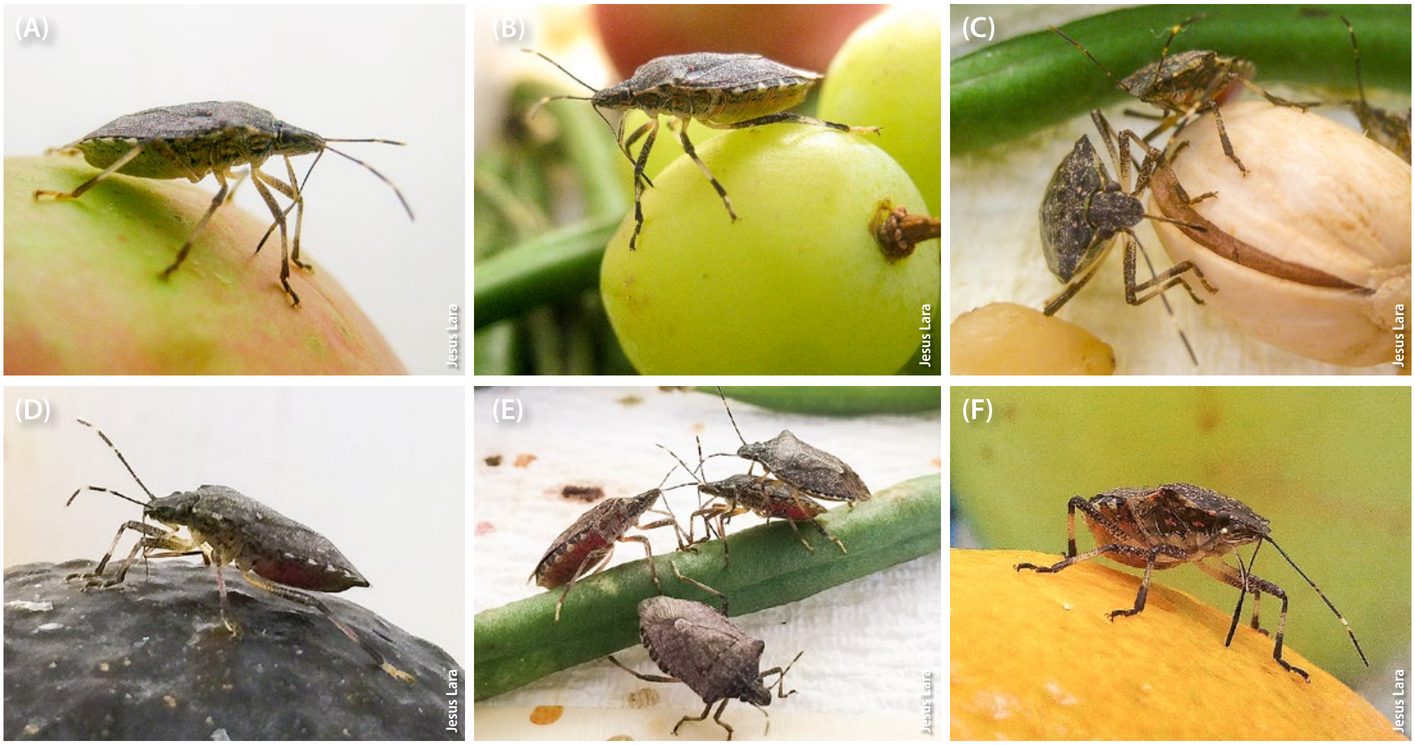
Adult BMSB and developing instars (second to fifth) have a relatively strong dispersal capacity. Nymphs can readily walk short distances (e.g., > 100 centimeters in less than 30 minutes on grassy terrain and > 600 centimeters in 15 minutes on smooth plastic surfaces in the laboratory). Adult BMSB are capable of short (0- to 5-kilometer) and long-distance (> 5-kilometer) flights during a 24-hour period (Lee et al. 2014; Wiman et al. 2015). When disturbed, BMSB nymphs and adults hurriedly walk away, take flight (adults) or cease movement. These behaviors and the muted coloration of BMSB make it difficult to track and collect them in the environment when present at low densities. This combination of traits also suggests that BMSB can readily reach (by hitchhiking) and potentially colonize suitable new geographic areas.

In California, reproductive populations of BMSB have been known to occur in Los Angeles County since at least 2006. In fall 2013, reproductive BMSB populations were discovered in downtown Sacramento (Ingels 2014; Varela and Elkins 2011). Tracking the spread of BMSB in California has been made possible through a network of monitoring traps, with more than 100 traps deployed during 2014 and 2015 by California Department of Food and Agriculture (CDFA), UC ANR Cooperative Extension (UCCE), county agricultural commissioners and UC Riverside. In counties where BMSB populations are established, trap collections suggest there are at least one, and likely two, BMSB generations per year in some areas of California, with peak activity occurring over summer. These monitoring efforts are ongoing and will help track changes in BMSB phenology and geographic distribution in California.

Nuisance reports have been documented in Sacramento and Los Angeles counties. Aggregation behavior typically starts in late summer, with adult BMSB aggregating on outside walls as they seek refuge in garages, houses and apartment blocks, for overwintering. This behavior is troublesome not only because of the inconvenience of having to clean up bugs and remove frass stains from surfaces, but also because of the pungent cilantro-like stink BMSB produce.

Growing concern

As BMSB continues to spread to new areas in California and populations build



BMSB feeding on (A) apple, (B) grape, (C) pistachio, (D) Hass avocado, (E) green bean and (F) orange.

up, there is warranted concern that this polyphagous insect could become a pest on a variety of specialty crops in the state. Metcalf (1995) estimated that established invasive species cost California more than $3 billion per year (based on $100 per capita) in economic losses. When adjusted for inflation to 2014 dollars and population census data (USCB 2015), the cost is approximately $6 billion. Crop damage or quarantine trade restrictions resulting from BMSB infestations would increase the economic costs of invasive pests for California.

Nuisance problems associated with the ability of BMSB to overwinter in human-made structures and damage attributed to BMSB feeding on crops, including apples, soybeans, tomatoes, peaches, corn, grapes and caneberries, have been documented in East Coast states (e.g., Delaware, Maryland, New Jersey, New York, Pennsylvania, Virginia and West Virginia) (Jentsch 2012; Leskey et al. 2012; Nielsen and Hamilton 2009; Pfeiffer et al. 2012; Rice et al. 2014). The ability of BMSB to feed on a variety of crops explains the concern growers, researchers and the general public have of its potential to cause economic damage. Most notably, in 2010, apple growers in Mid-Atlantic states suffered an estimated $37 million in losses due to BMSB damage (Leskey et al. 2012). As a result, pesticide applications for BMSB control increased, in some cases as much as fourfold. Some of these pesticides have broad-spectrum activity (e.g., pyrethroids, neonicotinoids) for insects and can be harmful to natural enemies (Leskey et al. 2012; NIPMC 2014; Rice et al. 2014). Increased use of these pesticides can lead to secondary pest outbreaks and result in further economic losses. California pest management programs could be similarly disrupted by BMSB if populations spread to agricultural crops and no effective and sustainable control measures are developed.

There is a growing concern over BMSB detections in agricultural areas in Oregon on commercial crops such as hazelnuts, blackberries and wine grapes (Hansen and Mullinax 2014) and in Washington on crops such as peppers, apples, peaches, plums and cherries (Eddy 2015). These detections imply that if BMSB populations continue to grow, they could eventually have a significant economic impact on agricultural production in this part of the country. One report of economic damage by BMSB in the Pacific Northwest comes from a grower in Vancouver, Washington, who attributed losses of apple to BMSB feeding (Hansen and Mullinax 2014). Although BMSB damage to commercial agricultural crops has not been reported in California, the recovery of BMSB in fall 2014 from a monitoring trap in a Butte County kiwi orchard (E. Symmes, area IPM advisor, UCCE Butte County, personal communication) indicates that the distribution of BMSB in California is still in transition.

A BMSB pheromone-based monitoring trap set up in Los Angeles County.

Start of BMSB adult aggregation on an elm tree during August 2015 in Sacramento County.

Evidence of this distribution transition is being documented throughout the state (Warnert 2015). By September 2015, Siskiyou, Stanislaus and Yolo were added to the list of counties where BMSB is reproducing. In January 2016, CDFA confirmed the first detection of BMSB from trap samples collected during 2015 in Kern County, but it is not clear whether BMSB is established there; further monitoring in Kern County is planned for 2016. Establishment and detection of BMSB in several parts of the Sacramento Valley and San Joaquin Valley indicates that this pest has the potential to spread farther within California's economically important Central Valley farming region, and critical information on the types of crops that may be at risk is being documented as part of CDFA's and UCCE's monitoring efforts.

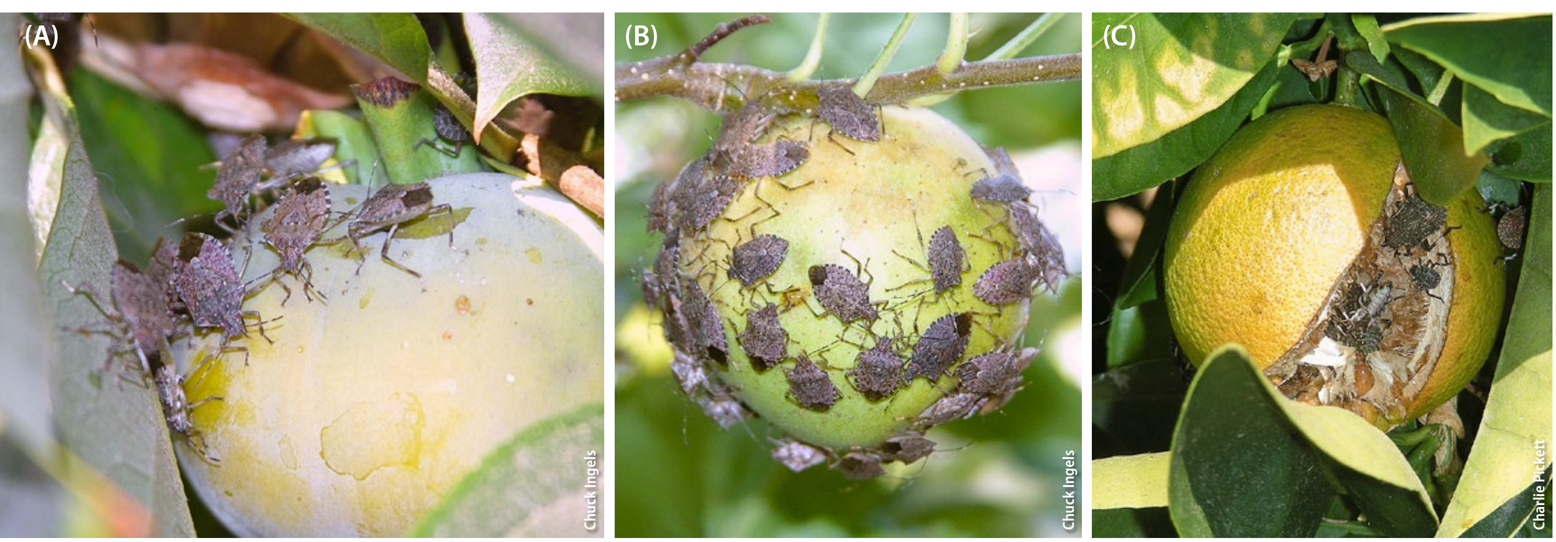
During August and September 2015, BMSB was found feeding on citrus, persimmons and apples in a Sacramento community garden. In July 2015 in Los Angeles County, BMSB nymphs were found for the first time in traps placed in close proximity to residential citrus, kiwi and avocado trees; no external signs of damage to fruit attributable to BMSB were noted at those sites, but BMSB feeding damage symptoms may take some time to appear.

The full range of damage that could result from BMSB feeding is unknown for certain California crops that could be at risk. The addition of a polyphagous species and direct fruit-feeder like BMSB could aggravate existing management problems caused by other exotic species for crops like citrus (under stress from Asian citrus psyllid and huanglongbing disease) and avocado (threatened by the polyphagous shot hole borer and the fungi it vectors).

Biological control research

Field surveys in the United States (i.e., Oregon, Delaware, Maryland, Pennsylvania, Virginia) led by USDA Agricultural Research Service (ARS) and academic research institutions have documented evidence of host associations between BMSB and resident natural enemies. Several species of generalist predators (e.g., lacewings, mantids, earwigs, lady beetles, assassin bugs, minute pirate bugs, big-eyed bugs and spiders) have been observed feeding on BMSB egg masses and motile stages in the field. Field surveys also revealed there are at least 12 North American species of stink bug egg parasitoids (e.g., *Anastatus* spp., *Gryon* sp., *Ooencyrtus* sp., *Telenomus* spp. and *Trissolcus* spp.) in at least three families (Encyrtidae, Eupelmidae, Platygastridae) that parasitize sentinel (laboratory-sourced) BMSB egg masses deployed in the field (see Rice et al. 2014 for complete species listing).

These new host associations between BMSB and resident parasitoid species will need to be assessed experimentally for their potential to provide some level of natural BMSB control, as the presence of resident natural enemies could complement other promising BMSB biological control strategies. One of these strategies is classical biological control, under which a host-specific natural enemy from the pest's native range is reunited



BMSB feeding on residential (A) persimmon, (B) apple and (C) citrus fruit in Sacramento County.

A *Trissolcus japonicus* female readily parasitizes eggs of BMSB in California.

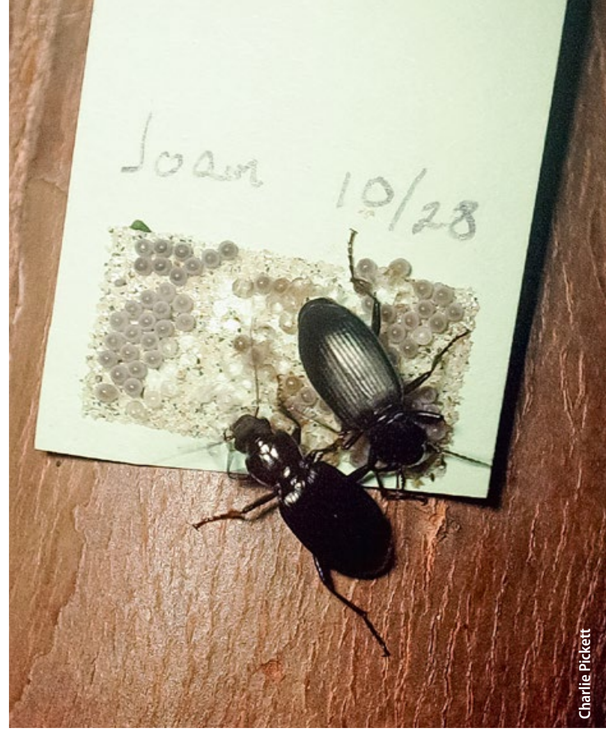
with the target pest in the introduced range. To this end, *Trissolcus japonicus* (Ashmead) and *T. cultratus* (Mayr) (Hymenoptera: Platygastridae) were sourced by USDA ARS Beneficial Insects Introduction Research (ARS BIIR) from parasitized BMSB eggs in Asia. These species are under evaluation in quarantine by USDA ARS BIIR as potential candidates for classical biological control of BMSB in the United States. In Asia, levels of field parasitism of BMSB by *T. japonicus* have been higher than *T. cultratus* (Haye 2014; Talamas et al. 2013), and this observation has directed the primary focus of classical biological control research on *T. japonicus*.

In California, UC Riverside and CDFA have led research efforts since 2014 to determine the potential of resident (i.e., native and naturalized species) and promising foreign natural enemies (demonstrated to control BMSB in its home range but not yet released in California) for effective BMSB control. Field studies in Riverside, Los Angeles and Sacramento counties have documented resident natural enemies in California attacking BMSB egg masses, suggesting they may be useful for future management programs. Beginning in 2014, research at UC Riverside focused on assessing the risk *T. japonicus* poses to native stink bugs, some of them beneficial predators such as the predatory stink bug *Podisus maculiventris* (Say). This nascent classical biological control program is being supported by UCCE, researchers at CDFA and USDA ARS, and some commodity boards (e.g., pear, pistachio and table grape).

Natural enemies

Time-lapse photography from BMSB monitoring field sites in Sacramento supervised by CDFA in 2015 revealed that a generalist beetle, *Laemostenus complanatus* (Dejean) (Coleoptera: Carabidae), can feed on sentinel BMSB egg masses. *L. complanatus* is an adventive, or nonindigenous, species whose presence has been documented in Northern and Southern California (Frank and McCoy 1995; SBNHM 2014; Sokolov and Kavanaugh 2014). In Southern California, predation of sentinel BMSB egg masses has been documented in Los Angeles County by UC Riverside researchers; time-lapse photography is planned to determine the identity of predators.

As part of the California BMSB monitoring program, traps baited with commercially available BMSB aggregation pheromone during 2014 and 2015 also captured two specialized resident stink bug natural enemies: *Euclytia flava* (Townsend) (Diptera: Tachinidae), a fly that parasitizes motile stink bug life stages, and *Astata* spp. (Hymenoptera: Crabronidae), a wasp that attacks motile stink bug stages. *E. flava* specimens were captured in BMSB traps in Northern and Southern California. *Astata* spp. were captured from traps in Northern, Central and Southern California and species identifications are being confirmed. Currently, all *Astata* specimens captured in Northern California have been identified as *A. occidentalis* Cresson, but field observations in Sacramento demonstrate that adults of another species, *A. unicolor* Say, can attack BMSB and carry them to their nest. Rice et al. (2014) reported that *Astata* spp. and another parasitic fly, *Trichopoda pennipes* (Fabricius) (Diptera: Tachinidae), were found attacking adult



Adult *Laemostenus complanatus* opportunistically feed at night on sentinel BMSB eggs deployed in Sacramento County.

and late-instar BMSB life stages on the East Coast.

The impact these resident natural enemy species may have on BMSB population dynamics in California is yet to be measured and may not be sufficient to provide adequate levels of population suppression. For example, in the laboratory *E. flava* has been successfully reared from *P. maculiventris* adults but not from BMSB adults, even though *E. flava* females will lay eggs on BMSB. The contributions of other candidate resident species and their potential impacts in agricultural areas will need to be assessed as part of the emerging biological control program.

Egg parasitoids

Understanding the suitability of BMSB eggs as a host for resident stink bug egg parasitoids is important. Ideally, this

***Euclytia flava*, a native parasitoid of stink bugs, has been recovered from BMSB monitoring traps deployed in Los Angeles and Sacramento counties.**

***Astata* species, a native predator of stink bugs, has been recovered from BMSB monitoring traps in Los Angeles and Sacramento counties and parts of the Central Valley.**

guild of natural enemies could provide some level of control if they attack the first generation of BMSB egg masses laid in the spring by female stink bugs coming out of diapause. In California, there are at least 11 reported species of stink bug egg parasitoids (table 1). Egg parasitoid activity is being monitored in Northern and Southern California by deploying sentinel BMSB egg cards; eggs are killed by freezing prior to deployment at field sites.

During spring 2015, *Anastatus pearsalli* Ashmead (Hymenoptera: Eupelmidae) was recovered from one of more than 100 sentinel BMSB egg masses deployed in Sacramento. To our knowledge, this is the only reported *Anastatus* species associated with stink bugs that occurs in this part of the state (Ehler 2000). Field data from the East Coast suggests that *A. pearsalli* parasitism levels are low (around 4%) on BMSB eggs masses when compared to parasitism levels of another North American congener, *A. reduvii* (Howard), which caused 79% BMSB egg mass parasitism at the same field study sites (Jones 2013). *A. reduvii* is a generalist parasitoid (Burks 1967), and its occurrence in California needs to be investigated.

In Southern California, several sentinel egg cards from more than 100 deployed in Los Angeles County from June to September 2015 were successfully parasitized by an unidentified *Anastatus* sp. and other platygastrid parasitoids. Successful parasitism of sentinel BMSB eggs has also been observed in Riverside County, but BMSB has not established there.

Fresh BMSB egg masses are being exposed to resident parasitoids from Northern and Southern California at the UC Riverside Insectary and Quarantine (UCR I&Q) facility to better assess the suitability of BMSB as a developmental host for these natural enemies. The follow-up exposure experiments are necessary because freezing BMSB eggs prior to field deployment likely disrupts their defense mechanisms and may make them easier for nonspecialist egg parasitoids to parasitize. Similar experiments were conducted by Haye et al. (2015) in Europe with BMSB and native egg parasitoids there.

TABLE 1. Some resident stink bug egg parasitoid species (Hymenoptera) found in California

Family	Species
Encyrtidae	*Ooencyrtus californicus*
	Ooencyrtus johnsoni
Eupelmidae	*Anastatus pearsalli*
Platygastridae	*Gryon obesum*
	Psix tunetanus
	Telenomus podisi
	Trissolcus cosmopeplae
	Trissolcus basalis
	Trissolcus euschisti
	Trissolcus hullensis
	Trissolcus utahensis

Source: Ehler 2000.

The suitability of BMSB eggs for other California parasitoids reared from egg masses of resident stink bug species (e.g., *Banasa* sp., *Cholorochora* sp. and *Nezara viridula*) or collected from sites with BMSB pheromone traps is also being evaluated at the UCR I&Q facility. Field-collected *T. basalis* (Wollaston), *T. utahensis* (Ashmead) and *Telenomus* 'near' *podisi* (Ashmead) have been exposed to fresh (24-hour-old) BMSB egg masses in the laboratory. *T. basalis* collected from parts of France, Italy and Spain were introduced into California during the 1980s as a classical biological control agent of another invasive stink bug, *Nezara viridula* (Linnaeus) (Hoffmann et al. 1991). Levels of successful parasitism of BMSB egg masses by these three candidate parasitoids are notably lower than those of *T. japonicus* under the same controlled conditions. Furthermore, attempts to culture strains of these three resident species from California on cold-treated BMSB egg masses have not been always successful.

***Anastatus pearsalli*, a native species known to parasitize BMSB egg masses in the United States.**

Together, these observations highlight the fact that some resident stink bug egg parasitoids may opportunistically exploit BMSB eggs but ultimately may not be effective for controlling BMSB. Instead, the establishment of a more host-specific BMSB egg parasitoid, like *T. japonicus*, as part of a classical biological control program may increase significantly parasitism of BMSB egg masses.

Classical biological control

One possible factor contributing to the growing presence of BMSB in the United States may be the absence of host-specific, coevolved natural enemies from its home range. In China, *T. japonicus* can achieve an average annual parasitism rate of 50%, but rates can range from 20% to 80% during the field season (Lan-Fen 2007; Yang et al. 2009). These parasitism rates refer to the percentage of the egg mass attacked. Other stink bug parasitoids associated with BMSB egg masses in China do not achieve parasitism rates higher than 10% (Yang et al. 2009). These field data suggest that *T. japonicus* could be a promising candidate for classical biological control of BMSB in the United States. Re-establishing the trophic linkage between BMSB and *T. japonicus* in California at an early stage of this invasion may reduce pest densities and help mitigate nuisance and agricultural problems caused by BMSB.

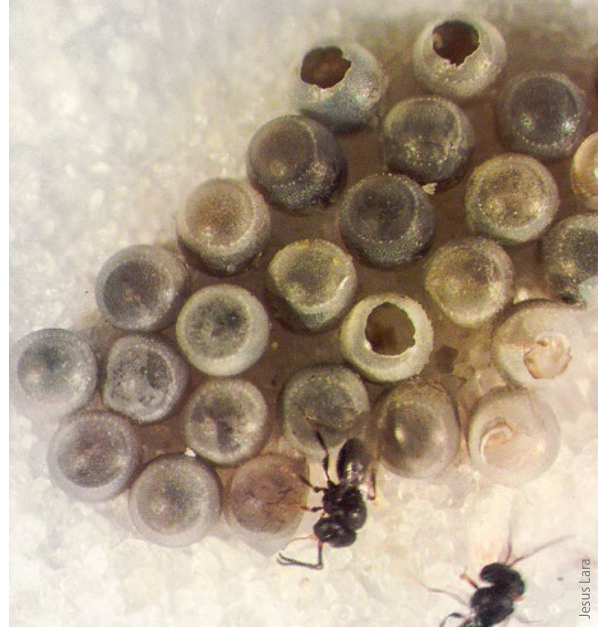
Before *T. japonicus* can be deliberately released for BMSB control in California and other parts of the United States, the impact this egg parasitoid may have on non-target stink bug species needs to be assessed. One of the key components of parasitoid–host interactions for developing successful biological control programs is quantifying parasitism rates of parasitoid–host encounters. Consequently, a variety of safety testing protocols (e.g., no-choice tests and choice tests described below) is being used to assess parasitism levels by *T. japonicus* on BMSB in the context of potential non-target species.

In California, *T. japonicus* is currently reared in quarantine at UC Riverside on BMSB egg masses. Some of the representative non-target stink bugs being reared at UC Riverside for host range safety tests include *Antheminia remota* (Horváth), *Agonoscelis puberula* Stål, *Banasa* sp., *Bagrada hilaris* (Burmeister), *Chlorochroa uhleri* (Stål), *P. maculiventris*, *Mecidea* sp., *N. viridula* and *Thyanta* sp.

Safety testing is conducted in quarantine and provides data on host use under highly artificial conditions as non-target species are exposed in vials, petri dishes or small cages to candidate natural enemies. Laboratory experimental arenas likely minimize the full range of cues natural enemies use for locating hosts and therefore facilitate determining the outcome of encounters. As part of the safety testing for *T. japonicus*, no-choice tests represent scenarios where a female *T. japonicus* encounters an egg mass of a single species stink bug (i.e., BMSB or a non-target species) and the parasitoid must decide whether to parasitize the host egg mass. In choice tests, *T. japonicus* is presented with egg masses of BMSB and at least one non-target stink bug species to elucidate its host preference.

Results from these types of tests are used to quantify level of parasitoid emergence, sex ratios, reproductive fitness of adults and other parameters that characterize the physiological host range and host specificity of *T. japonicus*. The physiological host range refers to the number of species that can support the successful development of *T. japonicus* and emergence of adults from parasitized eggs; host specificity refers to the degree of preference *T. japonicus* exhibits toward potential non-target species in the context of BMSB.

In addition, there are other key elements of host–parasitoid ecology influenced by the biology and ecology of each interacting species that researchers are considering when assessing and interpreting risk by an introduced natural enemy to non-target species. These include the likelihood of natural encounters between *T. japonicus* and non-target species in the environment. For example, there may be some climatic zones that support populations of non-target species in California, but these climatic conditions may represent an establishment barrier to *T. japonicus*, thus reducing risk of attack to non-target species.



Adult male platygastrid parasitoids, on guard, wait for future female parasitoids to emerge from a parasitized sentinel BMSB egg card (parasitism indicated by dark color of eggs) that was deployed in Los Angeles County on avocado.

Ecological niche modeling may help delineate the potential distribution of *T. japonicus* in California and reveal areas where *T. japonicus* is likely to establish and how likely populations of this natural enemy will overlap with BMSB and non-target stink bug populations. Under circumstances where some risk is determined to be likely to some non-target species, a cost-benefit analysis will need to be conducted to guide the use of *T. japonicus* as a classical biological control agent of BMSB.

Safety evaluations for *T. japonicus* are being spearheaded at the national level by USDA ARS BIIR in Newark, Deleware, with coordinated participation from other states (e.g., California, Florida, Michigan and Oregon). This team maintains an open line of communication to design science-driven biological control programs for BMSB specific to the regions that individual members represent, and consequently, non-target stink bug species from each region are being used in safety tests with *T. japonicus*. Safety evaluation results from each team are compiled by USDA ARS BIIR to provide a better understanding of potential non-target effects of *T. japonicus* across the United States.

Although safety testing is still in progress, preliminary results from no-choice and choice studies at UC Riverside suggest *T. japonicus* may have a preference for BMSB egg masses over egg masses of non-target species. Additional lab experiments at Michigan State University by Botch and Delfosse (2015) are under way to provide further understanding of the ecological host range of *T. japonicus* given that added factors (i.e., the ability of the parasitoid to disperse between sites and its foraging success in different habitats) may moderate the level of interaction between *T. japonicus* and non-target species, thus reducing the risk to these species even further. In 2016, UC Riverside entomologists plan to follow up on this line of research on non-target stink bug species from California.

Interestingly, in fall 2014 and during 2015, field populations of *T. japonicus* were detected in Maryland (at three sites), Virginia (at one site) and Washington state (at one site) (HOL 2015; Talamas et al. 2015; Weiford 2015). Preliminary molecular analyses suggest that these field populations of *T. japonicus* were self-introduced separately on the West Coast and East Coast, possibly via parasitized BMSB egg masses on imported host plant material or hitchhiking adults entering the United

In California, the introduced egg parasitoid *Trissolcus basalis* parasitizes eggs of *Nezara viridula* (shown here) but its ability to successfully parasitize BMSB eggs is limited.

States (Acebes et al. 2015; Hoelmer and Dieckhoff 2015).

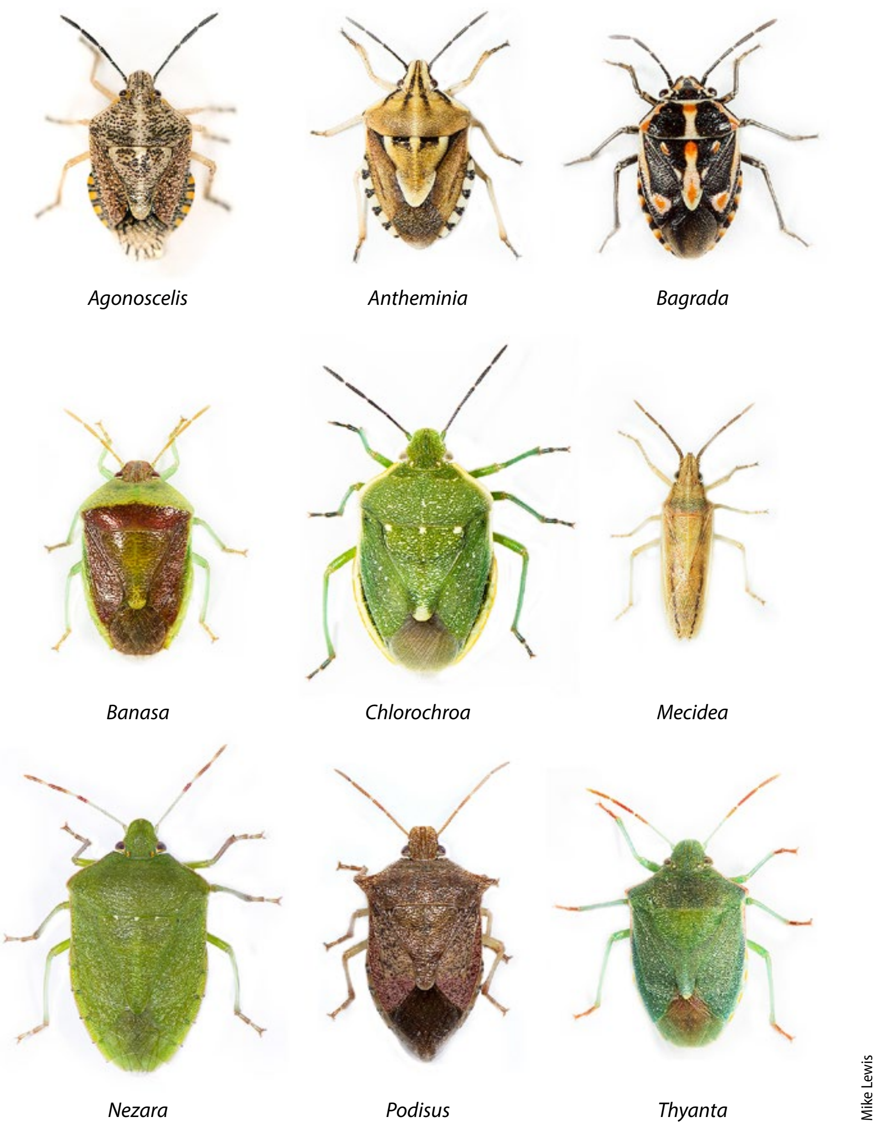
The discovery of small populations of *T. japonicus* on the East Coast and West Coast does not preclude the need for California (and other states with BMSB infestations) to complete the mandatory safety tests and submit host range and host specificity data to be included in an environmental assessment report by USDA ARS. Furthermore, *T. japonicus* cannot be moved across state lines or purposefully released to facilitate its dispersal without USDA Animal and Plant Health Inspection Service (APHIS) approval and the appropriate permits authorizing release. In the meantime, BMSB continues to be intercepted in counties where it may already reproduce. In November 2015, adult BMSB were intercepted in urban areas in Orange County and San Bernardino County and confirmed by entomologists at UC Riverside.

Future developments

Data from monitoring efforts and nuisance reports suggest the number of reproductive BMSB populations and their dispersal in California is increasing and this species has most likely not yet achieved its full potential geographic distribution. At this time, the location of the majority of discovered BMSB populations is limited to urban areas. In part, this may reflect a greater likelihood of BMSB establishment success in areas with a diversity of suitable host plants, such as Chinese pistache (*Pistacia chinensis*), butterfly bush (*Buddleja davidii*) and tree of heaven (*Ailanthus altissima*), and an abundance of overwintering sites such as human-made structures. Urban areas may serve as year-round sources of BMSB populations; from them, adults could migrate to neighboring agricultural areas and once there establish temporary populations that damage crops (Rice et al. 2014).

It is anticipated that biological control will be an important component of a successful integrated pest management program for BMSB across various habitats (agricultural, urban and natural) where it may be difficult to implement spray programs targeting this pest as part of coordinated management efforts. Such programs would require costly, concerted efforts in searching, treating (with pesticides) and following up on the status of infestations on host plants that might harbor this pest. In this regard, biological control may be the only sustainable management solution for BMSB because stink bug parasitoids, native and introduced species, are expected to have permanent, self-sustaining populations and could naturally disperse within habitats to efficiently find existing BMSB populations on host plants. Promoting biological control to lower BMSB populations in residential areas may reduce the size of adult populations invading houses and other buildings to overwinter, and in spring, when adult reproductive diapause breaks, fewer adults migrating out of urban areas in search of host plants could lessen pest pressure in agricultural areas.

T. japonicus is a promising candidate for classical biological control of BMSB. Results of the safety testing, still in progress, will be used to petition for its future release, in conjunction with other states. A general timeline for the completion of safety tests and the permit submission and approval process is still in development and will be influenced by results of safety evaluations. *T. japonicus* has yet to be found or released in California, but sentinel egg cards were deployed during 2014 and 2015 by CDFA and UC Riverside to detect its possible arrival from locations within the United States or from Asia. Monitoring for *T. japonicus* will be expanded in California during 2016 and



Some exotic and native adult stink bugs (size not to scale) from California that are being used to determine host specificity of the BMSB egg parasitoid *Trissolcus japonicus*.

is expected to continue in other states (e.g., Delaware, Virginia, Maryland, North Carolina, Washington).

The multistate safety testing of *T. japonicus* is essential, as it will help guide future field studies by teams of researchers from each state (i.e., CDFA and University of California) to monitor its dispersal once it is approved for release or self-introduces, document its ecological host range and measure its economic impact on BMSB populations. In California, safety testing with *T. japonicus* at UC Riverside may take another two to three years to complete. USDA ARS BIIR will evaluate safety results from all research teams in the United States. At the same time, the results of independent field work and laboratory studies led by CDFA and UC researchers is expected to elucidate the potential of resident natural enemies to reduce BMSB populations in California. Data from these California projects will be analyzed, and in conjunction with input from USDA ARS BIIR cooperators on *T. japonicus*, the results will be used to formulate a biological control program for California that can be implemented in residential and agricultural areas threatened by BMSB infestations. CA

J. Lara is Postdoctoral Scholar in the Department of Entomology at UC Riverside; C. Pickett is Senior Environmental Research Scientist at California Department of Food and Agriculture, Sacramento; C. Ingels is UC ANR Cooperative Extension (UCCE) Farm Advisor in Sacramento County; D.R. Haviland is UCCE Farm Advisor in Kern County; E. Grafton-Cardwell is UCCE Entomology Specialist at UC Riverside and Director of Lindcove Research and Extension Center; D. Doll is UCCE Farm Advisor in Merced County; J. Bethke is UCCE Farm Advisor in San Diego County; B. Faber is UCCE Farm Advisor in Santa Barbara and Ventura counties; S.K. Dara is Strawberry and Vegetable Crops Advisor and Affiliated IPM Advisor in San Luis Obispo, Santa Barbara and Ventura counties; M. Hoddle is UCCE Entomology Specialist at UC Riverside.

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Research Article

Phenology of spotted wing drosophila in the San Joaquin Valley varies by season, crop and nearby vegetation

by David R. Haviland, Janet L. Caprile, Stephanie M. Rill, Kelly A. Hamby *and* Joseph A. Grant

The spotted wing drosophila, first detected in California in 2008, has become a major insect pest in caneberries and sweet cherries, causing commercial crop losses. Managing it is challenging because it has many other hosts, including riparian and backyard fruit plantings, and it increases rapidly, with generations overlapping one another. In our study we monitored trap captures in two parts of the San Joaquin Valley, within sweet cherry orchards and in nearby locations. Captures of adult flies showed two main periods of activity — spring and fall — and low captures in the winter (except for citrus and evergreen riparian areas) and summer. On many occasions during the year, trap captures were higher outside of the cherry orchards than within them. Additionally, early in the season, when decisions about control programs are being made, the sex ratio of captured flies in cherries was strongly female-biased. The results suggest that during the weeks leading up to harvest growers should experiment by placing traps in different environments surrounding their orchards to determine SWD activity and potential pest pressure locally, and monitor for both male and female flies.

The spotted wing drosophila (SWD) (*Drosophila suzukii* [Matsumura]) was first detected in California in 2008 in Santa Cruz County raspberry fields, with subsequent detections in the spring of 2009 in Central Valley cherry orchards (Hauser 2011). SWD is unique among the ~1,500 species of *Drosophila* flies in its preference for laying eggs in intact, fresh, thin-skinned fruit rather than in damaged, overripe and rotten fruit (Hauser 2011; Walsh et al. 2011). Commercial fruit losses have been reported for blueberries, caneberries, sweet cherries and strawberries in California, Oregon and Washington (Walsh et al. 2011). In California, SWD has become a major insect pest of concern in both caneberries and sweet cherries.

In 2012, there were 31,000 acres of bearing sweet cherries (*Prunus avium* [L.]) in California with a total value of $258 million (NASS 2012). Most of California commercial sweet cherry production occurs in the Central Valley, where a diversity of other stone fruit, blueberries, citrus crops and grapes are also grown. Additionally, many rural home sites have diverse backyard fruit plantings. This mixed landscape presents a SWD management challenge because ample alternate hosts are available outside the commercial orchards.

Not only can SWD use a broad range of resources, but they also develop relatively rapidly. At temperatures between 79°F and 82°F (26°C to 28°C), SWD can complete a generation (from egg to adult) in about 10 days (Tochen et al. 2014). Therefore, populations can build rapidly

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Spotted wing drosophila lay eggs on cherries before the fruit is ready to harvest.

David Haviland

Dorsal view of male on leaf, showing a black spot on the tip of each wing (2× magnification). *Inset*, spotted wing drosophia uses a large, serrated ovipositor to lay eggs in the surface of thin-skinned fruits such as cherries and blueberries.

and generations begin to overlap early in the season, making degree-day models difficult to implement and creating a challenge for monitoring and management (Tochen et al. 2014). The goal of our research was to help growers improve their monitoring and management programs by using the information we collected on the seasonal phenology of SWD within commercial sweet cherry orchards and in nearby locations where they may find food and shelter throughout the year.

Seasonal phenology

Southern San Joaquin Valley. Adult populations of SWD were monitored weekly from April 5, 2010, to July 2, 2012, at three locations containing commercial plantings of sweet cherries, citrus and blueberries in southeastern Kern County. Each planting was mature and managed using standard production practices for the crop, including SWD insecticide treatments in the cherries. Each of the three locations consisted of all three crops planted so that they shared a common corner. Orchards and fields used in the surveys were a minimum of 20 acres (8 hectares).

For this study we developed a bucket trap for collecting SWD. These traps were made using a 3.2-cup (760 milliliter) plastic container (Rubbermaid, Huntersville, NC) with a 3.3-inch (8.5-centimeter) diameter hole cut in the top and covered with 0.13-inch (0.32-centimeter) wire mesh (hardware cloth). This trap became known as the Haviland trap during early trap evaluation studies (Lee et al. 2012).

Adult SWD were captured using bucket traps containing apple cider vinegar. Wire mesh on top of the trap allowed for the entry of SWD but helped keep out larger insects. (A) Haviland trap, (B) Van Steenwyk trap.

Two bucket traps were used within each crop at each location (total of 18 traps). Each week approximately 5 fluid ounces (150 milliliters) of apple cider vinegar (Amerifoods Trading Co., Los Angeles, CA) was placed into each trap; the traps were hung at a height of approximately 5 feet (1.5 meters) within the tree canopy for cherries and citrus, and on a horizontal wire at a height of approximately 1.5 feet (0.5 meter) for blueberries. After research in 2010 showed that reducing surface tension can improve trap capture, on Jan. 1, 2011, we began adding 1 teaspoon (4 milliliters) of dish soap (Colgate-Palmolive Co., New York, NY) to every 1 gallon (3.78 liters) of apple cider vinegar used in the traps. Each week the contents of each trap were removed from the field and evaluated under magnification in a laboratory by counting the total number of male and female SWD.

Captures of adult SWD in traps showed two main periods of activity — spring and fall — separated by periods of low captures in the winter (except for citrus) and summer. In citrus there were minimal SWD captures from early June through early October, during the hot, dry weather typical of the southern San Joaquin Valley (fig. 1A). The period of fall SWD activity began in mid-October, followed by a rapid increase in captures that peaked in mid- to late November. Captures remained relatively high throughout the winter and tapered off through May and June. In cherries (fig. 1B) there were two periods of SWD activity. The first occurred from March through June and peaked in April just prior to the initiation of insecticide treatments. If insecticides had not been used, it is likely that the peak would have shifted to May, when cherries in Kern County are harvested. The second period of activity was from mid-October to mid-December, peaking in mid- to late November. Very few SWD were captured during the winter, from January through March, or during the summer, from July through September. SWD activity in blueberries in the southern San Joaquin Valley (fig. 1C) had a pattern similar to cherries.

Despite similarities in the seasonality of adult SWD activity among the three crops, there were significant differences in SWD abundance. Citrus consistently exhibited the highest trap catches, with fewer catches in cherries and the lowest catches in blueberries (fig. 1). This relationship was consistent in both spring and fall flights even though the cherries were sprayed for SWD in spring (citrus and blueberries were not sprayed); no SWD sprays were applied to any of the crops in fall. As the citrus, cherry and blueberry plantings were adjacent to each other, this trap capture pattern suggests that SWD may have seasonal preferences in where they locate or that traps vary in attractiveness depending on season and crop. Additionally, trap captures did not correlate with fruit presence, especially when considering that peak captures in cherries and blueberries took place in the fall, approximately 6 months after harvest, when no fruit was present.

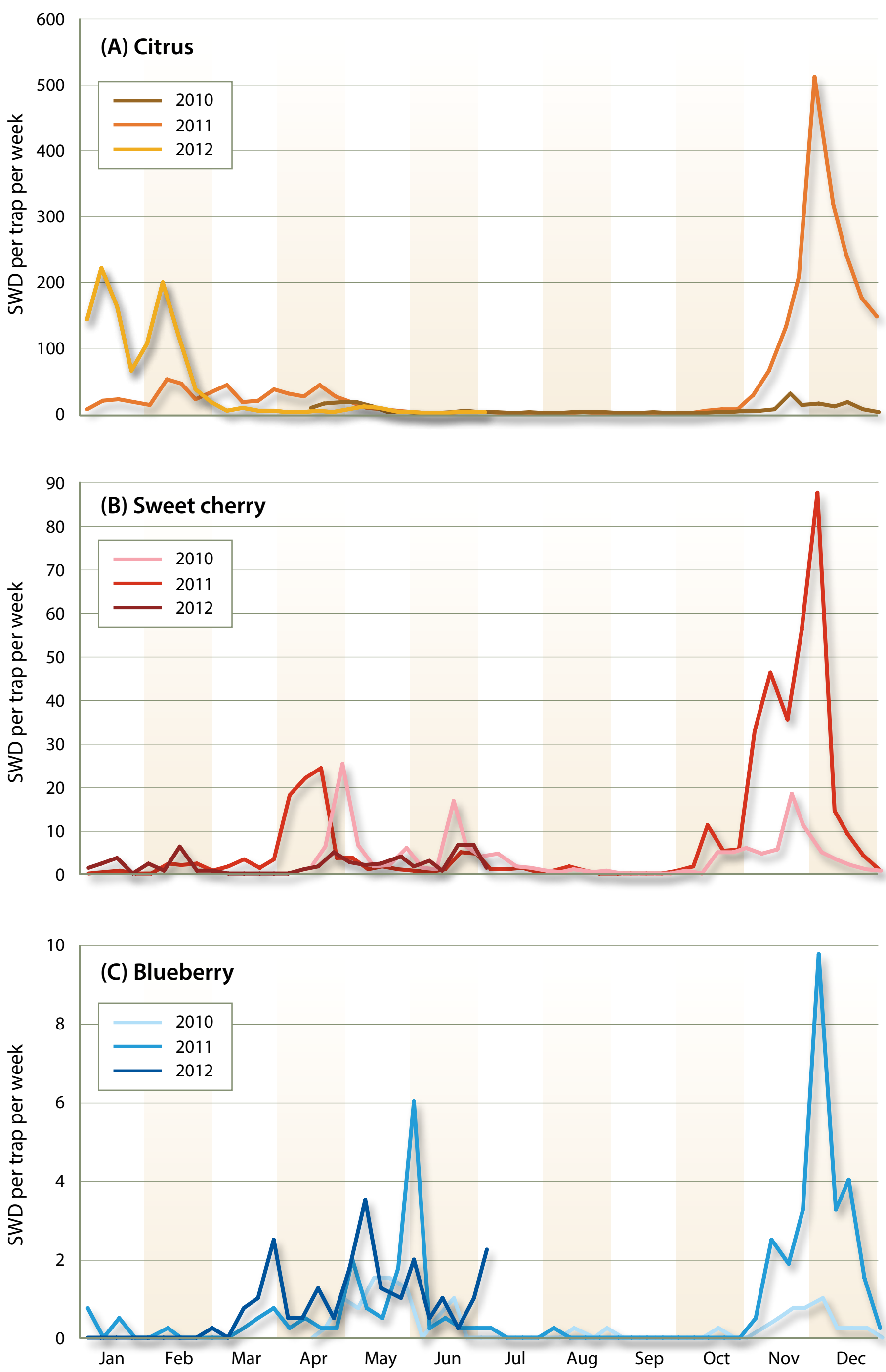


Fig. 1. Seasonal phenology of captures of adult SWD in adjacent (A) citrus, (B) sweet cherry and (C) blueberry plantings in the southern San Joaquin Valley from 2010 to 2012.

Both cherries and blueberries are hosts for SWD, and both crops have experienced commercial crop loss in California (Lee et al. 2011; Walsh et al. 2011), though damage to blueberries has been limited to cooler coastal regions; blueberries in the Central Valley have not experienced loss. In contrast, although citrus is not considered a host of SWD due to its thick rind (Atallah et al. 2014), there were high levels of adults captured in citrus orchards throughout their harvest season. In a small, replicated laboratory study (unpublished), Haviland found that SWD did not reproduce on intact or rotting citrus fruit but was able to reproduce on sound, split fruit. So while commercially harvested citrus fruit should not be considered a host of SWD, it is clear that damaged fruit in an orchard can serve as a reproductive host for SWD throughout the winter.

SWD distributions in citrus could also be tied to other food sources that were present in the planting since SWD are known to use some flowers and yeasts as food resources (Hamby et al. 2012; Mitsui et al. 2010). As SWD distribution was measured using an attractant-based trapping system, it is also possible that captures fluctuated due to seasonal variability in the attractiveness of the apple cider vinegar relative to the crop odors or fly activity.

Northern San Joaquin Valley. Adult populations of SWD were monitored in commercial sweet cherry orchards located near Brentwood in Contra Costa County and Stockton in San Joaquin County. Bucket traps were made using a 1-quart (1-liter), white plastic container that had 16 $^{1}/_{16}$-inch (4.8-millimeter) holes drilled around the side just below the lid. This trap later became known as the Van Steenwyk trap (Lee et al. 2012). Each week approximately 4 fluid ounces (150 milliliters) of apple cider vinegar (Amerifoods Trading Company, Los Angeles, CA) with 1 to 2 teaspoons (4 to 8 milliliters) of clear, unscented dish soap (Palmolive Pure + Clear) per gallon was placed into each trap, and traps were hung in a shaded portion of the cherry canopy at a height of approximately 5 feet (1.5 meters). Trap contents were collected weekly, and the number of male and female SWD were counted in a laboratory using a dissecting microscope.

In three orchards that were not sprayed for SWD, four traps were placed

Spotted wing drosophila introduces microbes into cherry fruit before harvest. As fruit begin to rot, they become highly attractive to other drosophila species.

Production of high-quality cherries in California now requires aggressive management programs for spotted wing drosophila.

in each orchard (total of 12 traps) and monitored weekly from mid-March 2010 to March 22, 2012, in two sites and from May 5, 2010, to March 30, 2011, in a third site. In 12 to 14 orchards that were commercially treated for SWD, traps were also deployed from late March 2010 through late March 2012 using one trap per orchard. Additional traps were deployed (one trap per site) in sites surrounding these sprayed cherry orchards from mid-July 2010 through March 2011 to identify other potential hosts and habitats after the cherries had been harvested.

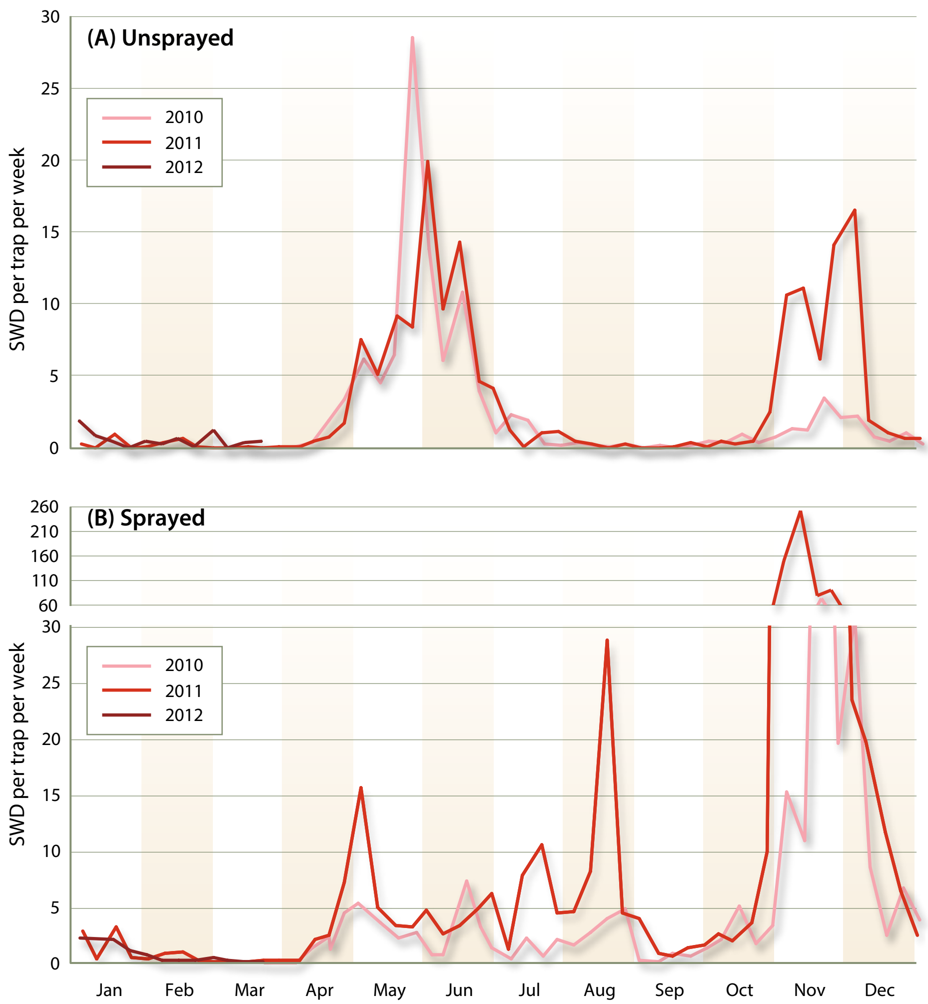


Fig. 2. Phenology of captures of adult SWD in sweet cherries in the northern San Joaquin Valley from 2010 to 2012 in (A) unsprayed orchards and (B) sprayed orchards.

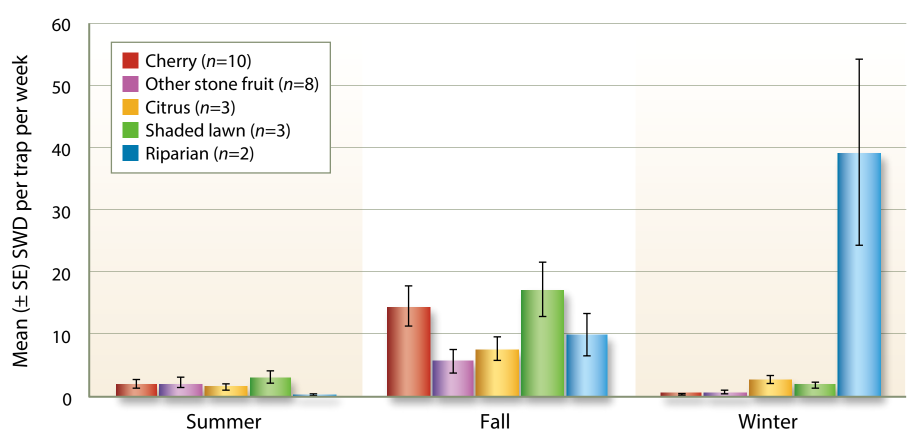


Fig. 3. Average weekly captures of SWD from five different environments surrounding cherry orchards in the northern San Joaquin Valley during the summer, fall and winter SWD flight periods after the 2010 cherry harvest.

This survey included a wide range of agricultural crops, rural home sites and natural environments. In this report we include only those data that had at least two different trapping locations for the same type of environment and were collected for the entire 8-month period between the 2010 and 2011 spring SWD flights in cherries. The result was a subset of data that included cherries (10 sites), other stone fruit (eight sites), citrus (three sites), irrigated lawns with shade (three sites) and riparian areas (two sites). Data from weekly trap catches were summarized by SWD flight season (summer: mid-July to September; fall: October to December; winter: January to March) and plotted to evaluate differences in SWD density across environments and to visualize changes in distribution patterns throughout the year.

Captures of SWD in unsprayed cherries in the northern San Joaquin Valley (fig. 2A) followed a similar pattern to the southern San Joaquin Valley, with the primary difference being that the spring period of activity occurred slightly later, extending from early April to mid-July, with peak captures approximately 1 week before harvest in late May to early June. Within the northern San Joaquin Valley, comparisons of unsprayed and sprayed orchards (fig. 2) showed that sprayed orchards had lower SWD densities when insecticides were used in May and June, but they had higher SWD densities after harvest in July and August as well as during the fall period of activity, from mid-October to mid-December.

SWD was found in varying densities in different environments around commercial cherry orchards throughout the year (fig. 3). In summer, fly captures were similarly low in all trap locations. SWD captures increased in fall, with the greatest numbers found in the shaded lawn and cherry environments and modest numbers found in the citrus, stone fruit and riparian sites. In winter, extremely high numbers were found in the riparian sites with evergreen ground or tree cover, but few flies were captured in any other environment. Many insects select special microhabitats to enhance survival during unfavorable conditions (Danks 1978), and during the winter evergreen plants provide additional shelter and favorable microclimates for insects compared with deciduous plants (Johnson et al. 1975). Our data suggest that SWD might choose riparian sites for those reasons. Growers should note that flies are not likely to be detected in their orchards all season long, and placing traps in favorable environments surrounding the orchards in winter to determine the local SWD pressure may be useful as they make their management decisions in spring.

High temperature effects on captures. During all 3 years of study, there were obvious voids in fly captures during the hot and dry summer weather typical of the San Joaquin Valley (figs. 1–3). The relationship between high temperatures and SWD trap captures was evaluated by regressing the average number of SWD collected on each trap collection date in the northern and southern San Joaquin Valley against the average daily high temperature for the week. The x-axis calculations were made using data from weather stations located in Kern County (CIMIS Station #125, Arvin-Edison) and Contra Costa County (CIMIS Station #47, Brentwood). Capture data were square-root transformed (because the data exhibited characteristics of an exponential decay curve as temperatures increased) before a linear correlation analysis was performed for dates where average daily high temperature during the preceding week was at least 70°F (21°C).

Our analyses revealed a significant negative correlation between the average daily high temperature and SWD captures in the southern San Joaquin Valley (fig. 4A) ($P < 0.0001$, $R^2 = 0.4817$) and in the northern San Joaquin Valley (fig. 4B) ($P < 0.0001$, $R^2 = 0.4007$). The x-intercept for these two locations suggests that adult captures can still occur when daily high temperatures are in the high 90s and low 100s (°F) (32°C and 38°C). However, captures when daytime temperatures reached 95°F (35°C) were typically less than one SWD per trap per week.

Other studies have shown similar declines in trap captures as well as reductions in survival and fecundity at high temperatures (David et al. 2005; Kinjo et al. 2014; Tochen et al. 2014). The negative effects of high summer temperatures on SWD may explain why SWD has not become a pest of commercial stone fruit and grapes, which are primarily harvested from July to October in the San Joaquin Valley.

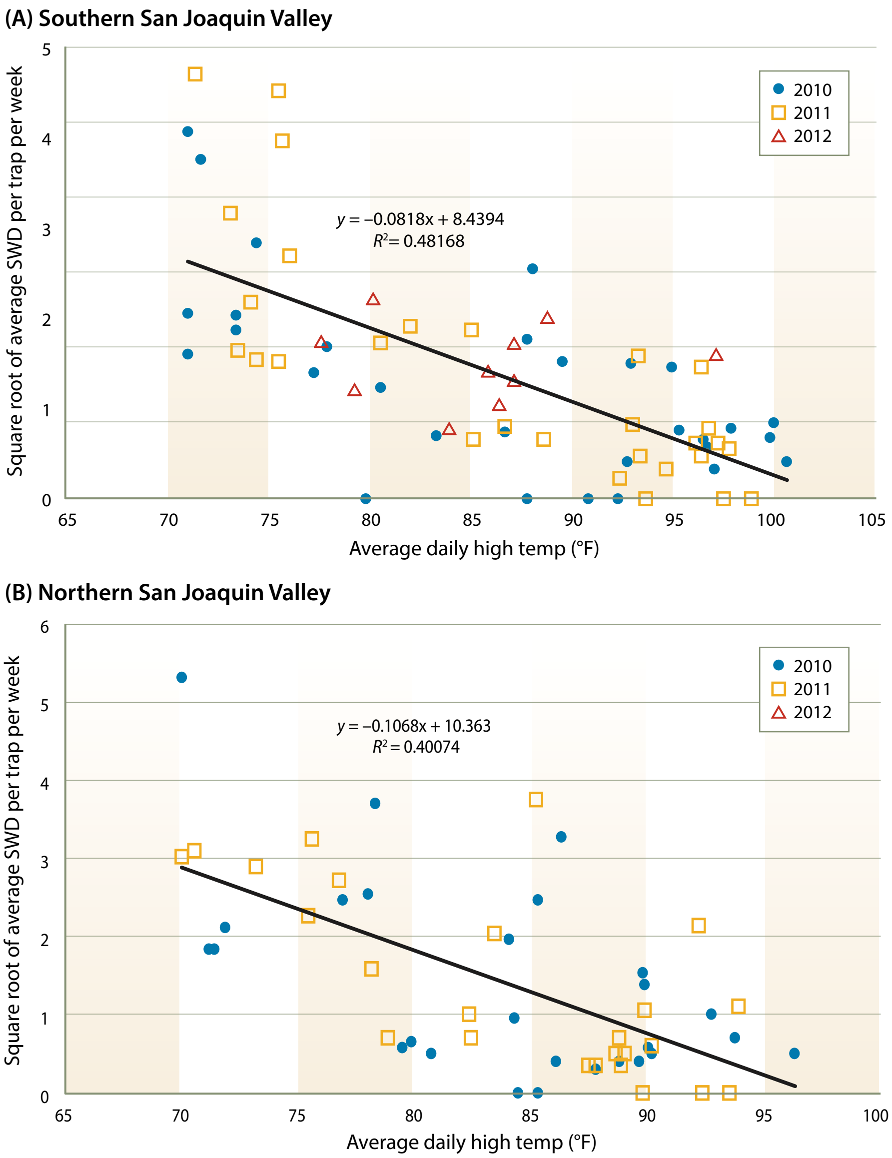
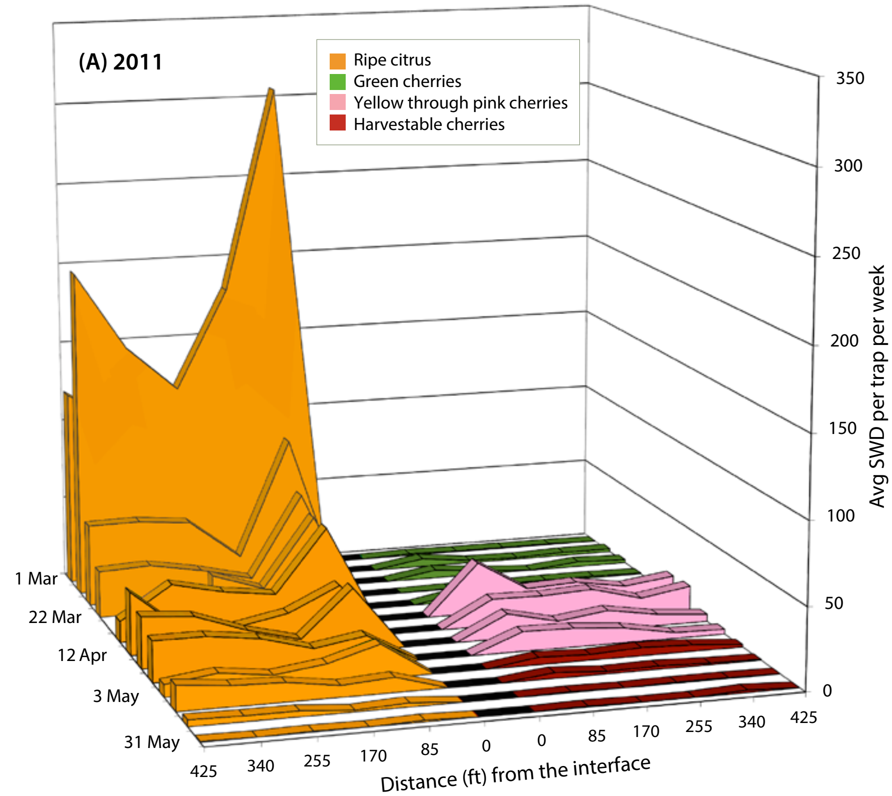


Fig. 4. Regression analysis of the effects of high ambient temperatures on captures of adult SWD in (A) the southern San Joaquin Valley ($y = -0.0818x + 8.4394$, $R^2 = 0.4817$) and (B) the northern San Joaquin Valley ($y = -0.1068x + 10.363$, $R^2 = 0.4007$). Each point represents the average trap captures (square-root transformed to linearize data) over a period of 1 week compared with the average daily ambient high temperatures during those same weeks from 2010 to 2012.

Interface between citrus and cherry

During the springs of 2011 and 2012, we conducted field studies to evaluate patterns of distribution of SWD in citrus and sweet cherries in the southern San Joaquin Valley. Haviland traps were placed in adjacent mature citrus and cherry orchards for a 13-week period comprised of the 10 weeks prior to harvest and the 3 weeks during harvest. Traps were placed in two transect lines, 656 feet (200 meters) apart, that ran perpendicular to the dirt road that served as the interface between the crops. Ten traps were located in each transect, with five located in each crop at 85-foot (26-meter) intervals from the interface. Trap contents were collected weekly and the number of SWD counted. During 2013 the same process was repeated for a 4-week period in March, recording the number of male and female SWD.

SWD captures showed strong variations between citrus and cherries at



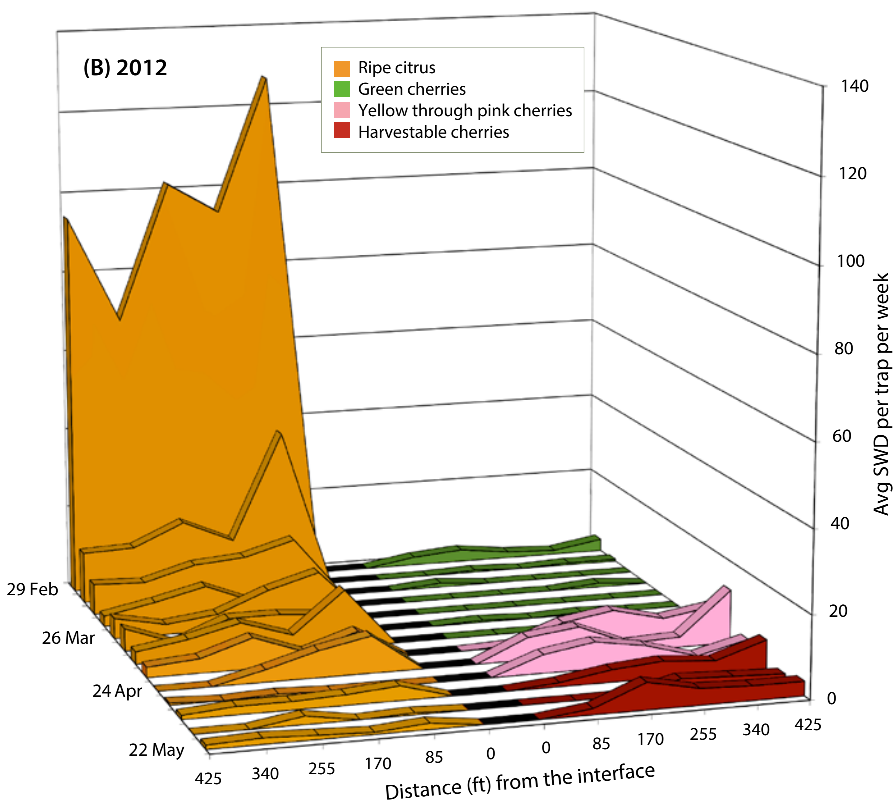


Fig. 5. Weekly SWD captures in transects of traps placed perpendicular to the interface between citrus (left) and cherry (right) orchards from late February to late May in (A) 2011 and (B) 2012. Colors denote fruit ripeness in the orchard (orange indicates ripe citrus, green indicates green cherries, pink indicates first yellow cherry through pink cherry stages, red indicates the presence of harvestable cherries). In both years of the study, cherry orchards were sprayed three times with insecticides for SWD while cherries were in the pink stages.

different times of the year. In 2011 (fig. 5A) and 2012 (fig. 5B), many more SWD were captured in citrus than in cherry while fruit on the cherry trees were still green. This changed approximately 4 weeks prior to harvest as the cherries began to turn from green to yellow and then pink. SWD captures in the cherry orchard with pink fruit were approximately 10 times higher than when fruit were green, despite the fact that the cherry orchards received three insecticide applications for SWD during the pink stage each year. During both years of the study, fly captures during cherry harvest were less than three per trap per week, presumably due to the effectiveness of the repeated insecticide sprays during the pink stages. No SWD damage was found in either year during harvest.

In cherries, only 13.3% of the flies captured during the first 3 weeks in March were male, and during the 4th week only 27% were male.

In 2013 a more detailed analysis of fly captures by gender revealed that sex ratios of SWD in citrus were approximately 50:50 (fig. 6A). However, during the first 3 weeks after cherries become susceptible to attack by SWD (first 3 weeks in March), only 13.3% of the flies captured were male; during the fourth week only 27% were male (fig. 6B). A similar pattern of female dominance was seen in cherry orchards in the northern San Joaquin Valley during the spring SWD flight period (data not presented). This pattern suggests that cherry growers should not rely on the more easily detectable male captures in traps but need to use magnification to identify the females in order to accurately gauge SWD abundance in spring, the critical time for making management decisions.

Management implications

Our study presents important considerations for SWD monitoring programs, including seasonal patterns in trap captures, trapping protocols, climatic factors and the influence of the local landscape, that can be used in integrated pest

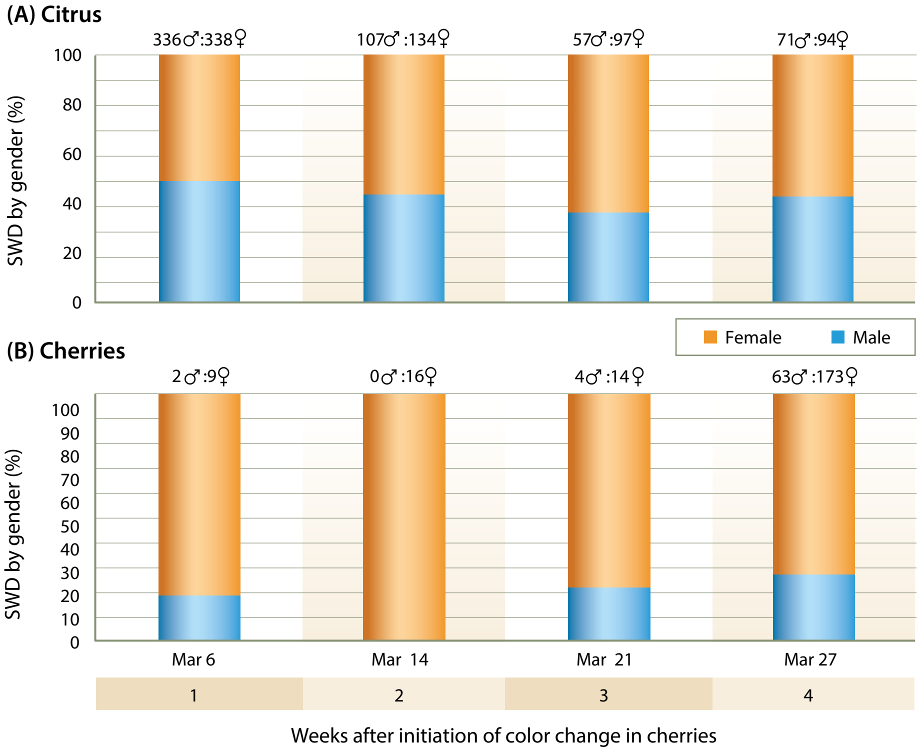


Fig. 6. Male-to-female ratios of SWD collected in (A) citrus and (B) cherries from late February when cherries are green through late March when cherries begin to change color and become susceptible to attack by SWD in the southern San Joaquin Valley.

management (IPM) programs for SWD. In some cases, such as stone fruit, peaches and nectarines, SWD management has not been needed because fruit are harvested during periods of the summer when our data show that adult SWD are not active. The opposite is true for cherries; phenology data confirm the presence of elevated SWD populations during the period of early color change through harvest, when cherries are susceptible to attack (Lee et al. 2011). The current standard practice in cherries is to control SWD with two or three insecticide applications during the 3 to 4 weeks prior to harvest (Haviland and Beers 2012). The decision whether to use two or to use three applications can be assisted by the use of traps. However, our data suggest that bucket traps baited with apple cider vinegar are likely to lead to false conclusions about SWD density unless both males and females are counted. If cherry orchards are located near commercial citrus or other favorable SWD overwintering sites, traps should also be placed in those environments to get a more accurate picture of the regional SWD pressure.

We anticipate that increased knowledge about SWD population changes throughout the year and movement among crops will lead to improvements in the ability of pest control advisers and growers in California to anticipate locations where problems with SWD may occur and to make site-specific decisions about the integrated pest management programs they use to protect their crops. CA

D.R. Haviland is UC ANR Cooperative Extension (UCCE) Entomology Farm Advisor in Kern County; J.L. Caprile is UCCE Farm Advisor in Contra Costa County; S.M. Rill is UCCE Staff Research Associate in Kern County; K.A. Hamby was Doctoral Candidate in the Department of Entomology at UC Davis and is now Assistant Professor and Extension Specialist at the University of Maryland; and J.A. Grant is UCCE Farm Advisor in San Joaquin County.

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Sticky traps saturate with navel orangeworm in a nonlinear fashion

by L.P.S. Kuenen *and* Joel P. Siegel

Trapping is an essential tool used to decide the need for and/or timing of an insecticide application. The assumption is that the information is accurate, but accuracy is dependent on trap reliability and efficacy. One factor that affects reliability is trap saturation, defined as the measurable decrease in trap capture due to reduced trapping effectiveness caused by the accumulation of insects already in a trap. In this study, we used unmated female navel orangeworm (NOW,* Amyelois transitella *(Walker)) as sex pheromone baits in wing traps that varied by color and glue/trapping surface in order to evaluate saturation thresholds and quantify trap effectiveness. Effectiveness decreased in each type of sticky trap as the number of insects caught increased, because of the accumulation of scales and insect bodies on the glue surface. The continued accumulation of insects further reduced trap capture, and this decrease in capture could be described by a regression using a power transformation. The resulting saturation equations that we calculated will help pest control advisers and growers interpret their trap data by better estimating the relationship between the number of males trapped versus those that visited the trap.

The navel orangeworm (NOW), *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae), is the primary insect pest of the multibillion-dollar almond and pistachio industries in California. Until 2013, male trapping, a potentially useful tool to monitor the NOW population and aid in control decisions, could only be used by those with access to a NOW colony to provide unmated NOW females for use as pheromone baits. Although the primary component of the sex pheromone was identified over three decades ago by Coffelt et al. (1979), it was only the recent elucidation of other critical NOW sex pheromone components by Kuenen et al. (2010) that enabled the development of commercially produced synthetic lures (Suterra, Bend, OR; Trécé, Adair, OK). These lures produce trap capture yields equivalent to female-baited traps (J. Siegel, unpublished data).

Adoption of this new tool to aid orchard management decisions is dependent on the accuracy of the trap data. Trap accuracy is affected by two issues, trap efficiency (Ramaswamy and Cardé 1982; Sanders 1978) and trap saturation, defined as a decrease in trap effectiveness due to the presence of trapped individuals (Houseweart et al. 1981; Sanders 1986). Understanding the relationship between trap design and these issues is critical for population monitoring and management, especially for insect pest populations that are historically high.

When saturation occurs, the number of insects in a trap does not accurately represent the number of entries into the trap, resulting in an underestimate of the population. Saturation of glue-based traps occurs when the trap's ability to retain insects that enter the trap is reduced by

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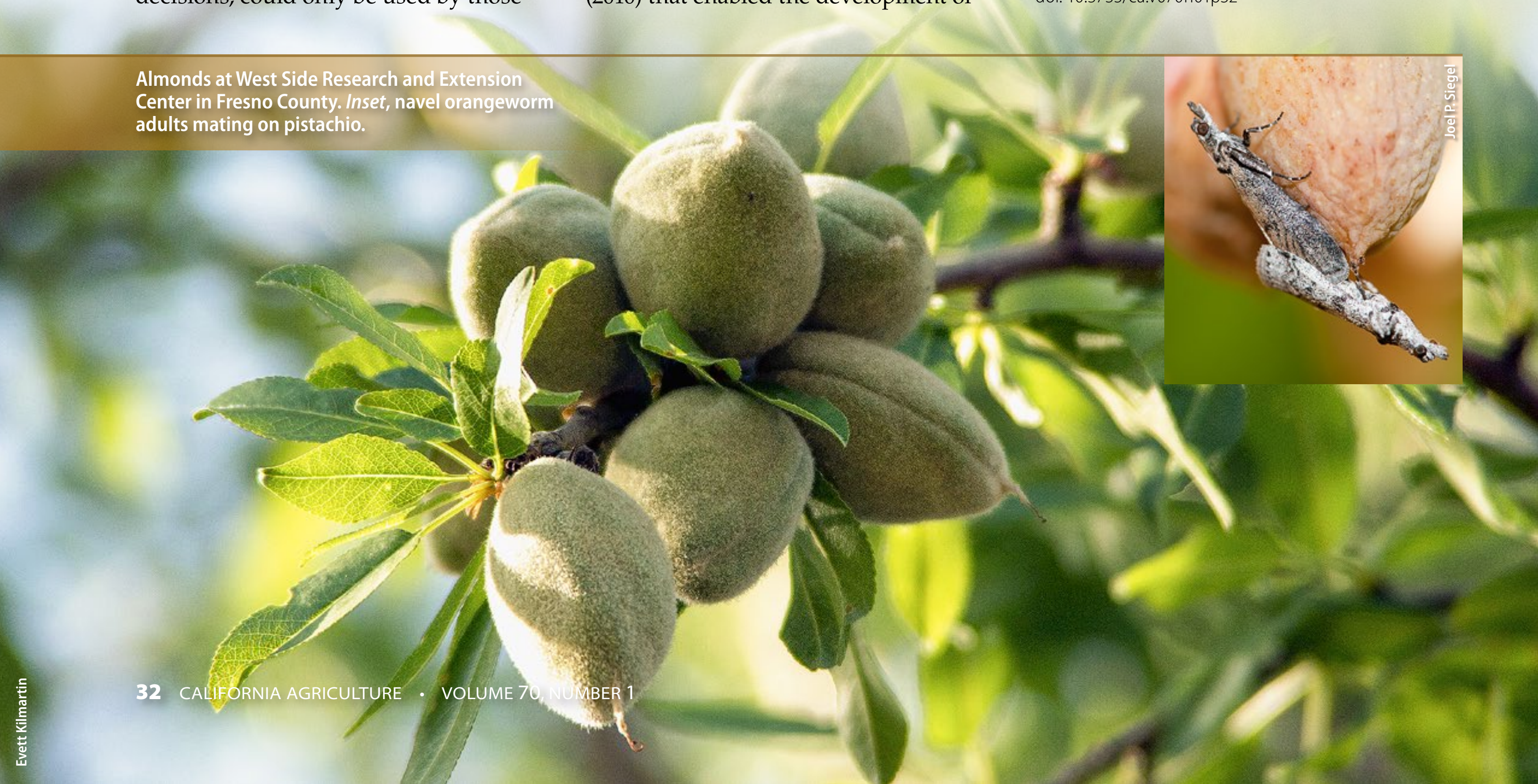


Joel P. Siegel

Almonds at West Side Research and Extension Center in Fresno County. *Inset*, navel orangeworm adults mating on pistachio.

Evett Kilmartin

Fig. 1. Trap bottoms from Suterra wing traps containing 5 (left), 79 (middle) and 149 (right) NOW males. Note the fouling of glue surfaces with moth bodies and scales on the two higher-count traps. Saturation begins at approximately 50 moths.

the presence of trapped insects or by the presence of other fouling material, such as scales shed by the trapped insects, dust and plant debris.

Saturation is not an all-or-nothing phenomenon. Rather, the sticky trapping surface becomes increasingly fouled as each trapped insect covers part of the glue surface (fig. 1), and also as trapped insects fan their wings and disperse scales onto the surrounding glue. From years of experience with the field biology of NOW (Kuenen and Siegel 2010; Siegel et al. 2008, 2010), including extensive trapping experiments, we know that trap capture in female-baited traps in some locations can be as high as 150 males per night (J. Siegel, unpublished data), but those trap counts do not reveal how many males visited the trap if the trap became saturated at 50 moths, which is the saturation threshold we suspected from our experience with trapping.

Previous studies of other insects have evaluated differences in trap design (Brown 1984; Knodel and Agnello 1990; Ramaswamy and Cardé 1982; Sanders 1978) and methods to increase trap capture (Houseweart et al. 1981; Ramaswamy and Cardé 1982; Sanders 1986). Our interest, however, was in determining the trap saturation threshold and efficiency of the sticky traps that are industry standards for monitoring insects that are in the same size range as NOW. Our goal was a more accurate estimation of a NOW population from trap capture numbers; eventually the relationship between the size of the population and damage to almonds and pistachios could then be established as part of an integrated control strategy for NOW.

Traps

The traps tested were as follows: (1) BioLure red wing trap (Suterra, Bend, OR; item 12533), with a glue surface area of ~ 49.6 square inches, (2) Pherocon 1C white wing trap (Trécé, Adair, OK; item 3302-00), with a glue surface area of ~ 60.5 square inches, (3) No-Mess Adhesive white wing trap (Alpha Scents, West Linn, OR), with a glue surface area of ~ 60.5 square inches and (4) BioLure red delta trap (Suterra, Bend, OR; item 12777), with a glue surface area of ~ 40.3 square inches.

BioLure red wing trap.

BioLure red delta trap.

Pherocon 1C white wing trap.

Nonsaturating water trap.

All wing traps were assembled using the methods described by Kuenen et al. (2005). The differences in capture between saturating and nonsaturating sticky traps were evaluated by placing two groups of each trap type in the field: the nonsaturating group had trap bottoms replaced on each day the traps were checked; the trap bottoms in the saturating group were not replaced during an entire test.

As another comparison, we utilized a different type of nonsaturating trap, a water trap, that does not use adhesive to capture moths. The water trap consisted of a 1-pint translucent plastic tub with a surface area of 14.75 square inches, suspended by the trap wires under a Trécé wing trap top; the cup was filled with ~ 8 ounces deionized water that contained ⅓ teaspoon unscented soap (as a surfactant) per quart of water. Moths were counted after being sieved from the decanted water, and then the trap was replenished with fresh water.

All traps were baited with three unmated NOW females, which served as pheromone sources. The females were hung in fiberglass screen cages (Curtis and Clark 1984) from the top-center of each trap. These female baits were replaced weekly with newly emerged females if daytime temperatures were ≤ 90°F, and at ≤ 4-day intervals when temperatures exceeded 90°F.

Traps were hung in trees 5 to 6 feet above the ground, with at least 150 feet between traps within a row (replicate) and at least 150 feet between replicate rows. Forty-five traps were placed out in a randomized complete block design. Five replicate rows were laid out, with each row containing a saturating trap of each type, a nonsaturating trap of each type, plus a water trap. Trap locations were freshly randomized for each site and test date and trap counts were recorded daily or every second day if daily numbers were low (≤ 10 moths per day in nonsaturating traps). Tests were terminated when saturating trap types had accumulated a mean of 150 or more moths per trap or when cooperators' orchards received insecticide applications; data from the latter group were excluded if a mean of 40 moths was not attained in the saturating group.

Sampling

Trapping studies were conducted between April and August 2009 to 2011 in pistachio orchards in Madera County, ~ 6 miles northwest of Fresno, California. Trapping tests were initiated if counts averaged ≤ 30 moths per trap per night so that we could compare both saturated and nonsaturated traps when they were equally effective. In prior studies (Kuenen and Siegel 2010), trap catch from late March through mid-May was less likely to exceed our proposed threshold of 50 moths per trap, and nightly trap catch could exceed 30 moths per trap after mid-July.

We report the results of five tests, comprising 88 days of sampling with the traps described above (table 1). Although we conducted more tests, they were terminated because cooperators' orchards received insecticide applications or rapid rises in trap capture led to saturation of all traps.

Data analysis

The data were analyzed in two stages. The first stage used the raw data for each trap type but did not account for differences in the surface area of the glue. The relationship between male capture in the nonsaturating and saturating traps during the sample period was evaluated using regression (JMP v 10.0, SAS Institute, Cary, NC). In these analyses, the nonsaturating trap served as the independent variable, because it never reached full capacity.

The data were transformed for both nonsaturating and saturating traps using $\log_{10}(x + 1)$ when a power transformation was the most appropriate. Total trap capture was compared separately for the saturating and nonsaturating sticky traps. The differences between trap types were then assessed using multiple regression with dummy coding (Cohen and Cohen 1983). In a separate analysis, differences in male capture between nonsaturating and

TABLE 1. NOW male trap capture by trap type over the 88-day monitoring period*

	Trécé wing		Delta		Suterra wing		AlphaScents wing		Water
	N	S	N	S	N	S	N	S	
Total capture	29,103	15,128	15,613	9,883	29,264	18,808	33,497	22,434	31,176
Mean capture†	66.14 ± 5.51	34.38 ± 2.71	35.48 ± 4.18	22.46 ± 2.25	66.51 ± 7.12	42.75 ± 3.32	76.13 ± 7.20	50.99 ± 4.25	70.85 ± 7.75

* Trécé = Pherocon 1C white wing trap; Delta = Suterra BioLure red delta trap; Suterra = Suterra BioLure red wing trap; AlphaScents = No-Mess Adhesive white wing trap. N = nonsaturating trap; S = saturating trap.

† Means are reported ± standard error.

Moth capture was greater in nonsaturating traps than in saturating traps, and this difference ranged from 33.0% to 48.0%.

saturating sticky traps and the water trap were evaluated using multiple regression with dummy coding.

In the second stage, the traps were standardized by converting the trap capture for each day into moths per square inch of the glue-covered surface. Differences among trap types were then assessed using multiple regression as described above.

Trap captures, equations

In the tests reported, we captured 204,906 NOW males, and the total trap-type captures ranged from 9,883 to 33,497 (table 1). For every trap type, moth capture was greater in nonsaturating traps than in saturating traps, and this difference ranged from 33.0% to 48.0%. Delta traps caught the fewest moths, and the AlphaScents wing trap caught the most.

Figure 1 illustrates how trap glue fouling by insect scales increases as the number of moths caught increases. This fouling of the glue combined with the space occupied by the male captures reduces the ability of the trap to capture additional moths. If we plot data from nonsaturating traps on the x-axis and data from saturating traps on the y-axis, if saturation did not occur we would expect a 1:1 correspondence between the moths captured in the two trap types. This did not occur, and the line through the data points reported in figures 2 to 5 represents the best-fit line. For the wing traps, we drew a vertical line for the nonsaturating traps (x-axis) at 50 moths and a horizontal line showing the number of predicted moths in the saturating traps.

In the following regression equations, saturating trap capture is designated as STC, and nonsaturating trap capture is designated as NTC. Initially, we calculated regressions using 50 moths in the nonsaturating trap as an upper limit (truncated dataset), and then calculated a second regression using our entire dataset for each trap type; the regressions using the entire dataset are illustrated.

Trécé wing trap. For the Trécé wing trap, using the truncated dataset, the relationship between the saturating and nonsaturating traps is a power function described by the equation

$$\text{Log}_{10}(\text{STC}+1) = 0.164 + 0.696 \times \text{Log}_{10}(\text{NTC}+1)$$

($r^2 = 0.605$; F = 56.781; df = 1, 38; $P <$ 0.0001). When 50 moths are captured in the nonsaturating trap, the predicted catch in the saturating trap is 21.1, a reduction of 57.9%. The relationship between the saturating and nonsaturating traps for the entire dataset is linear and described by the equation

$$\text{STC} = 4.129 + 0.457 \times \text{NTC}$$

($r^2 = 0.864$; F = 546.007; df = 1, 87; $P <$ 0.0001) (fig. 2). If 50 moths visited the trap, approximately 27 would be captured (46.0% reduction in trap capture). The equation derived from the entire dataset slightly improved the predictive ability of this trap.

Suterra wing trap. For the Suterra wing trap, using the truncated dataset, the relationship between the saturating and nonsaturating traps is described by the power function

$$\text{Log}_{10}(\text{STC}+1) = -0.021 + 0.004 \times \text{Log}_{10}(\text{NTC}+1)$$

($r^2 = 0.935$; F = 674.163; df = 1, 48; $P <$ 0.0001). When 50 moths are captured in the nonsaturating trap, the predicted catch in the saturating trap is 46.8, a reduction of 6.4%, confirming that saturation begins at approximately 50 moths for this trap. The relationship between the

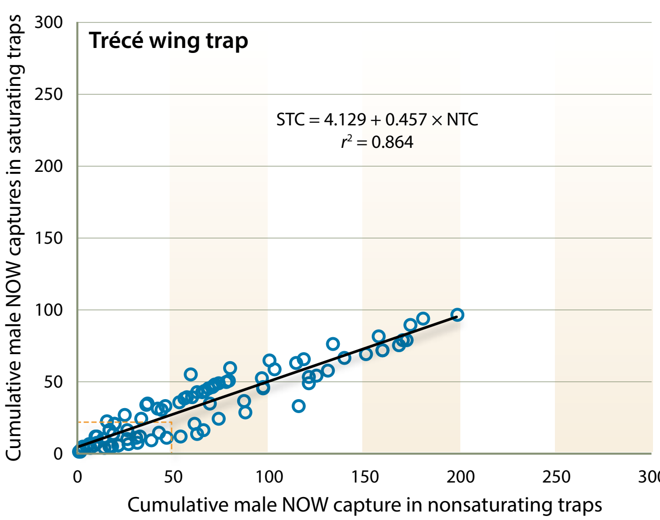


Fig. 2. Trécé wing trap. Plot of mean number of moths captured in saturating and nonsaturating traps ($n = 5$ tests). The relationship is linear and described by Saturating trap count = 4.129 + 0.457 × Nonsaturating trap count, $r^2 = 0.86$. Dashed vertical and horizontal lines are guides to note deviation of saturating trap counts from nonsaturating trap counts.

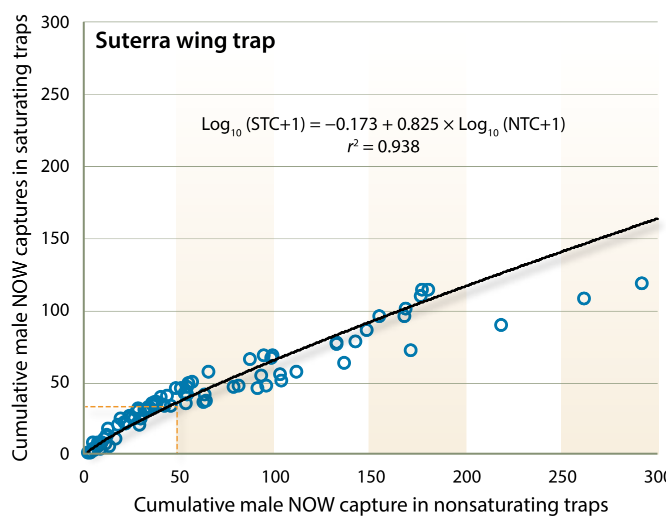


Fig. 3. Suterra wing trap. Plot of mean number of moths captured in saturating and nonsaturating traps ($n = 5$ tests). This is a power relationship described by Log_{10} (Saturating trap count + 1) = 0.173 + 0.825 × Log_{10} (Nonsaturating trap count + 1), $r^2 = 0.94$. Dashed vertical and horizontal lines are guides to note deviation of saturating trap counts from nonsaturating trap counts.

saturating and nonsaturating traps for the entire dataset is also a power function and described by the equation

$$\mathrm{Log}_{10}\,(\mathrm{STC} + 1) = 0.173 + 0.825 \times \mathrm{Log}_{10}\,(\mathrm{NTC} + 1)$$

($r^2 = 0.938$; F = 1,300.17; df = 1, 87; $P < 0.0001$) (fig. 3). If 50 moths visited the trap approximately 37 would be captured (30.0% reduction in trap capture). When the entire dataset is used, the reduced moth capture at high density flattens the curve, resulting in an equation that has greater error at densities of < 50 moths.

AlphaScents wing trap. For the AlphaScents wing trap, using the truncated dataset, the relationship between the saturating and nonsaturating traps is described by the power function

$$\mathrm{Log}_{10}\,(\mathrm{STC} + 1) = -0.228 + 1.108 \times \mathrm{Log}_{10}\,(\mathrm{NTC} + 1)$$

($r^2 = 0.844$; F = 199.81; df = 1, 38; $P < 0.0001$). When 50 moths are captured in the nonsaturating trap, the predicted catch in the saturated trap is 46.1, a reduction of 7.8%. This finding confirms that saturation also begins at 50 moths for this trap. The relationship between the saturating and nonsaturating traps for the entire dataset is also a power function and described by the equation

$$\mathrm{Log}_{10}\,(\mathrm{STC} + 1) = -0.016 + 0.924 \times \mathrm{Log}_{10}\,(\mathrm{NTC} + 1)$$

($r^2 = 0.91$; F = 823.78; df =1, 87; $P < 0.0001$) (fig. 4). If 50 moths visited the trap approximately 32 would be captured (36.0% reduction in trap capture). The reduced moth capture at high density flattens the curve, producing an equation that has greater error at the densities of < 50 moths.

Suterra delta trap. For the Suterra delta trap, using the truncated dataset, the relationship between the saturating and nonsaturating traps is described by the power function

$$\mathrm{Log}_{10}\,(\mathrm{STC} + 1) = -0.106 + 1.100 \times \mathrm{Log}_{10}\,(\mathrm{NTC} + 1)$$

($r^2 = 0.896$; F = 570.200; df = 1, 67; $P < 0.0001$). When 50 moths are captured in the nonsaturating trap, the predicted catch in the saturating trap is 40.0, a reduction of 20.0%. Saturation begins sooner in the delta trap than in the Suterra and AlphaScents wing traps. The relationship between the saturating and nonsaturating traps for the entire dataset is also a power function and described by the equation

$$\mathrm{Log}_{10}\,(\mathrm{STC} + 1) = -0.019 + 0.898 \times \mathrm{Log}_{10}\,(\mathrm{NTC} + 1)$$

($r^2 = 0.905$; F = 823.78; df = 1, 87; $P < 0.0001$) (fig. 5). There was an approximate 50% reduction in trap capture at 50 moths. Once again, the reduction in moth capture at high density flattens the curve, resulting in a greater error at densities < 50 moths than if the truncated dataset is used. The delta trap had a greater error than the Suterra and AlphaScents wing traps.

Saturation at ~ 30 to 50 moths. Figures 6A–D are randomly selected examples of moth capture by trap type, from single field tests conducted during the 3-year period of our study. The points of separation of the saturating and nonsaturating lines are similar in number to departure points on the projection curves (figs. 2–5). Together these figures support our hypothesis that trap saturation began after ~ 30 to 50 moths had been captured.

Trap comparisons. When the nonsaturating sticky traps and water trap were evaluated, there was no difference in overall capture between the water and glue traps ($P > 0.05$; table 1). Among the nonsaturating glue traps, the delta traps caught significantly fewer moths than the wing traps (F = 6.018; df = 4, 439; $P = 0.0001$). When the saturating traps were compared to the water trap and each other, there were significant differences in male recovery, F = 16.329; df = 4, 439; $P < 0.0001$. The water trap caught more moths than did the saturating glue traps ($P < 0.0001$) as expected, and the delta trap caught fewer moths than the wing traps ($P = 0.0001$). Among the wing traps, the Trécé wing trap caught the fewest moths ($P = 0.023$), followed by the Suterra and then the AlphaScents trap. When moth capture was standardized by converting

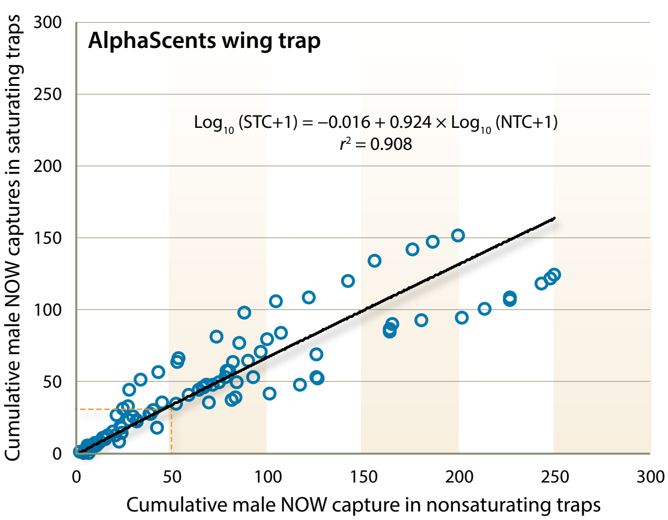


Fig. 4. AlphaScents wing trap. Plot of mean number of moths captured in saturating and nonsaturating traps ($n = 5$ tests). This is a power relationship described by Log_{10} (Saturating trap count + 1) = −0.016 + 0.924 × Log_{10} (Nonsaturating trap count + 1), $r^2 = 0.91$. Dashed vertical and horizontal lines are guides to note deviation of saturating trap counts from nonsaturating trap counts.

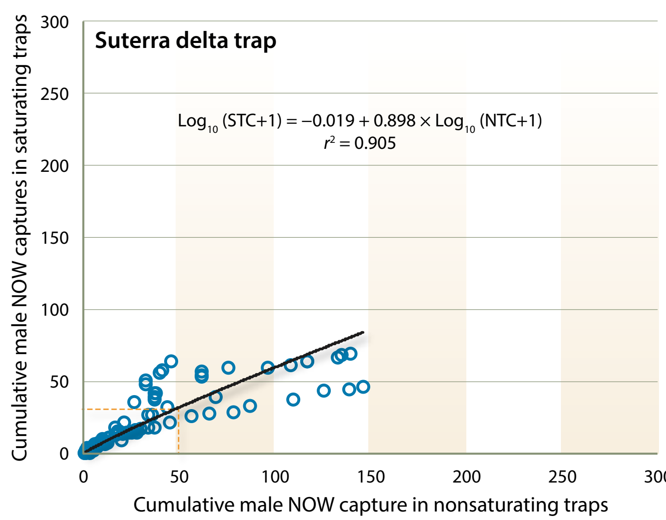
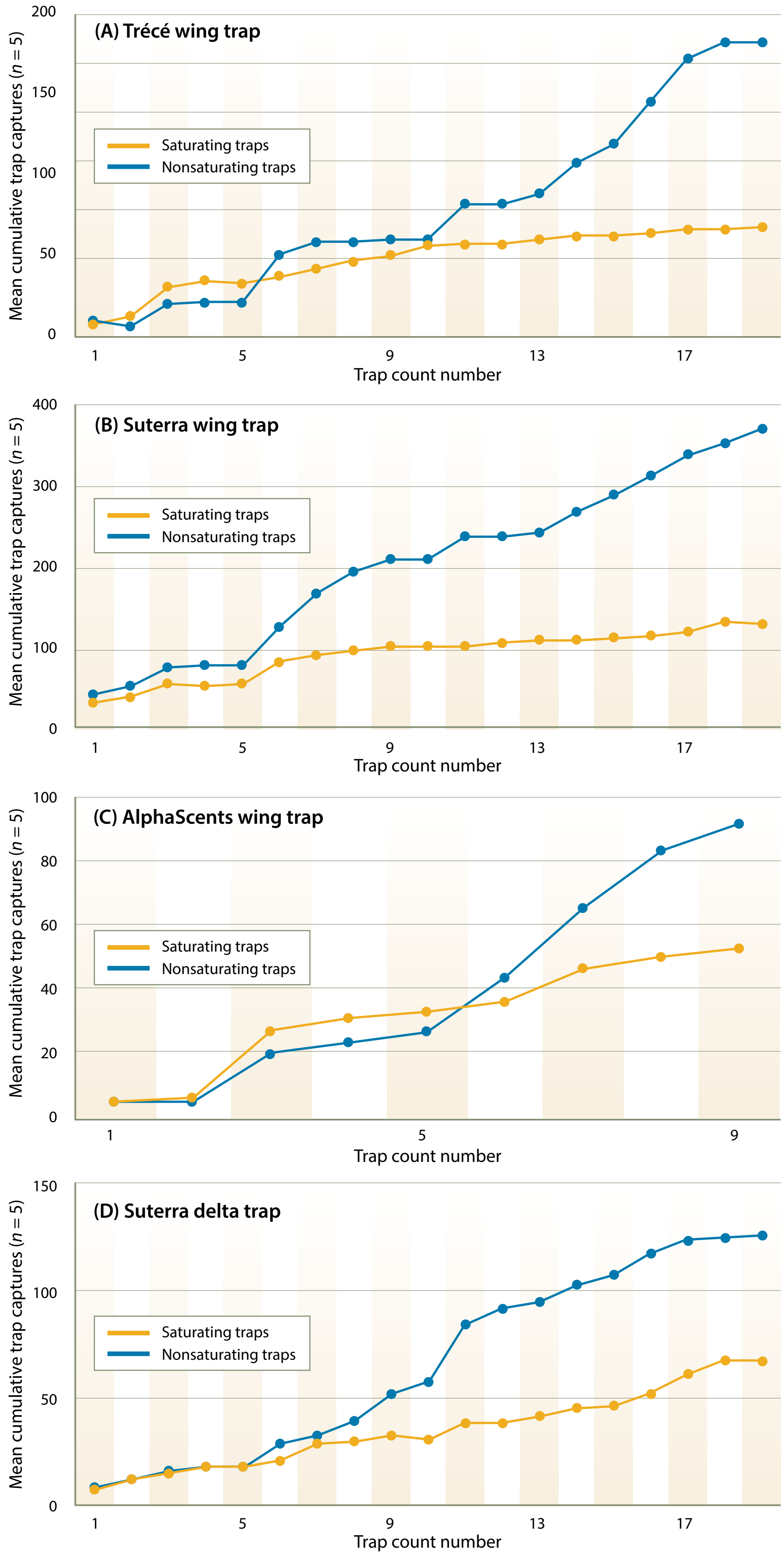


Fig. 5. Suterra delta trap. Plot of mean number of moths captured in saturating and nonsaturating traps ($n = 5$ tests). This is a power relationship described by Log_{10} (Saturating trap count + 1) = −0.019 + 0.898 × Log_{10} (Nonsaturating trap count + 1), $r^2 = 0.91$. Dashed vertical and horizontal lines are guides to note deviation of saturating trap counts from nonsaturating trap counts.

Fig. 6. Representative trap capture data from saturating and nonsaturating sticky trap pairs showing points of separation between saturating traps and nonsaturating traps (5 trap replicates within a single test). (A) Trécé wing trap; (B) Suterra wing trap; (C) AlphaScents wing trap; (D) Suterra delta trap.



the data to the number of moths recovered per square inch of glue, this pattern remained.

Previous studies of saturation

Sanders (1978) noted that some researchers regarded trap saturation as an all-or-nothing situation, where trap capture increases linearly until the traps reach capacity. Brown (1984) shows linear regression equations on his increased trap capture data; however, the data are presented as "relative efficiencies" and related in various ways to the changing day-to-day efficiency of the traps, apparently buffering out the curvilinear nature of trap saturation, which is still hinted at by the graphed data. Others (Houseweart et al. 1981; Riedl 1980; Sanders 1978, 1986) have also shown that trap saturation starts at some trap capture level and then trap capture begins to decline steadily from that point. We have demonstrated that for NOW, trap saturation progresses nonlinearly at densities below 50 moths per trap for all sticky traps tested, and also it progresses in a nonlinear manner above 50 moths per trap with the exception of the Trécé wing trap. Factors such as trap design and trap efficiency, which affect the likelihood of trap entrance, also contribute to the number of moths captured (Elkinton and Childs 1983; Ramaswamy and Cardé 1982; Sanders 1986).

Trap differences

In this study, we examined three wing traps that differed only minutely in dimensions but differed in sticky surface area, color, glue material/compound or a combination of these factors. For example, the Suterra trap, which has a sticky surface area 20% smaller than the other traps tested, has a red top and caught more moths than the Trécé white traps (L. Kuenen and J. Siegel, unpublished).

The two white-topped wing traps had equal sticky surface areas, but the Trécé trap had a conventional (polybutene-based) sticky surface, whereas the AlphaScents trap had a proprietary "magic" sticky surface that caught more males than the Trécé trap. On trap count days, males trapped in the AlphaScents traps appeared to flap their wings less frequently than moths in conventional glue, as they appeared to be closely adhered to these sticky surfaces. Such reduced wing fanning would clearly reduce glue fouling by scales and may explain the higher trap capture rate in the AlphaScents traps.

The delta traps caught disproportionately fewer moths even when their reduced sticky surface area was accounted for (table 1). We suspect that the trap entry behavior in these traps was responsible for the difference. The closed-tunnel delta trap design produces longer and more defined pheromone plumes than a wing trap (Lewis and Macaulay 1976), which likely led to a more straight-in trap entry (but only when the wind was reasonably aligned with the delta traps' open ends) compared to wing trap entries. Wing trap plume structure is more diffuse but can come from 360 degrees. Lateral entries are possible in the wing traps and are often seen (personal observations in field and wind tunnel), whereas entry into the delta traps is limited to the two ends. When these two factors — plume structure and ease of entry access — are combined with the smaller sticky surface of delta traps, they help explain the lower trap catch for NOW.

Dry, nonsticky, traps are potential alternatives to sticky traps (Elkinton and Childs 1983; Knodel and Agnello 1990; Sanders 1986), but these traps can also begin to saturate due to insect escape as the trap fills toward the entry "port" level. In addition, both sticky and dry trap efficiencies may begin to decrease (saturate) due to the odor of the captured males (eastern spruce budworm, Sanders 1978) or the odor of decomposing corpses (gypsy moths, Elkinton and Childs 1983; eastern spruce budworm, Sanders 1986) but odor did not affect the trap capture of codling moth (Riedl 1980). This possible odor effect deserves future study to determine if dry traps are more appropriate for NOW.

Use in the field

In this study some wing traps captured more than 400 moths in a 3-day period, indicating that when populations are high, so many moths visit the trap that a fraction continues to be captured even though the trapping surface has been substantially reduced. In these high trap capture orchards, cooperating growers incorporated our catch information into their decision-making process and applied insecticides when the weekly trap count jumped. The absolute number of moths captured was not as important as the rapid increase in trap capture. In these orchards, our pheromone traps complemented egg traps and were more reliable later in the season when egg trap capture rates dropped because split nuts are both more attractive as oviposition sites than egg traps and vastly outnumber the number of egg traps deployed.

Our analyses validate our hypothetical saturation threshold of 50 moths for the Suterra and AlphaScents wing traps, and our graphs illustrate the process of trap saturation. This information can be used by growers and pest control advisers as they integrate the use of synthetic lures into their current methods of assessing NOW populations (primarily egg counts on egg traps (Rice et al. 1976)) and direct sampling for NOW life stages. Every technique has its own strengths and weaknesses, and the saturation effect above 50 moths per trap can be remedied by changing the trap bottoms more frequently.

The ultimate goal is to use trap monitoring to predict the potential for NOW damage. Trap saturation is one of several factors that can affect the relationship between capture in pheromone traps and subsequent damage to nuts. Standardization of trap type and lure as well as the density of traps affect the validity of trap data and its subsequent use for developing treatment thresholds. Further study on optimal trap density and trap design is needed before pheromone trap data can be used to determine an economic threshold for NOW. CA

L.P.S. Kuenen is Research Entomologist and J.P. Siegel is Research Entomologist at San Joaquin Valley Agricultural Sciences Center, USDA Agricultural Research Service, Parlier, CA.

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Management of blue gum eucalyptus in California requires region-specific consideration

by Kristina M. Wolf *and* Joseph M. DiTomaso

Blue gum eucalyptus (*Eucalyptus globulus*) is a large tree native to Australia that was widely planted throughout California for reforestation, building and timber, but in some areas has spread beyond its planted borders and substantially altered wildlands. Due to its fast growth, large size and reproductive potential, blue gum's impacts on native vegetation, wildlife and ecosystem processes are of concern, particularly in areas with reliable year-round rainfall or fog, where it is most likely to spread. Depending on levels of invasion and rate of spread, blue gum may have negative, positive or neutral impacts on fire regimes, water and nutrient availability, understory vegetation and higher trophic levels. Additional research on the abiotic and biotic impacts of blue gum, quantitative estimates of area covered by blue gum, and weed risk assessments that allow for region-specific climatic information and management goals to be incorporated are needed to guide management of blue gum populations.

For many Californians, eucalypts (*Eucalyptus* spp.) are a valued part of the natural landscape, while for others, they are a nightmare that fueled the disastrous 1991 Oakland hills fire that claimed 25 lives (NPS 2006). Introduced to California from Australia circa 1856 (Esser 1993), *Eucalyptus globulus* Labill. (blue gum eucalyptus, hereafter "blue gum") was the most widely planted species within the genus, and mainly occurs in grasslands and some previously forested areas. About 40,000 acres (> 16,000 hectares) of blue gum were planted in California between 1856 and the 1930s (Butterfield 1935), extending from Humboldt County in the north to San Diego County in the south, with best individual growth and survival occurring in the coastal fog belt in the vicinity of San Francisco (Burns and Honkala 1990). Herbarium collections today show blue gum occurrences in at least 23 counties (UC Regents 2014).

However, blue gum has naturalized (escaped from its original plantings into wild areas) in some parts of California (Esser 1993; Ritter and Yost 2009). And, in some areas, invasive populations — those that have naturalized and cause economic or ecological harm — have so altered landscapes and ecosystem processes that the impacts raise many ecological, social and cultural questions. For example, should blue gum be retained as overwintering habitat for monarch butterflies (*Danaus plexippus* L.), whose populations have dropped by an estimated 90% due to declines in suitable habitat (Griffiths and Villablanca 2013)? Should we perhaps plant even more? Or should these "weeds" (i.e., plants out of place) be removed? While an often contentious subject with proponents on both sides (Jones 2009), it is important to consider the pros and cons when making decisions regarding management of blue gum (LSA Associates 2009).

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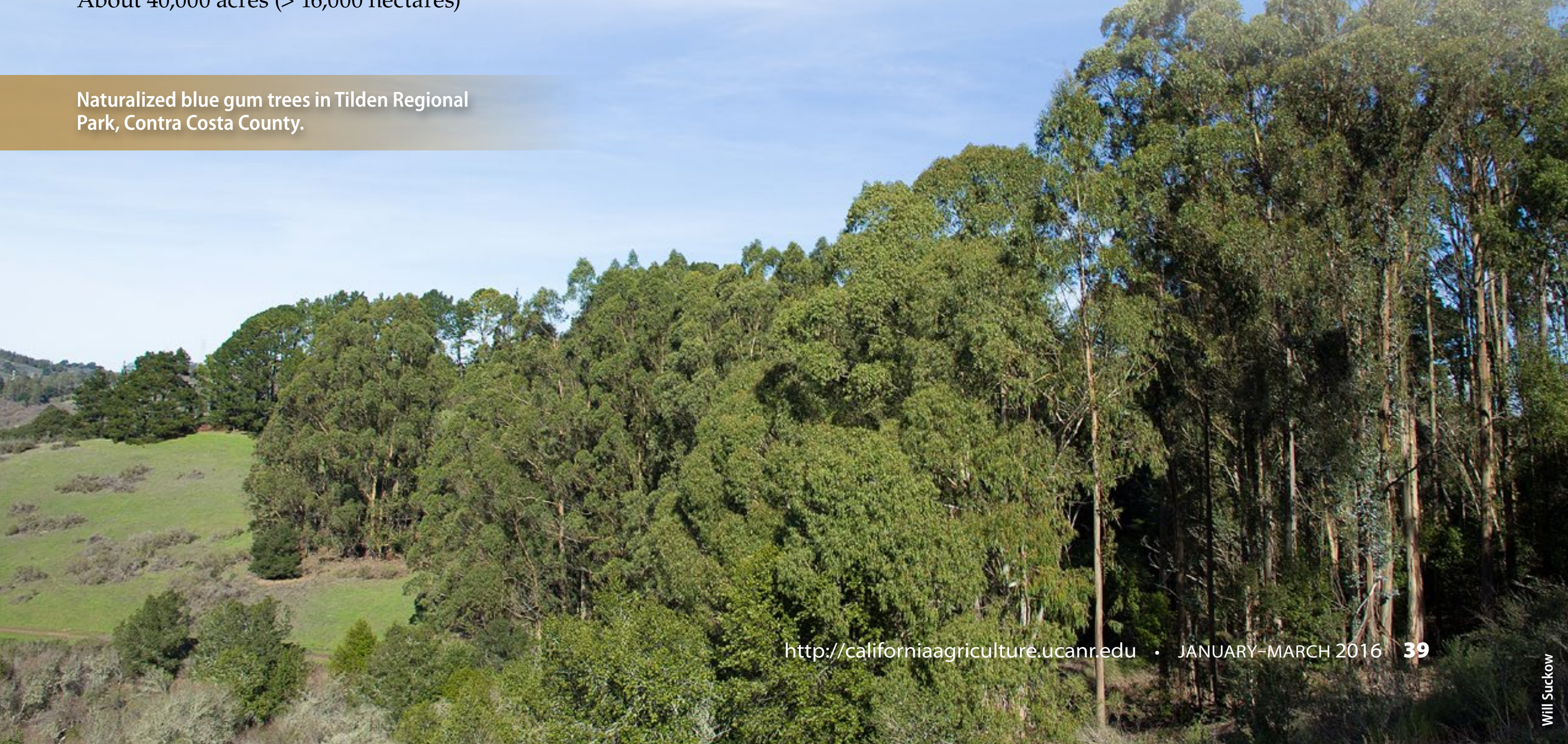

Naturalized blue gum trees in Tilden Regional Park, Contra Costa County.

Will Suckow

Our objectives are to (1) summarize the traits of blue gum that may contribute to invasiveness and identify factors contributing to spread, (2) describe biotic and abiotic impacts of nonnative blue gum in California, (3) describe current trends in the spread, removal and introduction of blue gum in California, and (4) clarify research needs and management implications regarding blue gum presence and invasiveness.

Literature review methods

Because much information regarding the biotic and abiotic impacts of blue gum exists in the non-peer-reviewed literature, including agency reports, blogs and personal observations by land managers, this paper is not a systematic review of the scientific literature. Limiting our search to peer-reviewed scientific literature could result in the omission of critical information on the general status of blue gum and research needs. Rather, we obtained information via scientific database searches (including Web of Science, Google Scholar and AGRICOLA), general Internet searches, and solicitation of information regarding invasions (or lack thereof) and management via emails and phone calls to professionals working in landscapes containing blue gum (including California State Parks, California Invasive Plant Council, California Polytechnic State University San Luis Obispo, UC Berkeley and UC Davis).

Origin and characteristics

Blue gum, a large tree in the Myrtle family (Myrtaceae) that is native to southeastern Australia (UC Regents 2014), is the most extensively planted *Eucalyptus* species in the world (Burns and Honkala 1990). Trees can grow to 180 feet (55 meters [m]) tall with bark that sheds in long strips, leaving smooth surfaces of contrasting colors (Farmer 2013; Skolmen 1983). Mature leaves are a waxy grey-blue-green and sickle shaped, while young leaves are oval shaped and bluish green, with distinctive square stems (Brooker 2000). The species has a wide range of climatic adaptability, with the most successful introductions in mild, temperate climates, or cool, high elevations in tropical areas. Ideal climates for establishment and growth have no severe dry season, mean annual rainfall of 35 inches (90 centimeters) and a minimum temperature above 20°F (–7°C) at all times.

In the United States, blue gum is present in Hawaii (National Tropical Botanical Garden 2015) and California, where it has naturalized (Baldwin 2012). Its fast growth, large size and ability to thrive in California's Mediterranean climate made it an attractive choice for building, furniture, firewood, medicinal uses, cleaning products and, originally, reforestation and afforestation efforts. Many naturalists, scientists and government agencies extoled its merits, recommending the species for large-scale planting, even offering awards for individuals who planted the largest number of trees (Farmer 2013; Santos 1997).

However, after planting millions of trees, lumber production intended for railroad ties was abandoned because blue gum wood often split, twisted and cracked. Further, the wood could not be treated properly for lumber or furniture (Groenendaal 1983). However, this did not prevent ardent supporters from recommending it for other uses, including ornamental plantings, windbreaks, shade, medicinal purposes, firewood and anticipated environmental benefits such as reductions in soil erosion. As a result, blue gum plantations continued to persist in California (Farmer 2013).

Some plantings exhibit invasive characteristics and environmental impacts that contributed to an initial "moderate" invasive status by the California Invasive Plant Council (Cal-IPC), although these have been poorly documented in the scientific literature. Opposing views of blue gum's invasive potential have sparked heated debate in recent decades, and in 2015, its status was reexamined in response to a request from stakeholders for another review. The reassessment of the available ecological evidence resulted in Cal-IPC downgrading blue gum's invasive status to "limited" (Cal-IPC 2015)

According to the Cal-IPC criteria, a limited invasive status is either due to a species that is widespread, but does not cause significant negative impact, *or* a species that is widespread, but causes significant ecological impacts in specific regions or areas of the state, yet minimal or no impact in other areas. Cal-IPC found that blue gum's limited status corresponds to the latter category, where significant negative ecological impacts occur in limited areas along the California coast.

Reproductive traits and dispersal

Reproductive traits. Depending on the region and climatic conditions, certain reproductive traits can be significant contributors to the invasiveness of a plant, such as asexual reproduction and the production of a high number of propagules (Radosevich et al. 2007). Reproductive traits that could contribute to blue gum's ability to spread include yearly seed production (in many areas), seed production for more than 3 months per year (November to April, in California) and a tendency to resprout prolifically after damage (e.g., cutting, fire) (Rejmánek and Richardson 2011).

In California, blue gum produces flowers during the wet season, generally from November to April, and the fruit (a distinctive top-shaped woody capsule, 15 millimeters long and 2 centimeters wide) ripens between October and March. Although many sources indicate prolific seed production at 3- to 5-year intervals, these "heavy seed crops" have not been verified in the scientific literature. The seeds of blue gum are very small, with an average weight of just over 2 milligrams per seed (460 seeds/gram) (Burns and Honkala 1990). However, little is known about what fraction of blue gum seeds are viable.

While blue gum might produce abundant seed, it does not generally find appropriate conditions for germination. As such, it does not often encroach into treeless areas without purposeful cultivation. Germination rates are typically very low under natural conditions, ranging from a high success rate of 1% to the more typical low of 0.1% (Bean and Russo 2014). Seed germination is highest on bare mineral soil (Bean and Russo 1989), particularly under high light conditions, such as after logging or fire (Burns and Honkala 1990).

Germination within dense plantations is even less common (Bean and Russo 1989). Blue gum produces a thick litter layer and allelochemicals (natural substances produced by plants that can suppress growth), which may inhibit not only its own germination, but also that of other plants (Molina et al. 1991; Watson 2000). Despite this, establishment of blue gum in undisturbed forests and scrub *has* been observed repeatedly in coastal areas of

California (Cal-IPC 2015), and young trees can produce seeds within 2 to 5 years of germination, although not in great quantities (Burns and Honkala 1990; Metcalf 1924). Seeds in the soil under natural conditions probably remain viable less than a year (Rejmánek and Richardson 2011).

Vegetative reproduction can also contribute to invasive potential, making control or removal difficult. Blue gum sprouts readily from stumps of all sizes and ages, as well as from the lignotuber (woody swelling of the root crown at or below ground level) and roots. Blue gum lignotubers can survive for many years in the soil after stems die back (Esser 1993; Skolmen 1983). If a tree is cut down, lignotubers become active and each bud may produce many new shoots, commonly known as "sucker growth" or coppice shoots (Bean and Russo 2014; Davidson 1993), which may be even more vigorous and difficult to control than the original growth (Farmer 2013). Resprouting is common after fire or cutting, but is not a primary mode of spread. Although reproduction can also occur when new shoots arise from roots/rhizomes (Esser 1993), this has rarely been noted in the literature, even in repeatedly harvested stands of blue gum (Skolmen 1983).

Dispersal. Most blue gum seeds are not dispersed long distances and are generally distributed by wind and gravity. In one study, the fruit capsules were calculated to disperse only 66 feet (20 m) from a 131-foot (40 m) tree height with winds of 6 miles/hour (10 kilometers/hour) (Burns and Honkala 1990). On occasion, blue gum seeds can be dispersed long distances by water when growing near streams or rivers. The lack of a long-distance dispersal mechanism would account for the relatively slow, if any, rate of spread (Rejmánek and Richardson 2011), although rate of spread across the state has not been rigorously documented in experimental or observational evidence.

Potential impacts of blue gum

Potential risks and impacts can be grouped into two categories — abiotic and biotic — that may work independently or interact to produce blue gum impacts on ecosystem processes.

Abiotic impacts.

Fire regime changes and fire hazards. Blue gum was most frequently planted in grasslands, although some plantings occurred in, or later escaped into, native tree stands (Griffiths and Villablanca 2013). Because of the dramatic shift in plant communities (e.g., from grasslands to tree plantations), it is not unexpected that the historic fire intensity and frequency (i.e., the natural fire regime) were also dramatically altered (Bossard et al. 2000; FEMA 2013; LSA Associates 2009; Russell and McBride 2002). As a consequence, vegetation management plans in blue gum–dominated communities should consider historic fire regimes, goals for fire risk management and potential hazards to adjacent businesses and homes.

In Australia, Dickinson and Kirkpatrick (1985) found that live blue gum leaves were resistant to combustion, but dead leaves were highly flammable and the most energy-rich component of the tree. Juvenile and adult leaves of blue gum had intermediate flammability in comparison to other species evaluated. They concluded that living blue gum trees and fuel components within litter had the greatest tendency to propagate fires relative to species from wet sclerophyll (high moisture, low light, dense eucalyptus forests) and gully habitats or *Casuarina* dry forest communities.

Species that produce oily resins, such as blue gum, are far more ignitable than those that do not. On a scale of 1 to 10 for ignition potential, with 1 representing species most easy to ignite and 10 most difficult, blue gum scored 1 to 2 (very high ignition potential). For comparison, oak/bay woodland received a score of 6 to 8, redwood 8, scrub vegetation 4 to 8, and annual grassland vegetation 1 to 3 (LSA Associates 2009).

In the 2013 environmental impact statement for the FEMA Hazardous Fire Reduction grant in the East Bay hills of California, blue gum flame lengths (used as a proxy for flammability) were estimated at 6 to 21 feet (1.8 to 6.4 m); in comparison, flame length for oak/bay woodland was 1 to 34 feet (0.3 to 10.4 m), Monterey pine (*Pinus radiata* D. Don) 1 to 6 feet (0.6 to 4.9 m), coastal redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) 7 to 31 feet (2.1 to 9.4 m), northern coastal scrub 14 to 32 feet (4.3 to 9.8 m) and nonnative grasslands 2 to 10 feet (0.6 to 3.0 m). Flame lengths in young blue gum plantations range from 7 to 31 feet (2.1 to 9.4 m), depending on fuel volumes, stand structure, treatment history and slope (FEMA 2013).

In addition to being generally more ignitable and highly flammable in comparison with some species, blue gum accumulates more fuel for wildfires than grasslands and native tree species. Blue gum can accumulate 68,000 pounds per acre (lb/ac) of dropped limbs, bark and leaves (76,000 kilograms/hectare [kg/ha]), compared to 42,000 lb/ac (47,000 kg/ha) for California bay (*Umbellularia californica* (Hook. and Arn.) Nutt.) and 26,000 lb/ac

Blue gum eucalyptus trees can produce a large quantity of seeds in woody capsules, but germination rates are generally low.

Blue gum bark sheds in long strips that accumulate high fuel loads, contribute to high flammability and propagate fire.

(29,000 kg/ha) for coast live oak (*Quercus agrifolia* Née; also called "California live oak") (NPS 2006). As a result, blue gum stands are particularly susceptible to fire during the dry season in California. The flammability of blue gum leaf litter may be exacerbated by rare deep freezes, which cause die-back of the trees and contribute to fuel loads (Rejmánek and Richardson 2011).

Blue gum also has a tendency to propagate fires via open tree crowns and long swaying branches that encourage maximum updraft (Esser 1993; LSA Associates 2009). Multiple stems originating from a single trunk create a basket structure that catches dead materials, which burn easily and intensely (Burns and Honkala 1990; Landrum 2013). When ignited, leaves and bark of blue gum are lofted into the air, sending firebrands (fragments of burning wood) "kilometers" from the fire front to ignite new spot fires. Because leaves and bark firebrands are large, embers are generally still burning when they land, which can rapidly increase fire spread (Rejmánek and Richardson 2011).

Overall, blue gum has a high fire hazard rating in comparison with native grass and tree species, which have low to moderate ratings (LSA Associates 2009). In summary, blue gum is highly ignitable and flammable, accumulates high fuel loads, propagates fire quickly, and can increase rate of fire spread to adjacent areas. In fact, the National Park Service (2006) estimated that 70% of the energy released through combustion of vegetation was due to blue gum in the deadly 1991 Oakland hills fire.

Potential allelopathic effects. Del Moral and Muller (1969) reported that natural unconcentrated fog drip from blue gum inhibited growth of annual grass seedlings, and unconcentrated stemflow from blue gum inhibited germination of some herbs. The volume of water channeled down the stem is about eight times more than that of falling rain, such that soil at the base of trunks could receive large quantities of water containing potentially allelopathic compounds. The associated suppression of plant growth at the base of trees is more likely due to allelopathy than water shortage given the amount of water delivered to the base of trees via stemflow. Thick litter layers may also interact with allelopathic chemicals to further suppress germination (May and Ash 1990).

Watson (2000) found that the germination of two California natives, yarrow (*Achillea millefolium* L., a perennial forb) and blue wild rye (*Elymus glaucus* Buckley, a perennial grass), was significantly reduced following water extract treatments with blue gum compared with an untreated control or water extract treatments from coast live oak (*Q. agrifolia* Née). Germination of yarrow and blue wild rye was 89% and 33% lower, respectively, in blue gum treatments relative to the untreated control, and 92% and 33% lower, respectively, in blue gum treatments relative to the coast live oak treatment. In addition, average time for yarrow germination was delayed by 4.5 days in the oak treatment and 6.2 days in the blue gum treatment. In contrast, germination and root length in the native perennial grass California brome (*Bromus carinatus* Hook. & Arn.) were not affected by blue gum treatment relative to the untreated control. Given these mixed results, Watson (2000) concluded that restoration projects designed to replace blue gum with native plants should at least consider the potential effects of persistent allelochemicals in the soil.

Concentrated extracts or leachates may not have the same effect as unconcentrated water flowing off plant materials, however. For example, a separate experiment with soil from under blue gum showed no significant inhibition of germination for any of the tested species relative to the control (although germination was reduced, albeit not significantly). The author hypothesized that winter rains may have leached allelochemicals deeper into the soil profile and suggested that in future studies samples be taken in multiple seasons (Watson 2000).

A similar hypothesis was proposed by Lange and Reynolds (1981), who indicated that allelopathy may be exacerbated in areas with low rainfall because allelopathic chemicals would concentrate in the upper soil surface rather than leach through the soil profile with heavy rainfall. Molina et al. (1991) also found allelopathic properties of blue gum in the Mediterranean (Spain). Additional research is needed to clarify the naturally occurring allelopathic potential of blue gum.

Changes to hydrology. Despite its ability to withstand prolonged dry summers (Florence 1996; Pryor 1976), blue gum is not particularly drought tolerant (USDA PLANTS 2015), and is only able to survive by tapping into deep water reservoirs and transpiring freely (DiTomaso and Healy 2007), which can alter water availability to depths of 45 feet (14 m) and distances of 100 feet (30 m) from the trunk. While blue gum does not economize in the use of water, it has deep and extensive root systems and can extract water from the soil at higher soil moisture tensions than most mesophytic (terrestrial plants that are not adapted to very wet or very dry conditions) plants (Florence 1996; Pryor 1976). This allows blue gum to compete strongly with other vegetation for water (HEAR 2007).

Compared with conifers, blue gum uses less water per unit of biomass, but blue gum's high biomass production, even under low rainfall conditions, may reduce nearby streamflows more rapidly than other slower-growing tree species (Davidson 1993). Thus, in dry areas the benefits of lower water use per unit biomass of blue gum may be outweighed by impacts on soil moisture content due to high total water consumption (Rejmánek and Richardson 2011).

In support of this finding, Williams (2002) noted that streambeds became eroded and dewatered near blue gum plantations. Potential allelopathic effects on the germination and cover of understory species in combination with the high water use capacity of blue gum may also result in a greater risk of erosion in hillsides covered by blue gum (HEAR 2007). Davidson (1993) also implicated non-wettability of soils (water repellence and hydrophobicity due to blue gum oils deposited on soil particles) as a contributing factor to low understory cover, which may alter erosion rates. However, research that more clearly elucidates the impacts of blue gum plantations on hydrology and erosive processes is necessary.

Changes to nutrient cycles and light availability. Leaves and branches of blue gum have been noted to decompose very slowly (DiTomaso and Healy 2007), which can alter nutrient dynamics and germination, emergence and growth of seedlings. Consistent with this, Aggangan et al. (1999) reported a reduction in nitrogen mineralization rates in soil below blue gum litter. However, in a riparian area, Lacan et al. (2010) found no difference in litter breakdown between blue gum and native vegetation.

Blue gum shading reduces light availability and might create conditions that inhibit the growth of seedlings and most other plants in the understory (DiTomaso and Healy 2007). While native trees growing in crowded conditions also shade understory plants, the combination of a thick litter layer and potential allelopathy may exacerbate the effects of blue gum shading (Bossard et al. 2000). Moreover, blue gum alters light availability in otherwise open grasslands and within invaded native forests, which could interfere with the germination and growth of some plant species (Peter Warner, Botanical and Ecological Consulting, personal observation as listed on original Cal-IPC assessment form, 2004).

In general, while some evidence is observational, or additional research is needed to clarify the abiotic environmental impacts, blue gum appears to alter historical abiotic conditions and ecosystem processes not only where it is planted, but also in natural areas to which it has spread. In some cases, these impacts are severe, hazardous or ecologically irreversible (Cal-IPC 2003).

Biotic impacts.

Changes to plant community dynamics. While blue gum stands are often monocultures (in terms of tree cover), this is not necessarily due to competitive exclusion of native trees — it could be that they were purposefully planted at high densities. Some sources indicate that blue gum outcompetes native vegetation as it naturalizes in mesic areas (see review by Griffiths and Villablanca 2013), but experiments have not been conducted to confirm this. However, in both planted and invaded areas, blue gum stands can form near monotypic canopy covers, particularly in coastal ecosystems (Cal-IPC 2015). Ritter and Yost (2012) sampled 52 unique stands of blue gum in coastal regions of California. Of these stands, 21 had not naturalized at all, 11 had extensive naturalization, and the remainder were somewhere in between. Sampled areas where naturalization was documented included riparian corridors and sites along the coast from Monterey Bay north, where summer fog provides sufficient water in an otherwise long, dry summer season.

Blue gum plantings in grasslands represent a dramatic change to community composition from open grassland to forest. In grasslands supporting livestock and native ungulates, blue gum has a considerable competitive advantage as compared with many other tree species, as its juvenile foliage is seldom browsed by cattle or sheep (its unpalatability may be related to its moderate toxicity rating [CPCS 2009]). This condition not only contributed to its popularity for planting in open grasslands years ago, but also permits newly recruited seedlings outside planted stands to survive in the presence of grazing animals (Burns and Honkala 1990).

Reports on the impact of blue gum stands on plant diversity are variable, with some observations noting the presence of several native species supported in the understory (LSA Associates 2009). While native plants may be found beneath blue gum trees at some locations in California (CAPRC 2011), evidence regarding the relative amounts of native cover and trends in native vegetation is minimal. However, most reports indicate that vegetation is "sparse" under blue gum stands (Bean and Russo 2014; DiTomaso and Healy 2007; Esser 1993), which may be due to the combined effects of competition for water, tree density and shading, allelopathy, non-wettability of soils and a thick inhibitory litter layer. For example, at Mount Davidson in San Francisco, only 36% of the blue gum understory is native, with 29 of 50 species recorded as nonnative (SFRP 2006). Even other rapidly growing nonnative trees may have difficulty persisting in blue gum plantations: Metcalf (1924) reported that Lombardy poplar (*Populus nigra L.*) planted among blue gum only persisted for 15 to 20 years before it was overtopped by blue gum.

Without removal of blue gum, plant community composition is not likely to support historic community composition. Even with removal, treatments must be repeated multiple times due to resprouting or new flushes of blue gum seedlings (LSA Associates 2009), resulting in continued disturbance and potentially detrimental impacts on community composition for several years. For example, Davidson (1993) points out that following blue gum removal, soils may be persistently non-wettable due to the oils deposited by blue gum. This could further affect remaining vegetation through detrimental impacts on water infiltration and runoff. Therefore, the potentially negative impacts of blue gum removal and long-term management should be carefully considered when developing a management plan.

Impacts on higher trophic levels. Impacts of blue gum on terrestrial vertebrates are mixed, with some reports indicating significantly lower species diversity of arthropods, small mammals and birds in blue gum stands (Cal-IPC 2015; Rejmánek and Richardson 2011). For example, in Angel Island State Park (San Francisco Bay), 41 species of birds were observed in native vegetation, but only 30 species in blue gum stands. However, approximately three times more California slender salamanders (*Batrachoseps attenuatus*) were found in blue gum vegetation than in native forests (Rejmánek and Richardson 2011). Sax (2002) found that species richness was nearly identical for invertebrates, amphibians and birds in native forests and blue gum plantations, although rodents had significantly more species in native forests; moreover, species composition was different between the two forest types for all groups. Many birds, mammals and invertebrates utilize blue gum plantations at some point, although there is no consistent trend across all species for relative use of blue gum as compared with native forests (LSA Associates 2009; Rejmánek and Richardson 2011). Macroinvertebrate species diversity did not differ between blue gum and native vegetation in riparian areas in California (Lacan et al. 2010).

Oils and resins in leaves may increase flammability of blue gum and contribute to non-wettability of soils.


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Impacts on avifauna are mixed, although there is little experimental or observational information available. At an Elkhorn Slough Coastal Training Program *Eucalyptus* workshop, Suddjian (2004) stated that habitat quality of blue gum depends on many factors, including tree size, stand density, canopy closure, understory development and type of surrounding habitat. Compared with dense, homogeneous blue gum stands of only one age, blue gum stands of low to moderate density with mixed age structure in proximity to native woodland habitat and water provide the highest habitat value. In the Monterey Bay region, over 90 birds make regular use of blue gum habitat, although many species that nest in blue gum appear to do so at lower densities than in native habitats. More specifically, the decay-resistant wood of blue gum offers limited opportunities for nesting to woodpeckers and birds that excavate their own holes. Birds that glean insects from foliage are also present at notably lower densities in blue gum stands (Suddjian 2004).

Some bird species nest preferentially in blue gum compared with native trees, possibly due to blue gum's tall growth patterns and large limbs. In Santa Cruz County, great blue herons, great egrets and double-crested cormorants only nest in blue gum, while 85% of red-shouldered and red-tailed hawk nests were found in blue gum (Suddjian 2004). However, Suddjian also noted that while some birds use blue gum stands more than native stands, blue gum plantations do not provide equivalent habitat compared to native oak woodland and deciduous riparian vegetation for many other species. Some avifauna (e.g., cavity-nesting, foliage-gleaning and ground-nesting birds) are comparatively less abundant in blue gum stands than in native habitats, and many breeding species historically represented in the oak and riparian habitats that blue gum replaced make little or no use of blue gum in the Monterey Bay region.

In Santa Clara County, Rottenborn (2000) found that red-shouldered hawks nesting in blue gum and other nonnative tree species had higher fitness due to nonnatives' better stability and cover than that of native trees. In contrast, Williams (2002) stated that while native birds do use blue gum groves, species diversity drops by at least 70%. Moreover, 50% of the Anna's hummingbird nests in blue gum were shaken out by the wind, while only 10% of nests were destroyed by wind in native trees. The presence of nonnative blue gum may also alter migratory bird patterns, as rare wintering species are attracted to the blue gum food sources (Suddjian 2004). To our knowledge, no studies have been conducted to determine whether this had a positive or negative impact on rare bird populations.

Suddjian (2004) reported that when birds feed among flowers of blue gum, the feathers on their faces become covered with black pitch-like residue (often incorrectly called "gum") from flower nectar, resulting in feather loss and plugging of nostrils or bills that theoretically may prevent breathing or feeding. Articles published in the Point Reyes Bird Observatory newsletter (Stallcup 1997) and Audubon magazine (Williams 2002) also implicated blue gum in mortality of North American bird species feeding amid blue gum flowers. However, Suddjian's (2004) observations revealed little evidence of deaths among birds due to plugged beaks or nostrils. Nevertheless, Williams (2002) noted experienced bird watchers had reported finding hundreds of moribund warblers with blue gum nectar covering their faces, as well as Townsend's warblers, yellow-rumped warblers, ruby-crowned kinglets, Anna's and Allen's hummingbirds, and Bullock's orioles. Suddjian (2004) suggested that more research is needed in this area due to ambiguities in observations and a lack of rigorously documented evidence of deaths due to blue gum flower nectar.

Impacts on arthropods are also mixed: Fork (2004) showed that abundance of Diptera (flies) was higher in blue gum plantations as compared with oak woodlands, but that Coleoptera (beetles) abundance was higher in oak woodlands than in blue gum groves. Overall, order richness, total abundance and diversity of arthropods were not significantly different between oak woodland and blue gum habitats (i.e., they were either equally rare in both habitats, or equally abundant in both habitats [Fork 2004; Sax 2002]).

Blue gum is a major source of nectar and pollen for honeybees, as well as an important overwintering site for monarch butterflies (Rejmánek and Richardson 2011). Monarch butterflies may utilize nonnative habitat preferentially over native habitats (Meade 1999; Oberhauser et al. 2001; Pleasants and Oberhauser 2012); however, historical records suggest that monarch butterflies clustered on native trees prior to the introduction of blue gum (Riley and Bush 1882; Shepardson 1914). Moreover, an observational study in mixed stands (native trees mixed with blue gum) showed that monarch butterflies did not consistently cluster preferentially on blue gum, and at times, preferred native trees in some seasons and locations. For example, during mid-season overwintering (~ December 31 in California) when habitat conditions are generally the least favorable for monarch butterflies, they are likely to express a preference for the most favorable microclimate. It was during this sensitive time that monarchs clustered disproportionately on native trees. Planting of additional native conifers, rather than removal of blue gum (which could reduce total habitat), may provide additional beneficial microhabitat conditions for monarch butterflies (Griffiths and Villablanca 2013).

Overall, blue gum impacts on plant and animal abundance and diversity are mixed, and target species should be managed accordingly, depending on the potential positive or negative impacts that blue gum presence or removal may have on their populations and behaviors.

Blue gum spread and removal

Blue gum is no longer widely sold or planted in California, and only one California nursery was identified that reportedly sells seeds (Dave's Garden 2014). A Cal-HIP PlantRight survey of California nurseries indicated that few nurseries continue to sell blue gum (< 1%). Thus, retailers, growers and landscaping professionals have largely phased blue gum out of California's garden center supply chain, and replaced the species with noninvasive alternatives (Cal-HIP 2011).

CalWeedMapper (2014) allows landowners and managers to report on the status (spreading; spreading or decreasing with management; eradicated) and occurrence of blue gum in the state, and these are reported at a resolution of USGS 7.5-minute quadrangles, or approximately 8-mile × 6-mile areas. This may not account for duplicate reports or naturally decreasing populations. At the time of this review, of the approximately 250 reported occurrences, about 100 were spreading (all of which occurred along the coast and coastal ranges). Of these, eight were documented as spreading with management, 18 were decreasing with management, 52 required verification of occurrence, and 30 required verification of the species identification. Including those requiring occurrence or species verification, approximately 150 did not indicate a trend in spread.

While total cover may be increasing, decreasing or remaining stable at different sites, it is possible there may be no overall change in cover statewide (Cal-IPC 2015) even without management.

Climate change may also influence blue gum cover. In California, climate-matching models estimate that blue gum already exists in the regions with the most suitable climate (Calflora 2014). CalWeedMapper (2014) climate-matching reports predict a considerable increase in the suitable range for blue glum along the northern coast of California by 2050. However, the climate-matching program does not have the capability to predict acres of potential invasion. In addition, climate-matching, in itself, does not mean that blue gum will occupy all these suitable climatic areas, as other plant characteristics, including viable seed, germination rates, seedling competition and survival all play a role in its potential spread.

In most cases, establishment of new populations in California wildlands is dependent on proximity to previously planted or otherwise established, seed-producing stands. Ritter and Yost (2012) noted that blue gum of the same genotype can be invasive in some areas, while rarely reproducing in others. Thus, invasiveness does not appear to be related to genotypic variability, but rather environmental conditions, particularly reliable access to water. In the Central Valley, where blue gums were cultivated as a source of fuel, timber and windbreaks, they do not receive enough moisture to propagate from seed (HEAR 2007) and, as such, spread into wildlands is generally rare. Under ideal conditions where moisture is not limited, once a tree matures it can produce a large number of progeny in a few years, doubling stand area within 10 years, or spreading at a rate of 10 to 20 feet (3 to 6 m) in diameter per year (Boyd 1997; Esser 1993).

Coastal California — and in particular, Sonoma, Monterey and Humboldt counties — is most at risk for the continued spread of blue gum. Observations by land managers and agency personnel (Tim Hyland and Vince Cicero, California State Parks, personal communication, 2014) indicate blue gum has invaded disturbed coastal prairie and willow riparian corridors at Natural Bridges State Park in Santa Cruz, and Montaña de Oro State Park in Los Osos, respectively. Aerial photos from Humboldt State University (Bicknell 1990) from 1949 (original plantation established in 1907 to 1908) showed seven species of eucalypts covering 119 acres (48 ha). By 1989, the grove had expanded to 181 acres (73 ha), of which blue gum covered 108 acres (43 ha). Overall, the area covered by all *Eucalyptus* species increased by 52% between 1908 and 1989. Van Dyke (2004) reported a 50% to 400% increase in blue gum stand size between 1930 and 2001 across six sites in coastal California, although one location experienced an initial increase in the first 25 years and remained stable thereafter.

Research needs

Much research has been conducted on the commercial production of blue gum in California and international production for timber and other consumptive purposes (e.g., see Standiford and Ledig 1983). However, to guide future management, observational and experimental research is still needed on some of the basic impacts of blue gum (or other *Eucalyptus* species) on abiotic conditions or other trophic levels.

While Davidson (1993) pointed out that controlled, replicated and realistic experiments testing allelopathy are few and conclusions remain tenuous, he also indicated that trees should probably not be grown in low rainfall areas (15.75 inches/year, or < 400 millimeters) due to the risk for adverse effects from allelopathy and competition for water, especially when soils are coarse textured and nutrient poor. On the other hand, plantings in areas with higher rainfall or reliable summer fog are also more likely to exhibit invasive tendencies than those in drier areas and are therefore a concern, even if allelopathy is not an issue in these regions. Continued research under local conditions is needed to test the impact of natural levels of potentially allelopathic compounds in the soil and litter layer on growth of other nonnative naturalized and native plants at different moisture levels.

Suddjian (2004) indicated that research is needed to evaluate the impacts on birds that feed among blue gum flowers. At the very least, a systematic observational study should be conducted to investigate the occurrence and extent of nectar on feathers and beaks and determine if this has a detrimental effect on fitness and survival. Further information is also needed regarding the avian use of blue gum forests relative to native vegetation. As many bird populations and behaviors are at risk, the implications of blue gum spread or removal in areas of concern would be particularly helpful to land managers.

Some reproductive characteristics of blue gum are unclear as well. The number of seeds produced per square meter each year has not been clearly assessed. How quickly and under what circumstances vegetative reproduction occurs in California across a variety of different habitats needs to be clarified. Further research should elucidate whether or not blue gum reliably produces seed crops each year, and under what climatic conditions seeds are produced, so that regional weed risk assessments are more accurate in predicting potential invasiveness.

In addition, it is not known exactly where and *to what extent* populations of blue gum are naturally decreasing, increasing or remaining stable. While CalWeedMapper (2014) provides reports of blue gum occurrence, data regarding the status of these populations (rate of spread or decrease, if populations are naturally spreading or decreasing) is insufficient to determine the actual rate of spread or area covered locally, regionally or statewide.

While blue gum is a nonnative plant that in some cases can be particularly invasive or hazardous, eradication of blue gum populations is not always appropriate.

Finally, while weed risk assessments have been conducted on blue gum for the state of California, these assessments are not regional or context specific, do not account for the great variety of ecoregions within the state, and do not incorporate management goals, safety considerations or species-specific concerns or benefits. Local climate is particularly influential in determining whether or not blue gum is likely to spread, or will be difficult to either eradicate or maintain. Thus, assessments that allow for area-specific climatic information would be useful in guiding management efforts by state parks, conservation-based institutions and city planning organizations.

Management implications

Management of blue gum must be site and context specific and goal oriented, requiring sufficient time be spent on clarifying the desired outcomes of vegetation management, compiling information regarding climate and native plant and animal communities, and considering social factors. For example, while blue gum is a nonnative plant that in some cases can be particularly invasive or hazardous, eradication of blue gum populations is not always appropriate. Where current plantings may be desirable for alternative monarch butterfly habitat, for instance, land managers should carefully consider potential outcomes on monarch populations. However, caution should be simultaneously exercised, because monarch butterflies overwinter in coastal regions (Marriot 1997) where blue gum is more likely to spread naturally and become invasive (Ritter and Yost 2012). In many areas, blue gum is considered an aesthetically desirable landscape component, and these cultural considerations should be accounted for when determining best methods for ensuring community safety (e.g., risks associated with blue gum include fire hazards and falling limbs). CA

K.M. Wolf is Graduate Student Researcher and J.M. DiTomaso is UC ANR Cooperative Extension Specialist and Professor in the Department of Plant Sciences at UC Davis.

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University *of* California
Agriculture and Natural Resources

California Agriculture
1301 S. 46th Street
Building 478, MC 3580
Richmond, CA 94804
calag@ucanr.edu
Phone: (510) 665-2163
Fax: (510) 665-3427

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UC ANR

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Time: All day
Location: Embassy Suites Monterey Bay, Seaside
Sponsor: UC ANR Cooperative Extension
Contact: Jennifer Heguy 209-525-6800 or jmheguy@ucanr.edu

Suzanne Paisley

Quad County Walnut Institute

http://ucanr.edu/?calitem=311974

Date: March 15, 2016
Time: 8:00 a.m. to 12:00 p.m.
Location: San Joaquin County Fairgrounds, 1658 S. Airport Way, Stockton, CA
Contact: Joe Grant 209-953-6100 or jagrant@ucanr.edu
Sponsor: UC ANR Cooperative Extension San Joaquin County

Ray Lucas

Conference on Soilborne Plant Pathogens and 48th Annual California Nematology Workshop

http://ucanr.edu/sites/CA_Nematology/?calitem=229181&g=38195

Dates: March 22–24, 2016
Time: 8:00 a.m. to 5:00 p.m.
Location: Kearney Agricultural Research and Extension Center (KARE), Parlier, CA
Sponsor: KARE, UC Riverside and California Nematology Workgroup
Contact: Andreas Westphal 559-646-6555 or andreas.westphal@ucr.edu