JANUARY–MARCH 2017 • VOLUME 71 NUMBER 1

California Agriculture

Drones

Also:
Breeding citrus
Irrigation and bees
The threats to California's palms

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

About *California Agriculture*

University *of* California
Agriculture and Natural Resources

California Agriculture is a quarterly, peer-reviewed journal reporting research and reviews, published by University of California Agriculture and Natural Resources (ANR). The first issue appeared in 1946, making *California Agriculture* one of the oldest, continuously published, land-grant university research journals in the country. There are about 10,000 print subscribers.

Mission and audience. *California Agriculture* publishes refereed original research in a form accessible to a well-educated audience. In the last readership survey, 33% worked in agriculture, 31% were university faculty or research scientists, and 19% worked in government agencies or were elected office holders.

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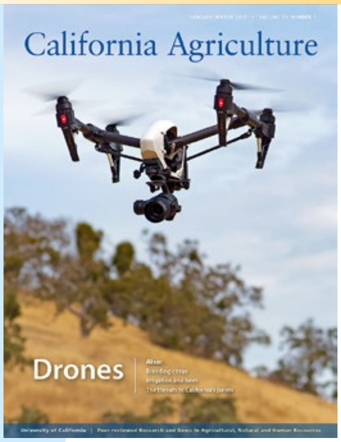

COVER: Drone-mounted cameras and sensors promise more and better data to guide the management of working landscapes and natural areas. Here, a DJI Inspire 1 drone flies over the UC Berkeley Blue Oak Ranch Reserve in Santa Clara County during a training for managers from across the UC natural reserve system. *Photo by Evett Kilmartin.*

Drones

News and opinion

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Drones in California research and extension

Maggi Kelly, Professor and UC Cooperative Extension Specialist, UC Berkeley, and Director, Statewide IGIS Program

For more than 150 years, people have been taking aerial photos of the Earth. In the early days, cameras loaded with panchromatic film were mounted on kites, balloons and the occasional unfortunate pigeon. Today we have over 100 operational earth observation satellites in orbit owned by individual countries and private companies. These satellites collect digital imagery from a broad range of the electromagnetic spectrum beyond visible light, and at spatial resolutions from 1 kilometer down to 1 meter. This global image archive has provided a 40-year record of how our crops, cities and natural landscapes change and function in response to seasons, management and disturbances.

Maggi Kelly

While this source of digital earth observation has been incredibly useful, satellite imagery presents certain challenges. The pixel size of typical satellite imagery can be too large for fine-scale ecological or agricultural research. The timing of satellite overflights does not always synchronize with research or management needs, and the cost of proprietary imagery can be prohibitive.

UAS, or unmanned aerial systems, commonly referred to as *drones*, can address these spatial, temporal and cost-related challenges.

We have heard about drones as nuisances: the 2015 "drunk droning" case at the White House, or hobbyists interfering with firefighting aircraft, etc. However, drones have also been labeled as democratizers of scientific data collection because they allow for timely, responsive, highly detailed and relatively cheap imagery collection.

Both of these views of drones are true.

First, the good news: drones are revolutionizing the way we collect data about agricultural and natural resources, and the University of California is poised to be a leader in this emerging field.

For scientific research, we typically use small rotorcraft that can cover 50 to 200 acres per 15- to 25-minute flight. Cameras mounted on these drones range from true-color digital cameras to multispectral cameras that are ideal for mapping vegetation. Drones can also carry cameras sensitive to thermal radiation, and LIDAR sensors. From sets of overlapping drone images, we can create high-resolution digital elevation models (DEMs), 3-D models of structures or vegetation, and high-resolution digital image mosaics.

The applications for drones in California are broad and far-reaching. Drone imagery has been used to map invasive weeds in agricultural fields, measure critical aspects of ecosystem function such as vegetation dynamics, water status and plant productivity, and to monitor animal population ecology and biodiversity inventories. Meanwhile, DEMs have been used to evaluate canopy structure and micro-topography important to soil moisture, and drone-created 3-D models are being used to map campus infrastructure and individual trees with detail not seen before.

While revolutionary, drones also come with challenges.

Drone flight in commercial airspace is highly regulated for researchers, while hobbyists fly with abandon to collect personal imagery (witness the profusion of "drone selfies" on YouTube). Flying drones for work, business purposes, or for compensation or hire means that certain steps must be taken *before* flying. These are detailed in the accompanying article by Sean Hogan et al. (page 6) that addresses drone registration and a remote pilot certification.

A California framework for drone science and outreach

There are numerous examples of drone data supporting science and outreach across UC. These are largely individual projects that are not connected. Now more than ever, we need a collective effort to support *drones at scale* throughout UC and California. This vision builds on the broad base of applications already evident in the UC system, and creates a framework for science, education and entrepreneurship around practical large-scale drone implementations. To build this, we need to (1) utilize UC's broad technical expertise in open data repositories, big data workflows and data synthesis, (2) expand on the ability of UC to be a partner and incubator to local businesses, (3) develop more application-specific use cases from our network of living laboratories — the UC Natural Reserve System and the UC ANR Research and Extension Center System — and (4) leverage UC ANR's long experience in community-engaged science and outreach.

Drones represent an important strategic opportunity for UC and for California. By supporting this technology, the sky is the limit! CA

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Unmanned aerial systems for agriculture and natural resources

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Brandon Stark, Director of the Center of Excellence on Unmanned Aircraft System Safety, UC Merced and UC Office of the President

YangQuan Chen, Director, Mechatronics, Embedded Systems and Automation (MESA) Lab, UC Merced

Small unmanned aerial systems (UAS), also known as drones or unmanned aerial vehicles, have a rapidly growing role in research and practice in agriculture and natural resources. Here, we present the parameters and key limitations of the technology, summarize current regulations and cover examples of University of California research enabled by UAS technology.

Motorized UAS were introduced as a potential remote sensing tool for scientific research in the late 1970s. However, due to a variety of limitations (the weight and limited functionality of available sensors and cameras, the lack of GPS-guided autopilots and so on) these platforms had few practical applications (Przybilla and Wester-Ebbinghaus 1979; Wester-Ebbinghaus 1980; cited by Colomina and Molina 2014).

For years, UAS technology was led by military needs and applications. The relatively few applications in research and agriculture included deployments in Japan for crop dusting and in Australia for meteorological studies (Colomina and Molina 2014).

In the past decade, several factors have greatly increased the utility and ease of use of UAS, while prices have fallen. Consumer demand drove the hobby craft industry to make major improvements in UAS vehicles. Integrating improved battery technology, miniature inertia measurement units (IMU, initially developed for smartphones), GPS and customizable apps for smartphones and tablets has delivered improved flight longevity, reliability, ease of use and the ability to better utilize cameras and other sensors needed for applications in agriculture and natural resources (see below, Types of UAS). Innovations in sensor technology now include dozens of models of lightweight visible-spectrum and multispectrum cameras capable of capturing reliable, scientifically valid data from UAS platforms (see UAS sensors) (Whitehead and Hugenholtz 2014). Meanwhile, the Federal Aviation Administration (FAA) has helped facilitate increased UAS use, with rule changes adopted in August 2016 that lowered what have previously been significant regulatory obstacles to the legal use of UAS for research and commercial purposes (see Regulations sidebar).

UC faculty throughout California are using UAS in a wide range of agricultural and environmental research projects — from grazed rangelands to field crops and orchards, forests, lakes and even the ice sheets of Greenland

The Inspire 1 drone, made by DJI, flies with an RGB camera over the UC Berkeley Blue Oak Ranch Reserve in Santa Clara County.

Will Suckow

Andreas Anderson, an instructor with the Center for Information Technology Research in the Interest of Society at UC Merced, checks the control systems for a drone-mounted multispectral camera before a research flight in Merced County for a study on water stress in almond trees.

(see below, Research case studies). UAS also have become a part of the curriculum across the UC system, and are increasingly used by campus staff in departments from facilities to athletics to marketing (see UAS at UC sidebar).

UAS are already in wide use in agriculture, and the sector is projected to continue to account for a large share — 19% in the near term, per a recent FAA report (FAA 2016a) — of the commercial UAS market in the United States. The use of UAS for research, particularly remote sensing and mapping, is soaring: A search in Scopus (2016) finds 3,079 articles focused on UAS or UAV applications in 2015, compared with 769 in 2005. Across all commercial uses, the FAA estimates 2016 sales of commercial UAS (including those used for research purposes) at 600,000 units and expects that figure to balloon to 2.5 million units annually as soon as 2017 (FAA 2016a).

Regulations

The U.S. Federal Aviation Administration (FAA) provides guidance and regulation for U.S. airspace. The agency has adopted different rules for recreational and nonrecreational uses of UAS.

The recreational use of UAS is regulated by Title 14, Part 101 of the Code of Federal Regulations commonly known as the "model aircraft" regulations. These regulations apply only if the operator is not compensated in any way for the UAS operation, and if the flight is not incidental to a business purpose regardless of compensation (so, for instance, farming-related uses of UAS do not count as recreational, even if the UAS is operated by the grower or a farm employee). Recreational UAS operators are not required to have a license, and must comply only with basic safety rules such as:

- Fly at or below 400 feet
- Keep your UAS within sight
- Never fly near other aircraft, especially near airports
- Never fly over groups of people
- Never fly over stadiums or sports events
- Never fly near emergency response efforts such as fires
- Never fly under the influence
- Be aware of airspace requirements (FAA 2016b)

Nonrecreational use — defined as deployment of a UAS for any type of "work, business purposes, or for compensation or hire" (FAA 2016c) — falls under a different set of rules, those for "small unmanned aircraft" of up to 55 pounds: Title 14, Part 107 of the Code of Federal Regulations. These rules were updated in several important ways in August 2016.

Previously, the only legal way to fly a UAS for nonrecreational use was with a FAA Certificate of Authorization (COA) for each aircraft issued under Section 333 of the FAA Modernization and Reform Act of 2012 (FAA 2016d). Obtaining a COA was difficult (often requiring the operator to hold a pilot's license for manned aircraft) and time-consuming, requiring abundant documentation followed by FAA processing times of several months. Once a COA was granted, the pilot was typically required to file a notice to airmen (NOTAM) with the FAA prior to every flight; many businesses and institutions were hesitant to authorize flights due to concerns of liability, given the absence of standardized safety guidelines.

The new rules eliminate the need for a manned pilot's license, replacing it with a requirement that nonrecreational operators hold a newly created type of license specifically for UAS operation. This license is obtained after passing an "Unmanned Aircraft – General" aeronautical knowledge test at an FAA-approved knowledge testing center (the test fee is $150). The FAA estimates that the average applicant will spend 20 hours for self-study in preparation for the two-hour exam, and anticipates that 90% of applicants will pass the exam on the first try. By comparison, obtaining a manned pilot's license costs thousands of dollars for instruction, in-flight-training and exam fees. In addition, the new rules create a simple online registration process for commercial and research UAS ($5 per UAS) (FAA 2016e).

Records must still be kept for each flight in case this information is requested by the FAA. Fortunately, this reporting process has been significantly streamlined for UC-affiliated researchers, who must submit flight information to the UC Center of Excellence for Unmanned Aircraft Systems Safety, to both satisfy FAA recordkeeping requirements and for the UC to track its UAS operations (ehs.ucop.edu/drones).

The full list of rules governing UAS flight for research and commercial purposes is provided on the FAA website.

Despite the growing ubiquity of UAS, a variety of practical and scientific challenges remain to using the technology effectively.

Collecting and processing data that is useful for management decisions requires a disparate range of skills and knowledge — understanding the relevant regulations, determining what sensing technology and UAS to use for the problem at hand, developing a data collection plan, safely piloting the UAS, managing the large data sets generated by the sensors, selecting and then using the appropriate image-processing and mapping software, and interpreting the data.

Will Suckow

Author Sean Hogan discusses drone technology with a group of managers from the University of California Natural Reserve System during a field day in October at the UC Berkeley Blue Oak Ranch Reserve, Santa Clara County.

In addition, as highlighted in the research cases presented below, much science remains to be done to develop reliable methods for interpreting and processing the data gathered by UAS sensors, so that a user can know with confidence that the changes or patterns detected by a UAS camera reflect reality.

The UC Agriculture and Natural Resources (ANR) Informatics and GIS (IGIS) program has recently incorporated drone services into the portfolio of support that it offers to UC ANR and its affiliated UC Agricultural Experiment Station faculty. You can find out more about these services and UC affiliates can submit service requests via the IGIS website, igis.ucanr.edu. Working closely with UC Office of the President, Center of Excellence on Unmanned Aircraft System Safety (UCOP 2016), IGIS has also developed a workshop curriculum around UAS technology, regulations and data processing, which is open to members of the UC system as well as the public. Please check the IGIS website to learn about upcoming training events around the state in 2017, including a three day "DroneCamp" that will intensively cover drone technology, regulations and data processing.

UAS at UC

UAS are becoming part of the standard curriculum across the UC system, helping to prepare students to plug into a sector that is expected to generate thousands of new jobs in the coming years (more than 12,000 by 2017 in California alone, per a 2013 study (AUVSI 2013)). Here are several examples:

- UC Berkeley: Electrical Engineering and Computer Science 98/198, Unmanned Aerial Vehicles Flight Control and Assembly
- UC Davis: Aerospace Science and Engineering 10, Drones and Quadcopters; Geography 298, Environmental Monitoring and Research with Small UAS
- UC Irvine: Engineering 7, Introduction to Engineering
- UCLA: Architecture and Urban Design students fly drones to collect images that are used to create 3-D visualizations of projects
- UC Merced: Mechanical Engineering 190, Unmanned Aerial Systems
- UC San Diego: Course credit for competing in the American Institute of Aeronautics and Astronautics (AIAA) Design, Build, Fly competition
- UC Agriculture and Natural Resources: The IGIS program provides workshops on UAS technology and regulations across California in collaboration with the UC Berkeley Geospatial Innovation Facility that are UC oriented but also open to the public (igis.ucanr.edu/IGISTraining)

Campus staff, too, are using UAS in a wide range of applications — from monitoring construction projects and inspecting buildings to shooting video for marketing and sports programs.

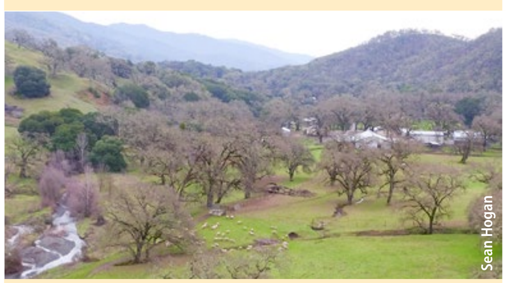
Changes in August 2016 to the federal regulations governing UAS operation (see Regulations sidebar) make it far easier to legally operate a UAS for nonrecreational purposes. Based on anecdotal information tracked by the UC Center of Excellence on Unmanned Aircraft System Safety, UAS use has grown dramatically across multiple UC campuses in the few months since the adoption of the new rules.

Unmanned aerial systems and the sensors they carry

Types of UAS

Fixed-wing	Rotor
Advantages: A fixed-wing aircraft generates lift as it moves through the air, meaning that the propeller doesn't have to do all the work of keeping it aloft. Thus, fixed-wing UAS typically have larger payload capacity, higher top speed, longer flight times and longer range compared to rotor systems with similar battery capacity. For these reasons, fixed-wing systems are particularly useful for collecting data over a large area.	**Advantages:** Rotorcraft are highly maneuverable, with the ability to hover, rotate and capture images at almost any angle. Manual takeoff, flying and landing are easy to learn, and some models have built-in "sense-and-avoid" technology. There are many low-cost models on the market, along with more costly units with larger payload capacity and/or flight time.
Disadvantages: Compared to rotor UAS, fixed-wing systems are less maneuverable, require more open space for landing and more skill to pilot, and tend to be several times more expensive than similar-grade rotor systems.	**Disadvantages:** Shorter range and flight time compared to similar-grade fixed-wing UAS are the main drawbacks to rotorcraft.

UAS sensors

	RGB digital camera	Thermal camera
Description	Captures visible-spectrum (red, green and blue, or RGB) photographs or video between 390 and 700 nanometers in wavelength	Captures thermal images or video in the long-infrared range, roughly 7,000 to 12,000 nanometers
Typical applications	Creation of true color orthomosaics (composite images of a large area), topographic modeling using photogrammetry, and 3-D visualization	Monitoring relative surface temperatures to provide information on, for instance, water features, wildlife, evapotranspiration and soil moisture content.
Image example		
Other considerations	Photogrammetry can be used to model elevation at a spatial resolution similar to that of the processed image pixel resolution. Visible-spectrum photogrammetry is not effective for mapping below-canopy vegetation and ground elevation.	Generally not suitable for photogrammetry due to lack of sharp contrast

The type of sensor that a UAS can carry is determined by the UAS's designed payload capacity. Any type of instrument may be used as long as it's light enough for a given UAS platform. Most conventional UAS have a maximum payload between 300 and 1,500 grams (0.66 to 3.3 pounds). There is a tradeoff between instrument payload and fight time, especially for rotorcraft.

Autopilots

Will Suckow

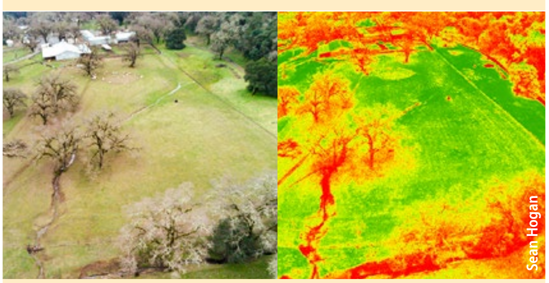
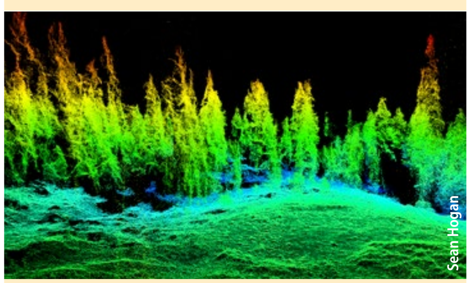
Controller for a DJI Inspire 1 drone. The attached tablet shows an inflight view and other information.

Both fixed-wing and rotor UAS can be flown manually, but nonrecreational users rely primarily on what are known as "integrated flight systems" that enable safe precision flying, improved stability control and the ability to precisely replicate data-collection flights. These systems typically include GPS-enabled autopilots, inertial measurement units (IMU) to monitor the aircraft's orientation, battery-monitor systems to ensure that the UAS reserves enough charge to fly "home" and systems that attempt to land in the event of an emergency.

Flights are generally planned and executed through a tablet or phone application. GPS waypoints along flight paths can function as trigger points that activate or deactivate an on-board sensor. The autopilot systems are flexible and can be altered in midflight, for instance, by activating preset flight commands such as loiter (stay in one place), circle, land or return to home.

Controller for a 3D Robotics Solo drone. The attached Android tablet displays a programmed flight plan.

Integrated flight systems also can be programmed to assist during manually controlled flights by limiting flight speeds and flight distances. Recent advances in these systems include object avoidance systems and built-in maps of restricted airspace. Continuing improvements in the technical integration of flight controllers, UAS firmware (the control-system code in the UAS itself) and sensor software should result in safer and more reliable UAS that can further reduce safety issues and data-collection problems arising from user error.

Multispectral camera	LIDAR (light detection and ranging)	Hyperspectral sensor
Captures images from wavelengths in the visible spectrum (RGB) and from one or more segments of the infrared spectrum (>700 nanometers)	Uses laser pulses to map surface elevations at a very high level of accuracy.	Collects imagery for a large number (typically more than 50) of narrow spectral bands over a continuous range, generally somewhere between 300 and 2,200 nanometers
Agricultural and natural vegetation monitoring, by sensing reflected light wavelengths associated with plant vigor	3-D modeling of surfaces, most commonly for forestry and structural surveying	Precision agricultural monitoring requiring the detection of spectral signatures associated with specific plant traits
 Sean Hogan	 Sean Hogan	Hyperspectral data are often displayed as a cuboid made up of many layers, each representing a single spectral band.  NASA
Same photogrammetry possibilities and limitations as RBG sensors	Collects elevation data but not spectral data. Generally most suitable for mapping surfaces below a vegetation canopy, because lasers have better penetration than spectral instruments. LIDAR sensors tend to be heavier than others.	Higher cost than the other sensor types profiled here. Generates large amounts of data and requires more sophisticated methods of data analysis. Not appropriate for photogrammetric estimates of surface elevation.

Most sensors can transmit a live video stream to a base station receiver for the pilot or pilot's observer to monitor. This functionality drives much of the public's interest in UAS and has been useful for search and rescue and police applications. For most scientific purposes, however, the data are recorded for later visualization and analysis.

Research case studies

Crop agriculture

Seeing signs of stress in orchards

When a tree is stressed — whether due to pest infestation, nutrient deficiency or insufficient water — its leaves change. These changes may be detectable in the visible light spectrum — a shift in a leaf's shade of green. They can also be "seen" in other bands of the electromagnetic spectrum — for example, a change in the texture of a leaf's waxy coating may alter how infrared light is reflected.

Robert Starnes, a senior superintendent of agriculture in the UC Davis Department of Entomology, flies a drone over a field of strawberries in San Luis Obispo County to study how reflectance data may help detect outbreaks of spider mite, a common pest.

Different types of stress generate unique electromagnetic "signatures." If these signatures can be reliably correlated with specific causes, a UAS could be deployed to quickly scan a large orchard for signs of trouble, enabling early detection and treatment of pest infestations and other problems.

Christian Nansen, a professor of entomology and nematology at UC Davis, leads a team working to refine this monitoring technique. They use hyperspectral camera, which generates a very high-resolution signature across a wide range of wavelengths. One of the challenges is that the electromagnetic signatures often contain high degrees of data "noise" — due to shadows, dust on leaves, differences between leaves and other factors — making it difficult to discern a clear signal associated with the stress that the tree is experiencing. To address this problem, Nansen's team is refining a combination of advanced calibration, correction and data filtering techniques. As entomologists, they are also working to understand in fine detail the interactions between different pest species and tree stress, and how those affect the electromagnetic signature of a tree's leaves (Christian Nansen, UC Davis, chrnansen.wix.com/nansen2).

Detecting deficiencies in almonds and onions

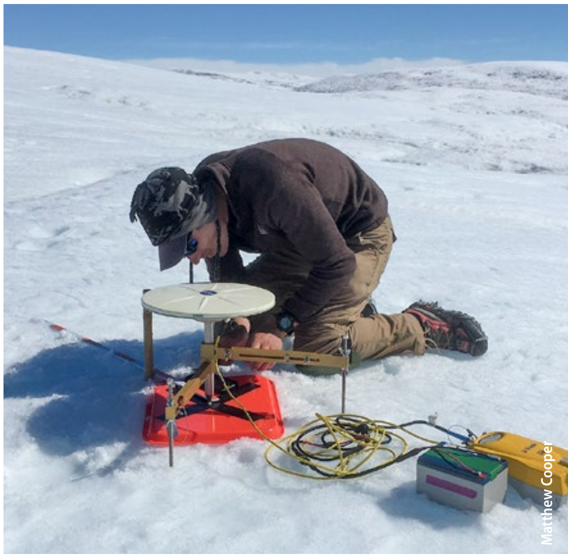
Rapid detection of water stress can help farmers optimize irrigation water applications and improve crop yields. In an orchard, precise assessments of water stress typically require manual measurements at individual trees using a device known as a pressure bomb that measures water tension in individual leaves. Tiebiao Zhao, a graduate student at UC Merced's Mechatronics, Embedded Systems and Automation (MESA) Laboratory, is collaborating with UC ANR Merced County pomology farm advisor David Doll with the goal of developing UAS-based tools to assess water stress across a large almond orchard at a high level of accuracy. Water stress can be detected by relatively low-cost multispectral cameras due to changes

Visible-spectrum, *left*, and near-infrared (NIR), *right*, images of an almond orchard in Merced County. UC researchers are developing methods to use NIR imagery to quickly and accurately detect areas of water stress.

Andreas Anderson, an instructor with the Center for Information Technology Research in the Interest of Society at UC Merced, carefully lands a drone following a research flight in an almond orchard in Merced County.

in how the canopy reflects near-infrared light. This project is building a database of canopy spectral signatures and water-stress measurements with the objective of developing indices that can be used to reliably translate UAS imagery into useful water-stress information.

In a related experiment, Zhao is working with Dong Wang of the USDA Agriculture Research Service (ARS) San Joaquin Valley Agricultural Sciences Center to detect the effects of varying irrigation levels and biomass soil amendments on crop development and yield in onions. As in Zhao's almond experiment, the researchers are comparing spectral signatures gathered by low-cost UAS-mounted multispectral cameras with ground-truth data to better understand the relationship between the two (Tiebiao Zhao, UC Merced, mechatronics.ucmerced.edu).



Above left, a 3D Robotics Solo drone carrying a Canon point-and-shoot camera flies a mapping mission over a lake in western Greenland the day after a jökulhlaup (a glacial outburst flood). *Above right*, precise ground control point surveys are needed to accurately geolocate imagery collected with a drone and produce high quality orthomosaics. The photo shows Rutgers University doctoral student Sasha Leidman conducting a differential GPS survey of a ground control marker on the Greenland ice sheet.

Natural resources

Mapping the Greenland ice sheet

The Greenland ice sheet covers 656,000 square miles and holds roughly 2.3 trillion acre-feet of water — the sea level equivalent of 24 feet. As the climate warms, ice sheet melt accelerates; therefore, understanding the processes involved is important. This knowledge can help to refine predictions about the ice sheet's future and its contribution to global sea level rise.

A team of researchers led by UCLA professor of geography Laurence Smith is using UAS-based imaging technologies to map and monitor meltwater generation, transport and export. The group's UAS carry multiband visible and near-infrared digital cameras that capture sub-meter resolution data, from which the researchers create multiple orthomosaics of the ice surface and perimeter over time. They are using the data to analyze a number of different cryohydrologic processes and features, including mapping rivers on the ice surface from their origins to their termination at moulins — vertical conduits that connect the ice surface with en- and sub-glacial drainage networks — and meltwater outflow to the ocean. The team is also generating digital elevation models of the ice surface

To monitor meltwater fluxes across the surface of the Greenland ice sheet, researchers generated orthomosaics like this one from digital imagery shot by a Canon point-and-shoot camera mounted on a 3D Robotics Solo drone.

A drone-mounted thermal sensor can monitor temperature in a water body or watercourse at various depths and times of day, helping to identify habitat zones for aquatic species.

to extract hydrologic features, micro topography and drainage divides. In addition, they are working towards mapping ice surface impurities and albedo (the measure of the fraction of the sun's energy reflected by the ice surface) at high resolution using multi-band visible and near-infrared images. Accurate and high resolution albedo data is important for modeling surface meltwater runoff on the ice sheet. Contributors to the project include UCLA doctoral students Matthew Cooper and Lincoln Pitcher, UCLA postdoctoral researcher Kang Yang, Rutgers University doctoral student Sasha Leidman and Aberystwyth University (UK) doctoral student Johnny Ryan (see also Ryan et al. 2015, Ryan et al. 2016, Ryan in preparation).

3-D thermal mapping of water bodies

Researchers at UC Berkeley, including professor Sally Thompson's group in the Department of Civil and Environmental Engineering, are using UAS as a novel thermal sensing platform. Working with robotics experts at the University of Nebraska, Lincoln, the team tested an unmanned system capable of lowering a temperature sensor into a water body to record temperature measurements throughout the column of water — which is useful in, for instance, identifying habitat zones for aquatic species. Initial field experiments that compared in situ temperature measurements with those made from the UAS platform indicate that UAS may support improved high-resolution 3-D thermal mapping of water bodies in a manageable timeframe (i.e., 2 hours) sufficient to resolve diurnal variations (Chung et. al. 2015). More recent work has confirmed the viability of mapping thermal refugia for cold-water fish species from this platform.

Mapping tree architecture

UC Berkeley professor Todd Dawson (departments of Integrative Biology and Environmental Science, Policy and Management) and his redwood science group are using UAS-mounted multispectral cameras to create 3-D maps of giant sequoias — trunks, branches and foliage — at higher resolution and with far less labor than was previously possible.

The maps were developed through a partnership with Parrot Inc. The company builds the cameras and UAS used in the research, and partners to manage the software, Pix4D, that was specially designed to analyze the images.

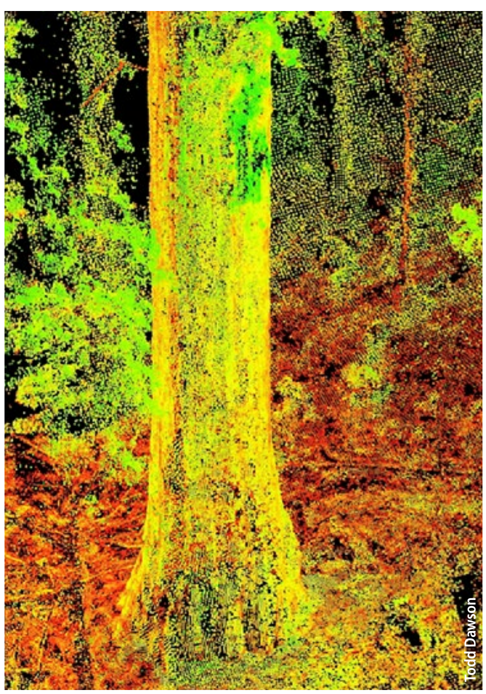
The maps have a range of potential applications, from climate science to forest ecology. Knowing the total leaf area and aboveground biomass of a tree and the structure of its canopy, for instance, allows researchers to calculate daily carbon dioxide and water uptake — important variables in assessing the interactions between trees, soil and atmosphere as the climate changes. A high-resolution map also yields information about a tree's influences on its immediate environment — how much leaf litter falls to the forest floor, for instance, and to what degree shade from the canopy influences the microclimate around the tree, or the habitats in it.

Another application: A precise map of a tree also provides a good estimate of how much carbon is stored in it as woody biomass. This information, in turn, can be combined with information from coarser (and faster) methods of forest mapping, such as LIDAR, to improve estimates of the carbon stored in a large forested area. Mapping every tree in a forest at a high level of detail isn't practical. But such maps of a sample of trees can provide good correlations between carbon mass and a variable like tree height, which LIDAR can measure to a high degree of accuracy — yielding a better estimate of the total amount of carbon in the forest.

Detecting bark beetle infestations

The forests of California are threatened by drought and disturbance. Bark beetle (subfamily *Scolytidae*) infestations in the state's coniferous forests are a particularly large concern considering recent drought conditions, the threat of potential forest fires, and climate change. There is a need for both better methods for early detection of beetle infestation, and for visualization tools to help make the case for investments in suppression (Six et al. 2014).

High spatial resolution multispectral UAS imagery and 3-D data products have proven to be effective for monitoring spectral and structural dynamics of



Precise 3-D maps of tress, like these of giant sequoias generated from multispectral images using Parrot Inc.'s Pix4D software, can yield information on water and carbon dioxide, forest microclimates and forest carbon stocks.

Aerial photograph of trees in El Dorado County killed by bark beetles, taken from a DJI Inspire 1 drone with a DJI Zenmuse X5 camera.

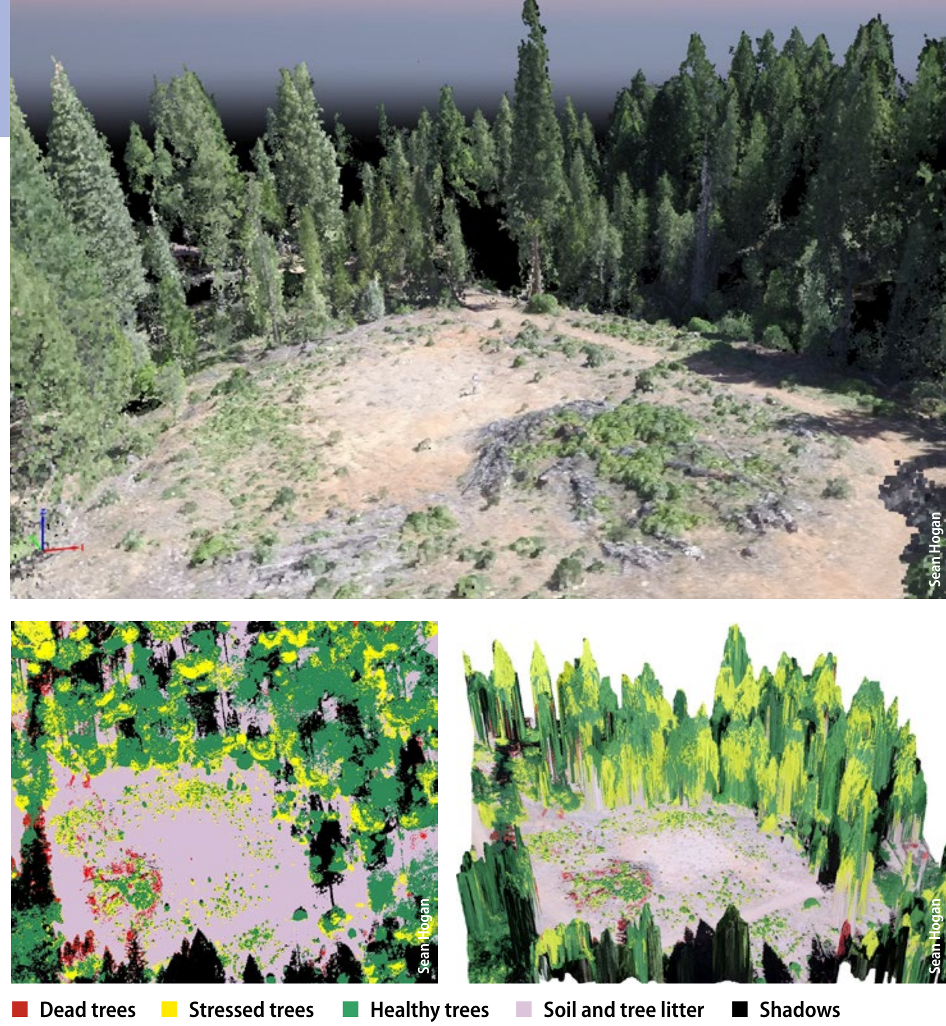
beetle-infested conifers across a variety of ecosystems (Minařík and Langhammer 2016). Sean Hogan of the UC ANR IGIS program is testing the use of machine learning algorithms applied to UAS imagery to efficiently classify early beetle infestations of ponderosa pines (*Pinus ponderosa*) in California's Sierra Nevada foothills. Preliminary results indicate that even imagery from a basic GoPro RGB camera can be used to accurately detect bark beetle–induced stress in these trees.

Rangeland ecology

Over 34.1 million of California's 101 million acres (33.7%) are classified as grazed rangelands (CDF 2008). The cattle industry contributes significantly to the state's economy, and the proper management of these rangelands is important for many reasons, including forage production, preservation of natural habitats and the maintenance of downstream water quality.

High-quality, timely information on rangeland conditions can guide management decisions, such as when, where and how intensively to graze livestock. UAS enable high-resolution aerial imagery of rangelands to be collected at much greater speed and lower cost than was previously possible. Translating that imagery into information that is useful to range managers, however, remains a challenge. A UC ANR team — including GIS and remote sensing academic coordinator Sean Hogan, UC Davis–based rangeland and restoration specialists Leslie Roche, Elise Gornish and Kenneth Tate, assistant specialist Danny Eastburn and Yolo County livestock and natural resources advisor Morgan Doran — is working on this problem from several angles at research sites in Napa County's Vaca Mountains, and in Lassen and Modoc counties.

- Low-cost multispectral UAS cameras may be able to collect images that would enable the differentiation of common rangeland weeds — such as barbed goatgrass (*Aegilops triuncialis*) and yellow star thistle (*Centaurea solstitialis*) — from forage grasses. Efficient classification and mapping of such invasive weeds could help inform scientific research on weed treatments; it could also guide range management, for instance by allowing rapid assessment of forage availability, which could in turn guide stocking rates. In this study, data from manual ground surveys of weed and forage cover

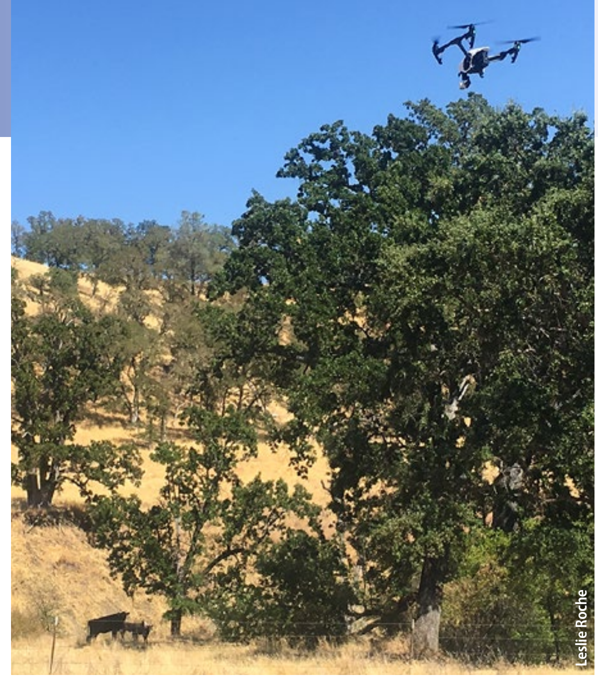


Photographic imagery gathered by a drone can be processed to enable early identification of trees stressed by bark beetles across a large area. The image at top shows a colorized point cloud, a 3-D representation of a stand of trees. The lower two images depict the same stand of trees (from slightly different angles); an analysis based on differences in foliage color is used to classify trees as healthy, stressed or dead. Images were collected with a GoPro 12-megapixel camera.

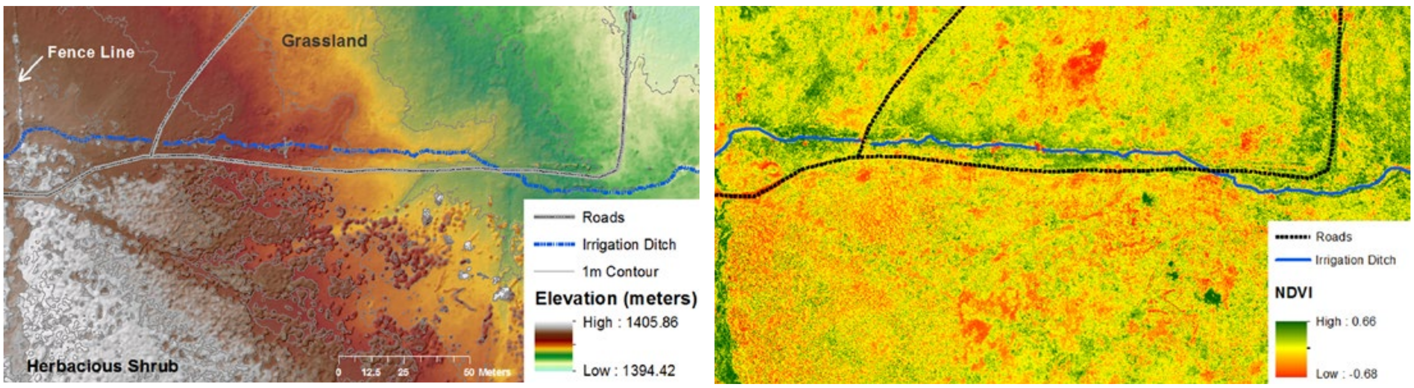
Author Sean Hogan flying a DJI Inspire 1 drone for a rangeland ecology study at Gamble Ranch in Napa County.

are being used to “teach” image-analysis software — via what’s known as a machine-learning algorithm — how the spectral signatures of goatgrass and yellow star thistle differ from those of forage species at various times of year.

- Cattle manure is a common source of bacterial contamination in California waterways. UAS imagery may enable precise mapping of the location and volume of manure deposits on the landscape. Such data could then inform models that predict likely fecal coliform loading in nearby streams.
- Photographic imagery collected by UAS may enable estimates of forage production by measuring changes in grass height over time. The research team is comparing ground-level measurements of vegetation height with the results of digital surface models — very high-resolution topographic maps — generated from images captured by UAS-mounted cameras. The image-processing software uses a photogrammetric approach, which analyzes multiple overlapping images to generate precise elevation maps (Sean Hogan, UC ANR, igis.ucanr.edu). CA



A DJI Inspire 1 drone flies over cattle for a rangeland ecology study at Gamble Ranch in Napa County.



High-resolution imagery gathered from a drone can be used to assess rangeland condition and forage production. The above images show 12 acres of rangeland in Inyo County. The image at left is a digital surface model (DSM) with a resolution of 0.8 inches, generated from digital photographs. Fine resolution DSMs like this can be used over time to monitor vegetation growth, and hence forage production. The image at right, captured by a Parrot Sequoia multispectral camera, shows the normalized difference vegetation index (NDVI) at a resolution of 1.45 inches. The NDVI is a measure of the relative absorbance of near-infrared and visible light and can be used to distinguish green vegetation (shown in the image as green) from stressed, dying or dead vegetation (shown as yellow to red in the image).

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Trump and U.S. immigration policy

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President Donald Trump campaigned on seven major issues, two of which involved migration: have the United States build — and Mexico pay for — a wall on the 2,000-mile Mexico-U.S. border, and deport the country's 11 million unauthorized foreigners,* over half of whom are Mexican. He has also promised to reverse President Barack Obama's executive orders that provide temporary legal status to some unauthorized foreigners, and to "put American workers first" in migration policymaking.

Since winning the election, Trump has modified some of his positions, notably announcing that deportation efforts would be focused on 2 million unauthorized foreigners convicted of crimes in the United States.

Trump's focus on unauthorized migration during the campaign has had several effects that may prove long-lasting, including polarizing public opinion about what to do about immigration in general and unauthorized foreigners in particular. Migration may join abortion and guns on the list of issues that deeply divide Americans.

Unauthorized migration

Unauthorized foreigners account for a quarter of the 44 million foreign-born U.S. residents. The remainder includes 19 million naturalized U.S. citizens, 12 million lawful immigrants, and almost 2 million lawful temporary visitors such as students and guest workers (Brown and Stepler 2016).

Between 2007 and 2014, the number of unauthorized U.S. residents who were born in Mexico fell by a million from 7 million to 6 million, indicating that departures have been exceeding arrivals.

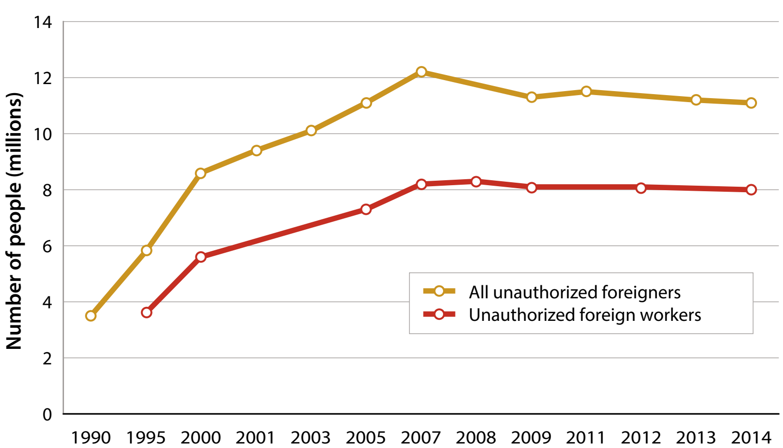

Fig. 1. Unauthorized foreigners in the United States and in the U.S. labor force, 1990–2014. Source: Passel and Cohn 2016a and 2016b.

The number of unauthorized foreigners rose rapidly from the 1990s through the mid-2000s, peaking at 12 million in 2007 before declining during and after the 2008–2009 recession (Passel and Cohn 2016a) (fig. 1). Some 8 million unauthorized foreigners are in the U.S. labor force (fig. 1), comprising 5% of a 160-million-strong national workforce that also includes 20 million lawful foreign-born workers (Passel and Cohn 2016b). In 2014, unauthorized workers accounted for 9% of California's workforce.

Between 2007 and 2014, the number of unauthorized U.S. residents who were born in Mexico fell by a million from 7 million to 6 million, indicating that departures have been exceeding arrivals. That shift is part of a larger trend of fewer new unauthorized foreigners: In 2014, 66% of unauthorized foreigners had been in the country for 10 years or longer, compared with 41% in 2005 (Passel and Cohn 2016a).

Agriculture has the highest share of unauthorized workers of any major industry. Based on data broken out by industry category, about 17% of those employed in agriculture were unauthorized in 2014, followed by 13% in construction and 9% in hospitality. According to data on occupation categories, 26% of those with farming occupations were unauthorized, followed by 15% in construction and 9% each in production and services. Dependence on unauthorized workers is high in certain areas — for instance, unauthorized workers account for over 50% of fruit pickers in California.

Enforcement-only versus comprehensive reform

There are two major policy approaches to deal with unauthorized migrants: enforcement-only, and comprehensive reforms. The latter generally involve

* In this article, "unauthorized foreigners" refers to people now in the United States who were born elsewhere and are not legal residents or visitors. "Immigrants" are legally admitted persons who can or have become naturalized citizens.

three components: enforcement, a path to legalization, and guest worker provisions. Congress has considered multiple proposals of both types in the past decade, but none have become law.

In December 2005, the House of Representatives approved an enforcement-only bill, HR 4437, requiring all employers to verify, using a government database, the legal status of newly hired workers (within a week of hiring) as well as current workers (within 6 years of the bill becoming law). Suspected unauthorized workers would have been required to contact the government to correct their records or be fired. HR 4437 also called for penalties on those who supported or shielded unauthorized foreigners, and ordered the construction of 700 miles of fencing along the Mexico-US border.

Despite pressure from farmers and other employers who hire large numbers of unauthorized workers, HR 4437 did not include new or expanded guest worker programs. It prompted strong reactions from Mexico and outcry in many U.S. cities, including the “A Day Without Immigrants” protests on May 1, 2006. Ultimately, the Senate did not pass the bill.

In May 2006, the Senate introduced a comprehensive immigration reform bill, S 2611. The enforcement provisions in S 2611 were similar to those in HR 4427, with the addition of a system of appeals and reimbursement in cases of government error in the verification process.

S 2611 took a tiered approach to legalization, dividing unauthorized foreigners into three groups based on their length of time in the United States. Under the bill, unauthorized foreigners who had been in the country for at least 5 years (estimated at 7 million people) could become “probationary immigrants” by meeting certain conditions, and would be eligible for regular immigrant visas after 6 more years of U.S. work and tax payments (Migration News 2006). Unauthorized foreigners in the country for between 2 and 5 years (roughly 3 million people) could receive a 3-year temporary lawful work status, but they would be required to return to their countries of origin within 3 years and re-enter the US legally — a so-called touchback requirement. Unauthorized foreigners in the country for fewer than 2 years would be required to leave.

According to data on occupation categories, 26% of those with farming occupations were unauthorized, followed by 15% in construction and 9% each in production and services.

S 2611 also provided for a new large-scale H-2C guest worker program. Employers in any U.S. industry could “attest” that they need to hire migrants, and a foreigner outside the United States with a job offer from such an employer could have paid $500 and obtained a 6-year work permit. Guest workers could change jobs if they received an offer from another employer that had completed the attestation process.

President George W. Bush supported S 2611, but House Republicans did not support the legalization provisions, and the bill died. A similar comprehensive bill, S 1348, was introduced in 2007. Although it included “trigger” provisions, meaning that stepped-up enforcement would have to be deemed effective before new guest worker or legalization programs could begin, it did not pass the Senate.

Obama to Trump

After his 2008 election, Obama said that immigration was not a first-term issue, and instead tackled the economic recession in 2009 and health care in 2010. However, during his first term, Obama met with migrant rights groups frequently and urged them to persuade Congress to act on comprehensive immigration reforms (Migration News 2009). Immigration reform also featured in his 2010 State of the Union speech.

Midterm elections in November 2010 increased the clout of Republicans in Congress, changing the conversation from comprehensive to piecemeal immigration reform. Piecemeal reform meant reviving efforts to pass measures that had bipartisan support, including the Development, Relief and Education for Alien Minors (DREAM) Act (introduced several times, first in 2001), which provided a path to citizenship for unauthorized foreigners brought to the United States as children; and the Agricultural Job Opportunity Benefits and Security Act (AgJOBS, originally introduced in 2003) to legalize unauthorized farm workers and make it easier to hire guest workers. Both measures had been blocked in the Democrat-controlled Congress by proponents of comprehensive immigration reform who feared that dealing with the “easy” aspects of immigration reform would become a substitute for comprehensive action.

While campaigning for re-election in June 2012, President Obama created by executive order the Deferred Action for Childhood Arrivals (DACA) program, which has so far granted 2-year work and residence permits to 741,000 unauthorized foreigners who arrived in the United States before age 16, are between the ages of 16 and 30, lived illegally in the United States at least 5 years, and have a high school diploma or are honorably discharged veterans.

Many hoped that Obama’s re-election in 2012 would encourage Congress to approve comprehensive immigration reform. A bipartisan group of eight senators introduced S 744, an immigration reform bill that increased border and interior enforcement, created a 13-year path to U.S. citizenship for most unauthorized foreigners, and revised and expanded guest worker programs. The Senate approved S 744 by a 68-32 vote in June 2013, but House leaders said they preferred an incremental or piecemeal approach to immigration policymaking, and did not act (Migration News 2013).

With no comprehensive immigration package attracting majority support in Congress, President Obama expanded DACA after the November 2014 elections and proposed the Deferred Action for Parental Accountability (DAPA) program, which would have given temporary legal status to unauthorized foreigners whose children were legal residents. Half of the states sued to block DAPA, and it was not implemented (Rural Migration News 2016).

Unknowns under Trump

During his campaign, President Trump pledged to deport unauthorized foreigners, so it can be expected that he will step up enforcement at the border and move aggressively to remove foreigners convicted of crimes. What is not yet clear is how fast an increase in enforcement could be implemented — for instance, such measures may require congressional funding appropriations.

Much of the debate about enforcement inside U.S. borders is likely to involve relationships between federal, state and local governments to identify unauthorized foreigners.

Under the Secure Communities policy that began in 2008, state and local police shared the fingerprints of all persons arrested with the FBI and Department of Homeland Security (DHS). If suspected unauthorized foreigners were detected, DHS could ask state and local police to hold the person until DHS agents arrived.

Secure Communities was ended in 2014 by the Obama Administration amidst complaints from migrant communities that "innocent activities," such as being stopped at a DUI checkpoint while driving to go shopping, could result in deportation. Many states and cities went further, declaring themselves to be "sanctuaries" and ordering their law enforcement agencies not to cooperate with DHS.

Trump has promised to withhold federal funds from sanctuary states and cities, but since his election, some cities have approved resolutions pledging not to cooperate with DHS enforcement efforts even if the result is less federal money.

One area where Trump can act quickly is refugee policy. The president, in consultation with Congress, determines the number of refugees to be resettled in the United States each year, and admitted 85,000 in the 2016 fiscal year. Obama proposed to admit 110,000 refugees in fiscal year 2017, but Trump could reduce or stop refugee admissions.

There are many other migration issues that Trump could tackle administratively. For example, Trump could order DHS to resume the workplace raids in meatpacking and other sectors thought to employ large numbers of unauthorized foreigners, or increase the number of audits of the I-9 forms completed by employers and newly hired workers, which could disrupt sectors that hire large numbers of unauthorized workers, such as agriculture. The Center for Immigration Studies (CIS) laid out 79 actions that the president could take administratively, including closer examination of those seeking student, investor and guest worker visas (CIS 2016).

Some administrative actions that President Trump could take are likely to be controversial. He has promised to rescind some of the executive orders issued by Obama, including the one that created DACA. Many have called on Trump to abstain from fulfilling this pledge, emphasizing that the 741,000 DACA youth have been screened and many are now working lawfully. Trump may allow current temporary DACA status to expire rather than to use the information provided by DACA recipients to target them for removal.

Trump's migration agenda is likely to interact with other agendas, including trade. The number-one source of migrants, Mexico, is also the third largest U.S. trade partner, with two-way trade totaling $584 billion in 2015.

One reason for the upsurge in Mexico-U.S. trade is the North American Free Trade Agreement, a trade agreement that Trump has pledged to re-negotiate. Mexico's oil monopoly PEMEX faces declining production and is seeking foreign partners to invest in new oil fields. Since Trump wants to increase fossil fuel production, there could be a complex negotiation with Mexico involving migration, trade and energy. Similarly, with China the number two source of migrants and also a target of Trump's ire for running a trade surplus with the United States, there could be negotiations with China that link migration and economic issues.

The number-one source of migrants, Mexico, is also the third largest U.S. trade partner, with two-way trade totaling $584 billion in 2015.

Trump's election was a surprise, and there may be similar surprises about his migration policies. His campaign rhetoric changed the vocabulary of politics in many areas, including migration, but it is not yet clear if this changed rhetoric will also change migration policy. The United States is likely to remain the country with the world's largest immigrant population, but the fate of the 11 million unauthorized foreigners is uncertain. The extremes of removing most of them at one end, and putting most on a path to U.S. citizenship at the other, are less likely than an in-between solution that gives most unauthorized foreigners some type of temporary legal status. CA

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Lindcove REC: Developing citrus varieties resistant to huanglongbing disease

Of the many citrus varieties trialed at the Lindcove Research and Extension Center (REC), one has been a source of more than $14 million in licensing revenue to UC since 2006: the seedless, easy peel Tango mandarin, bred by Mikeal Roose, professor of genetics in the Department of Botany and Plant Sciences at UC Riverside, and UC Riverside researcher Tim Williams. Many millions of Tango trees have been planted worldwide, 4 million or so in California alone.

Lonnie Duka

Three trees with inedible fruit at Lindcove REC, on the eastern edge of the San Joaquin Valley near Visalia, have Roose's attention now. They are 34-year-old trees, crosses of sweet orange (two) and Rangpur lime (one) with *Eremocitrus glauca*, the desert lime, a wild Australian citrus relative, which he had forgotten about until recently. It's a long shot, but they could lead to an even bigger winner than Tango has been — a citrus variety resistant to huanglongbing (HLB) disease, the greatest threat to California's citrus industry.

Mikeal Roose, professor of genetics at UC Riverside, whose program bred the seedless Tango mandarin, which has been a huge commercial success. Now he's working on a solution to the citrus industry's greatest challenge — huanglongbing (HLB) disease.

Eremocitrus crosses at Lindcove REC are potentially promising in the pursuit of a genetic source of resistance to HLB. The fruit is golfball size and inedible.

Elizabeth Grafton-Cardwell

Elizabeth Grafton-Cardwell

Lindcove REC's annual fruit display and tasting event in mid-December draws 200 to 300 people, including citrus growers making decisions about what to plant. HLB has halved citrus production in Florida; it is expected to arrive in commercial orchards in California within 5 years.

Therese Kapaun

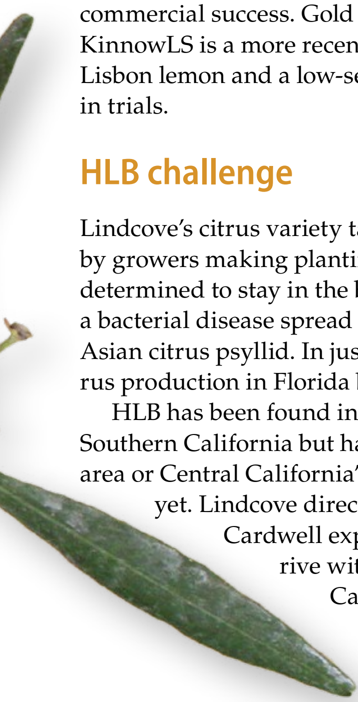
Researcher Rock Christiano collects budwood in the CCPP screen house at Lindcove REC. Pathogen-tested propagation material from here is distributed to licensed nurseries that produce trees for commercial growers.

Variety trials

Lindcove plays a key role in citrus variety trials and in providing clean citrus propagation material for commercial releases. Ten Tango trees grow inside screened areas in the Foundation Block belonging to the Citrus Clonal Protection Program (CCPP), which provides pathogen-tested budwood from the mother trees to licensed nurseries that propagate trees for California citrus growers. No plantings of Tango are allowed in California unless the trees originate from these CCPP Foundation Block trees at Lindcove REC. Georgios Vidalakis, director of CCPP, when asked about their value, said: "I have repeatedly heard experienced members of our industry referring to Tango as the most influential citrus variety since the introduction of the Parent Washington navel orange in Riverside in 1873."

Tango is just one of several recent varieties that have come through Lindcove REC trials and achieved commercial success. Gold Nugget preceded Tango. KinnowLS is a more recent release. A low-seeded Lisbon lemon and a low-seeded Nova mandarin are in trials.

HLB challenge



Lindcove's citrus variety tastings are well attended by growers making planting decisions and seemingly determined to stay in the business in spite of HLB, a bacterial disease spread by a tiny flying insect, the Asian citrus psyllid. In just 10 years, HLB has cut citrus production in Florida by more than 50%.

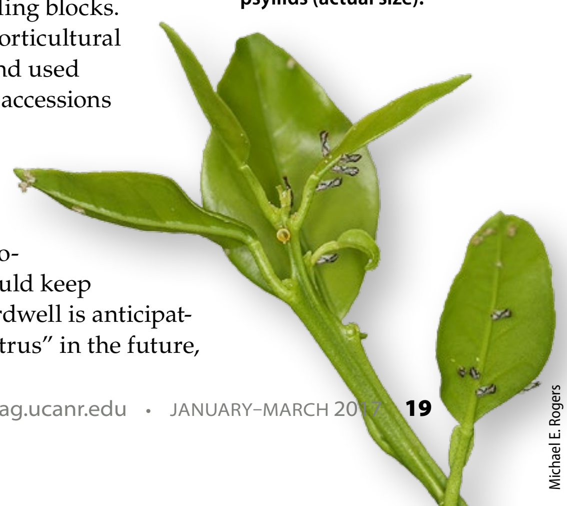
HLB has been found in residential citrus trees in Southern California but hasn't reached the Lindcove area or Central California's vast commercial orchards yet. Lindcove director Elizabeth Grafton-Cardwell expects the disease will arrive within 4 or 5 years. Lindcove, California's main center for citrus field research and extension, is a staging ground, she says, for dealing with it.

Researchers from around the state are conducting research at Lindcove REC related to the Asian citrus psyllid and HLB problem. For example, studies of the best use of systemic neonicotinoid insecticide applications to protect new growth, preferred by psyllids for feeding and reproduction, are under way by UC Riverside scientist Frank Byrne. Professor Cristina Davis's research group at UC Davis has tested the use of a gas chromatograph at Lindcove REC to describe the profile of volatile organic compounds emitted by sick and healthy trees. At Lindcove, it was used to differentiate between trees infected with citrus tristeza virus and healthy trees. In Florida, the equipment shows promise for early detection of HLB infection.

In addition, ground at Lindcove is being prepared for two new studies. The CCPP has received industry and federal funding to introduce at least 50 citrus varieties that seem to be surviving the HLB epidemic in Florida research breeding blocks. These will be evaluated for their horticultural characteristics at Lindcove REC, and used by Roose and other scientists. The accessions include rootstocks, mandarins, sweet oranges, grapefruit and pummelos.

Another trial will assess mandarin productivity under a protective screen structure, which would keep out psyllids and HLB. Grafton-Cardwell is anticipating a "different style of growing citrus" in the future,

HLB is spread by tiny Asian citrus psyllids (actual size).



Michael E. Rogers

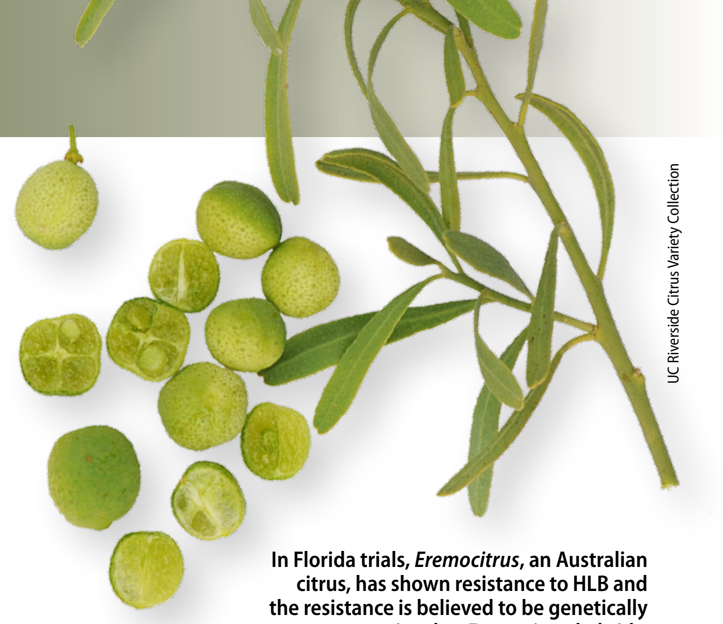
she says, perhaps under screens, perhaps as dwarfed trees in high-density plantings (a production method studied at Lindcove REC since 1998). Increasing the number of trees per acre might allow orchards to continue to be profitable after quickly detected HLB-infected trees are removed.

In Florida, where 80% of citrus trees or more are infected with HLB, citrus growers are struggling with orchard productivity. Yields are down around 40%, and some growers are shifting to other crops or businesses. The California citrus industry has had the benefit of time to prepare for HLB, but Grafton-Cardwell stresses that there is an urgent need for the research community to develop new growing methods and new technologies to help growers adapt to the disease when it arrives.

Breeding for HLB resistance

Citrus breeding is a slow business, even if transgenic techniques are used. A genetically engineered (GE) juicing orange that has an anti-HLB gene taken from a variety of spinach is in trial in Florida. If successful and granted regulatory approval, the GE orange could be available commercially in 5 years, though growers will perhaps be risking planting citrus that some consumers would reject. At present, no transgenic trials are under way in California.

The *Eremocitrus* crosses at Lindcove are 34 years old and can be bred from right away. Crosses with mandarins are planned for this spring.



In Florida trials, *Eremocitrus*, an Australian citrus, has shown resistance to HLB and the resistance is believed to be genetically transmitted to *Eremocitrus* hybrids. Fruit and leaves shown actual size.

Roose acknowledges that HLB is likely to arrive in commercial orchards long before a resistant variety, GE or not, is available, and yet he is optimistic a solution can be found. He cites UC Riverside scientist Chandrika Ramadugu's project that tested, in Florida, HLB resistance in 100 California accessions of citrus and closely related genera from the National Clonal Germplasm Repository for Citrus and Dates. After years growing in orchards and greenhouses infected with HLB, an Australian citrus variety, *Eremocitrus* sp., was one of the few accessions discovered to be resistant to the HLB bacterium. And the resistance has been determined to be genetically transmitted to hybrids of *Eremocitrus*. However, it will be years before the juvenile trees of those *Eremocitrus* hybrids flower and produce pollen for crosses that might eventually produce a marketable variety.

Last year, puzzling over next steps, Roose remembered the collection of citrus trees he had inherited from his predecessors in the plant breeding program at UC Riverside and had been maintaining at Lindcove REC for 30 years. Among them are three *Eremocitrus* crosses, mature trees that may be carrying HLB resistance and can be bred from right away. He collected seed last year, and Ramadugu, his collaborator, plans to test these for HLB resistance, in containment facilities in California, as soon as the seedlings are large enough. They also plan to make crosses between these hybrids and mandarins this spring. If they can identify the genes that control resistance, there may be rapid methods to activate these genes in the citrus genome, causing it to become HLB resistant.

The trees are nondescript — glaucous leaves, weeping habit, fruit inedible and the size of a golf ball — but Roose has a breeder's patience. "It's hard to know what the value of something is. The world changes, and something not valuable can become valuable," he says. Reminded of his and Williams's experiments with mandarin budwood in a medical irradiation unit years ago, he laughs. "Long shots can be quite important." CA

— Hazel White

Mark Hoddle: Smiting weevils

Mark Hoddle's research article in this issue documents a major achievement in invasive species control — a successful eradication, in this case of the Asian palm weevil, *Rhynchophorus vulneratus*, from Laguna Beach.

Hoddle, a UC Riverside-based entomology specialist and director of the Center for Invasive Species Research (CISR), is now working to address another weevil infestation.

This time, the invader is *Rhynchophorus palmarum*, the South American palm weevil. Over decades, the insect has steadily increased its range northward in Mexico, enabled by abundant plantings of Canary Island palms which the weevil infests in irrigated desert areas. These unnatural oases have provided stepping stones for the weevil through inhospitable habitat all the way to California.

Mike Lewis

The South American palm weevil, *Rhynchophorus palmarum* (actual size), infests the Canary Island palm, a common landscape tree in California.

The South American palm weevil was first found in the United States in 2011, just north of the border near San Diego. After that detection, a two-year, federally supported trapping program concluded that the infestation hadn't spread beyond San Diego and Imperial counties.

After 2013, funding for the trapping effort ran out, leaving no system for monitoring the weevil. After a visit to Tijuana last May, Hoddle found 125 weevil-killed palms in a day of driving around the city with a colleague from Tijuana. After this he decided to take matters into his own hands. The following month, he and his wife, Christina — also an entomology researcher at UC Riverside and a co-author on the research paper in this issue — began a family mission to assess the state of the infestation in California.

"We are spending a significant amount of our spare time trapping in San Diego," he said. They bring along their three-year-old son, Nicholas, who likes hunting for the satisfyingly large black weevils.

"It was easy to get him on board, because we are looking for super cool big beetles," said Hoddle, who grew up in New Zealand and has loved hunting for bugs since he was a small boy.

Because Canary Island palms are such a ubiquitous part of the California landscape, they could provide food for weevil invasion all the way up to Northern California. Laboratory tests Hoddle has conducted using "flight mills" — treadmills for flying insects — have shown that the weevils have the potential to fly tens of miles in a day. The weevil is also known to carry a pathogen known as the red ring nematode which also infects the Canary Island palm, making weevil infestations particularly deadly. The nematode hasn't yet been found on the weevils trapped in the United States, but Hoddle says it's probably only a matter of time until it appears.

So far, the Hoddle family monitoring program hasn't found any South American palm weevils north of San Diego County. But the insect appears to be well-entrenched in some areas, such as the Sweetwater River Trail, a natural area near Bonita in San Diego County where many palms grow wild and unmanaged, amidst thickets of willows. Areas like this provide reservoirs for the weevil population to grow and spread into new areas. As one part of their monitoring effort, the Hoddles have assigned GPS coordinates to 300 trees in and near the Sweetwater River Trail area, and are monitoring them to better understand the dynamics of the weevil's spread. Hoddle will be using drone-mounted cameras to do regular monitoring of the trees in infested areas, many of which are difficult to reach.

Hoddle has been working with the California Department of Food and Agriculture (CDFA) to draw attention to the infestation, yielding media coverage all the way up to an article in the New York Times. People finding a South American palm weevil

Christina Hoddle

UC Riverside entomology specialist Mark Hoddle and his son, Nicholas, set weevil traps along the Sweetwater River Trail in San Diego County, a natural area where weevils have infested many unmanaged Canary Island palms.

are encouraged to report it via a dedicated CISR website. More information on this pest and the invasion can be found at http://cisr.ucr.edu/palmarum.html.

There's currently no public funding for monitoring or controlling the weevil, however. Federal support likely won't be available until the adoption of the next Farm Bill, currently slated for 2018. Hoddle is also applying for funding through the CDFA Specialty Crop grant program, and plans to apply for research funding from UC Agriculture and Natural Resources.

While Hoddle radiates positive energy, he's also distinctly realistic about the prospects for eradicating the South American palm weevil, given the large population in Tijuana, its flying ability, and the extent of the invasion already in the San Diego area. In the future, he said, control strategies may turn to defending selected, high-value trees using systemic insecticides that can kill weevil larvae. In Spain, he said, where the red palm weevil — native to Southeast Asia and a close relative of the South American palm weevil — are well-established, ornamental Canary Island date palms in public areas are commonly fitted with showerhead-type applicators that douse a tree with insecticide every few months. CA

— Jim Downing

Research news

Research to policy: Enabling oak woodland restoration

California black oak and Oregon white oak woodlands throughout California have been shrinking due to decades of conifer encroachment, which has led to a loss of wildlife habitat, biodiversity and grazing land.

Many years of fire suppression have created conditions that enable conifers to invade oak woodlands. Slowing the process of encroachment is difficult, as trees need to be removed manually, which is expensive. Additionally, landowners have been hindered in removing confers from oak woodlands by California's Forest Practice Rules, which require that owners replant conifer trees after harvesting trees even when the goal is to promote oak restoration.

A collection of policy changes adopted last year make it significantly easier for California landowners to manage this type of conifer encroachment. AB 1958, authored by Assemblymember Jim Wood (D-Healdsburg), removes permitting hurdles for removing small-diameter conifers from oak woodlands on a 7-year pilot-test basis starting January 1, 2018. Separately, the state Board of Forestry established a new timber-harvest rule for oak woodland restoration projects, effective January 2017, that allows landowners to remove conifers that have encroached on Oregon white and California black oak woodlands.

"AB 1958, developed with the expertise of UC Cooperative Extension, allows private land owners to manage their land and preserve these valuable oak habitats," said Wood. "It's a great step forward in responsibly managing our environment."

UC Cooperative Extension (UCCE) worked directly with the Board of Forestry, the California legislature and interested stakeholders to facilitate these changes. UCCE also helped establish the scientific basis for the new rules by documenting the degree and nature of the encroachment in a three-year study completed in 2016. Under a UC Agriculture and Natural Resources competitive grant, UCCE Humboldt County director and forest advisor Yana Valachovic led a broad team of researchers that included area fire advisor Lenya Quinn-Davidson, UC Berkeley–based specialists Rick Standiford and Maggi Kelly and professor Matthew Potts, along with private landowners and collaborators from Humboldt State University and government agencies.

"This is an exciting time for oaks and it has been great to help create science-based policy," said Valachovic. "I am grateful for UC's support. This much-needed scientific assessment has helped to develop awareness of these important habitat types in need of restoration."

The team evaluated the impact and extent of Douglas-fir encroachment in 10 oak sites across Humboldt and Mendocino counties, and documented the age structure and tree health of these oak stands. The team learned that most of the encroachment began after 1940 and that the oaks are much older than the Douglas-fir trees. The researchers also studied factors that influenced encroachment, such as climate and moisture, and mapped oak woodlands and compared them to historic photos. The data collected directly informed and gave confidence to the policymakers working on the rule changes. CA

—Debbie Thompson

UC and UCCE research on the impact of conifer encroachment helped facilitate policy changes that make it easier for California landowners to remove conifers from oak woodlands.

Yana Valachovic

The palm weevil *Rhynchophorus vulneratus* is eradicated from Laguna Beach

by Mark S. Hoddle, Christina D. Hoddle, Mohammed Alzubaidy, John Kabashima, J. Nicholas Nisson, Jocelyn Millar *and* Monica Dimson

In October 2010,* Rhynchophorus vulneratus*, originally identified as the red palm weevil,* R. ferrugineus*, was discovered infesting Canary Island date palms in Laguna Beach, California. The red palm weevil has caused extensive mortality of palms in the Mediterranean, the Middle East and North Africa, and its discovery in California caused concern for the state's ornamental palm and date industries and the many palms in Southern California landscapes. A rapid, coordinated effort led to the deployment of traps baited with the weevil's aggregation pheromone, coordinated pesticide applications to privately owned palms and destruction of palms at advanced stages of infestation. Research confirmed the chemical components of the aggregation pheromone, assessed the efficacy of trapping strategies and resolved the taxonomic identity, native range and putative region of origin for the population detected in Laguna Beach. The last confirmed detection of a live* R. vulneratus *was Jan. 20, 2012. USDA-APHIS declared this weevil eradicated from California on Jan. 20, 2015. The estimated cost of the eradication was $1,003,646.

On Aug. 3, 2010, a badly damaged Canary Island date palm, *Phoenix canariensis* Chabaud (Arecales: Arecaceae), was removed by a professional arborist in Laguna Beach, Orange County, California. Examination of the crown by the arborist resulted in the recovery of adult and larval weevils (Coleoptera: Curculionidae). This material was submitted to the Orange County agricultural commissioner's office for identification on Sept. 1, 2010, and the California Department of Food and Agriculture (CDFA) subsequently identified the adult specimens as *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae), the red palm weevil.

The CDFA's tentative identification was confirmed by the United States Department of Agriculture (USDA) on Sept. 24, 2010. On Oct. 26, 2010, a live adult male weevil was recovered from a second heavily damaged Canary Island date palm in Laguna Beach. The weevil was identified as *R. ferrugineus* by specialists at the CDFA and USDA (Hoddle 2010a). These two find sites were 0.07 miles (0.12 kilometers) apart.

Laguna Beach is a small (~ 8.8 square miles [23 square kilometers], 23,250 inhabitants), relatively isolated, wealthy residential area between the Pacific Ocean, to the west, and the dry, relatively undeveloped San Joaquin Hills, to the east. One north-south highway, California State Route 1, and one west-east highway, State Route 133, run through Laguna Beach; the city has no airport, seaport or interstate

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Adult male *Rhynchophorus vulneratus* recovered from an infested Canary Island date palm in Laguna Beach.

Fig. 1. Two color morphs of *Rhynchophorus vulneratus* recovered from an infested coconut palm in Java, Indonesia. (A) The orange and black morph of *R. vulneratus* (left) is very similar in appearance to *R. ferrugineus*. The black morph with the red dorsal stripe (right) is similar to adult *R. vulneratus* recovered in Laguna Beach. (B) Two color morphs of *R. vulneratus* copulating.

border crossings. Tourism is a major industry, with ~ 3 million people visiting the city annually (Turnbull 2004).

Rhynchophorus spp. weevils, especially *R. ferrugineus*, are notoriously destructive palm pests in native and invaded ranges (Faleiro 2006; Murphy and Briscoe 1999). *R. ferrugineus* attacks more than 40 palm species in 23 genera. It is a destructive pest of the coconut palm, *Cocos nucifera* L. (Arecales: Arecaceae), (Giblin-Davis et al. 2013) in its native range, which is the northern and western regions of continental Southeast Asia (e.g., northern Thailand, Vietnam and Cambodia), Sri Lanka and the Philippines (Rugman-Jones et al. 2013). Accidental introduction of *R. ferrugineus* into regions outside of its native range has occurred via the movement of live palms infested with weevils, and this pest has caused extensive mortality of *P. canariensis* in the Mediterranean and of date palms (*Phoenix dactylifera* L.) in the Middle East and North Africa (Faleiro 2006; Faleiro et al. 2012; Giblin-Davis et al. 2013; Murphy and Briscoe 1999).

Discovery of red palm weevil in California was of major concern because the ornamental palm and date industries are estimated, respectively, at $70 million and $34 million annually (CDFA 2013), and palms are ubiquitous in Southern California landscapes. Furthermore, the native California fan palm, *Washingtonia filifera* (Lindl.) H.Wendl. (Arecales: Arecaceae), restricted to a limited range comprising desert riparian habitats in the western United States, was considered vulnerable because it is a known host for *R. ferrugineus* (Ju et al. 2011; Longo et al. 2011).

Weevil biology

Palm mortality caused by *R. ferrugineus* results from internal feeding by larvae (mature larvae can exceed ~ 2 inches [5 centimeters] in length), which are concealed within the palm during the entire larval life cycle, making detection of early infestations and subsequent control difficult (Giblin-Davis et al. 2013). Internal feeding by two or three generations of weevil larvae over 1 to 2 years can kill infested palms. Palm death results from mortality of apical growing areas (typical for *C. nucifera* and *P. canariensis*) or trunk collapse (typical for *P. dactylifera*) (Faliero 2006; Giblin-Davis et al. 2013; Murphy and Briscoe 1999).

A second Southeast Asian palm weevil species, *R. vulneratus* (Panzer), was reported to have a more southern distribution in Asia than *R. ferrugineus* (Wattanapongsiri 1966). A taxonomic revision by Hallett et al. (2004), with specimens collected from west Java, in Indonesia, separated the species primarily on the basis of color differences, with *R. vulneratus* typically being black with a red stripe on the dorsal surface of the thorax and *R. ferrugineus* being orange with black markings). Unable to find any significant molecular, morphological or behavioral differences or mating incompatibilities between these two color morphs, Hallett et al. (2004) synonymized *R. vulneratus* with *R. ferrugineus*, with *R. ferrugineus* having naming priority. Therefore, the black palm weevils with a prominent red stripe on the dorsal surface of the thorax (i.e., the *R. vulneratus* morph) discovered in Laguna Beach were officially identified as *R. ferrugineus*.

Subsequent work investigating the origin of the palm weevil invasion in Laguna Beach used molecular markers to investigate the identity of the species detected and to ascertain its probable area of origin. DNA-based analyses of weevils collected throughout the presumptive native ranges of *R. ferrugineus* and *R. vulneratus* concluded that the weevil species collected in Laguna Beach was *R. vulneratus*, a species distinct from *R. ferrugineus*.

Molecular analyses by Rugman-Jones et al. (2013) indicated that *R. vulneratus* has a native range confined largely to southern Thailand and northern Malaysia on the Malay Peninsula, Singapore, and Indonesia, and that this species has a range of color forms, including that typical of the invasive *R. ferrugineus* (fig. 1). The results of these molecular studies on species identities and geographic distributions supported earlier work by Wattanapongsiri (1966). It was concluded that Hallett et al. (2004) had been studying different color morphs of *R. vulneratus* in Java and that *R. vulneratus* had been incorrectly synonymized with *R. ferrugineus* (Rugman-Jones et al. 2013). From this point forward, we will refer to the weevil species found at Laguna Beach as *R. vulneratus*.

The only find of *R. vulneratus* outside of its native range has been in Laguna Beach. The nearest molecular match to the Laguna Beach population was with *R. vulneratus* collected in Bali, Indonesia (Rugman-Jones et al. 2013). It was hypothesized that the introduction of *R. vulneratus* into Laguna Beach may have been

John Kabashima

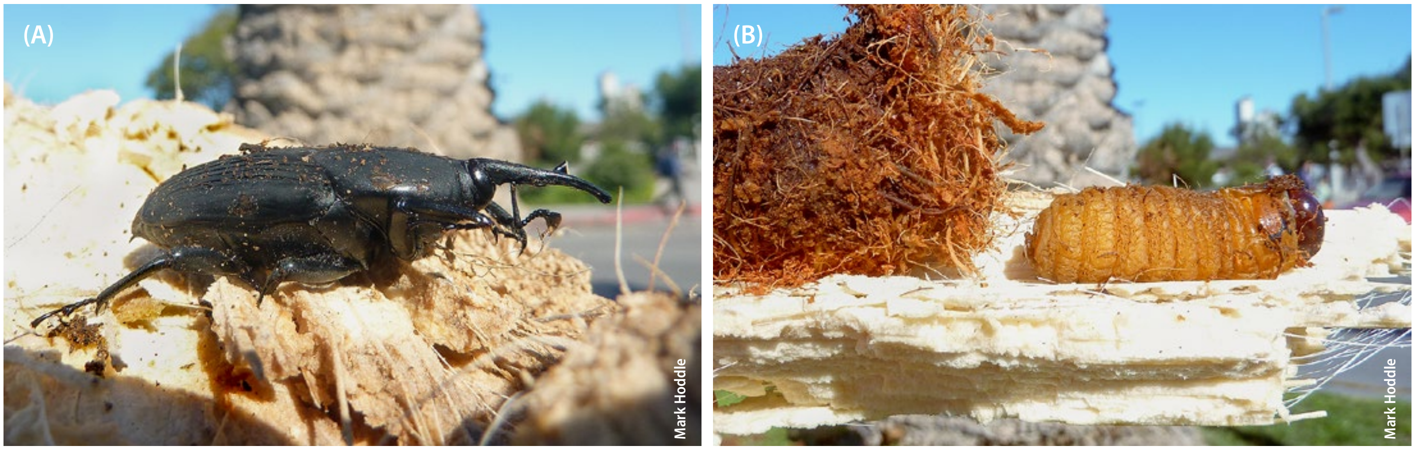

Fig. 2. ***Rhynchophorus palmarum*** **adult (A) and larva (B) extracted from a cocoon of palm fibers. Both were collected from an infested** ***Phoenix canariensis*** **in Tijuana, Mexico. This weevil was detected as a result of the public's response to requests for help with the** ***R. vulneratus*** **invasion in Laguna Beach.** ***R. palmarum*** **may have established in San Diego County and potentially poses a serious threat to California's palms.**

deliberate, possibly to start a local source of palm weevil larvae and pupae to be used in the preparation of traditional Asian dishes (Hoddle 2015).

Response in Laguna Beach

To delineate the areas in Laguna Beach infested by *R. vulneratus*, 1-gallon (3.78-liter) bucket traps were loaded with Ferrolure 700 mg (ChemTica Internacional S.A., Costa Rica), which contains the aggregation pheromone 4-methyl-5-nonanol (ferrugineol). Also in the bucket were ethyl acetate (a synergist), fermenting apples as bait and 0.26 gallon (1 liter) of a 50:50 mixture of water and propylene glycol (to drown and preserve weevils).

Trapping commenced Oct. 7, 2010. A total of 150 traps were deployed by CDFA at two different densities within a survey area of 6 square miles (15.6 square kilometers; ~ 68% of the land area of Laguna Beach). High-density trapping was set at 50 traps per 1 square mile (2.6 square kilometers) around find sites. Outside of this zone, 25 traps were deployed per 1 square mile (2.6 square kilometers). Two additional traps (total number used for monitoring was 152) were deployed at a green waste facility 15 miles (24 kilometers) south of the find sites to monitor for weevils inadvertently moved there in disposed palm material. Traps were attached to palm trunks ~ 6.6 feet (2 meters) above the ground and inspected daily from Oct. 7, 2010, to Oct. 17, 2010, weekly until March 19, 2011, then biweekly until Jan. 20, 2015, when eradication was declared.

Visual surveys of 13,485 palm trees for weevil damage on 1,963 properties within 6 square kilometers of the initial find sites were conducted by CDFA over the period Sept. 27, 2010, to Oct. 28, 2010. Detection of empty pupal cases or body fragments of dead adult weevils confirmed the presence of this pest in five survey locations. Visual surveys were aided by a large response from residents, local arborists and palm enthusiasts. Reports of symptomatic palms by these groups were investigated by CDFA and Orange County program personnel, and cooperating home owners provided access to private properties. Survey results in Laguna Beach indicated that the area infested with *R. vulneratus* was ~ 0.39 square miles (1 square kilometer), which equated to ~ 4% of the land area of the city of Laguna Beach.

The public response to outreach efforts and subsequent surveys resulted in another pest discovery in Southern California: the first confirmation of the South American palm weevil, *R. palmarum* (L.) (fig. 2), in California and the neighboring state of Baja California, Mexico (Hoddle 2011a). The high mortality of Canary date palms in Tijuana since at least 2011 has been the source of weevils entering Southern California, and it is likely that *R. palmarum* will become a problematic pest of ornamental, date and native palms in California, as there are increasing reports of *P. canariensis* being killed by this pest in San Ysidro in San Diego County. At this time there are no active programs targeting *R. palmarum* in Southern California.

A technical working group (TWG) was assembled by the USDA to provide expert input into the emerging monitoring and management program for *R. vulneratus* in Laguna Beach. The TWG included international palm weevil experts, research scientists from UC Riverside, CDFA and USDA, UC Cooperative Extension personnel from San Diego, Orange and Los Angeles counties and county entomologists from the agricultural commissioner's offices in Orange and San Diego counties.

The TWG met at Laguna Beach from Nov. 29 to Dec. 1, 2010 (Hoddle 2010b). The group produced a document with recommendations pertaining to (1) detection and identification of visual symptoms typifying infestations, (2) trapping guidelines, (3) assessment of techniques for early detection of infestations, (4) pesticide treatments, (5) removal and destruction of infested palms and (6) education, outreach and information dissemination to local communities and palm industry professionals (Hoddle 2010c; Hoddle 2011b; Hoddle 2011c).

Despite evidence of damaged palms in Laguna Beach, baited pheromone traps captured only one adult weevil, which was found on Jan. 18, 2012, within 0.21 kilometer of the original find sites. In response to this find, between Jan. 31, 2012, and Feb. 15, 2012, visual surveys of palms for weevil infestations were conducted by CDFA within an area of 0.6 square miles (1.6 square kilometers). A total of 5,564 palm trees were inspected on 782 properties. Two additional properties with palms exhibiting characteristic weevil feeding damage to fronds (leaf notching or holes in the petiole base) were identified. However, weevil presence (pupal cases or adult weevils) was not confirmed.

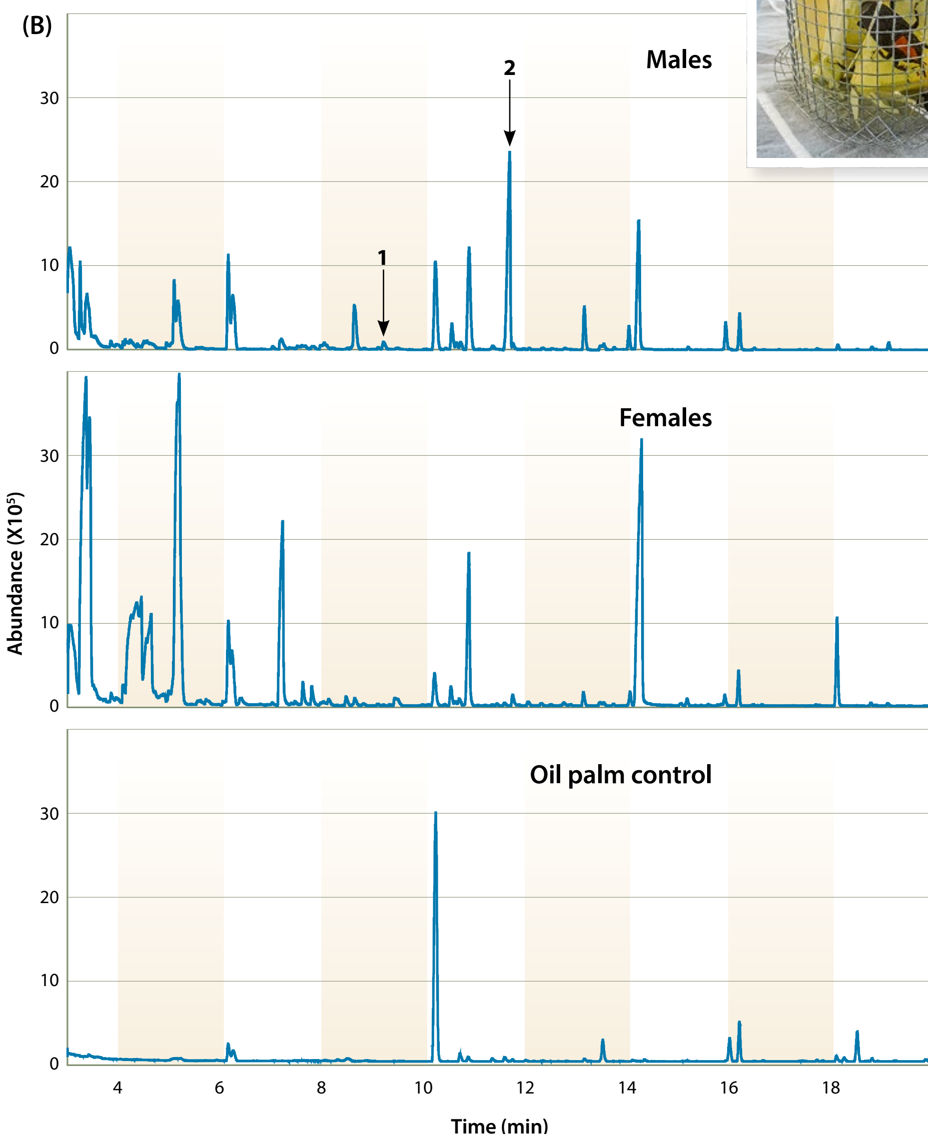

Fig. 3. (A) *Rhynchophorus vulneratus* pheromone aeration set up in an outdoor screen house in Sumatra, Indonesia. (1) Terinex odorless oven bag enclosing a sterilized wire mesh container holding adult male or female weevils with food (see inset photo). (2) Inlet with 6 to 14 mesh activated charcoal filter to purify ingoing air. (3) Outlet with thermally desorbed 50 to 200 mesh activated charcoal collector to collect volatile compounds emitted by weevils and food items. (4) Manifold to regulate airflow. (5) Aquarium pump to push and pull air through oven bags. (6) Airflow meters. (B) GC–MS chromatograms of volatiles collected from male and female *R. vulneratus* and the oil palm (food source for weevils) control. Peaks 1 and 2 in the chromatogram for male weevils are 4-methyl-5-nonanone (ferrugineone) and 4-methyl-5-nonanol (ferrugineol), respectively. Schematic prepared by Steve McElfresh.

The low capture rates of *R. vulneratus* in pheromone traps in areas with apparent or suspected weevil infestations caused concern because it suggested that the pheromone traps might not be attractive to *R. vulneratus*. If this was the case, then the lack of a sensitive and species-specific monitoring tool could significantly impair the management program targeting *R. vulneratus*.

Verifying pheromone compounds

Hallet et al. (1993) identified two aggregation pheromone components, 4-methyl-5-nonanone (ferrugineone) and 4-methyl-5-nonanol (ferrugineol), produced by male *R. vulneratus* (they incorrectly assumed that they were working with *R. ferrugineus*) collected in Java, Indonesia. To verify the chemical identify of the aggregation pheromone of *R. vulneratus* as reported by Hallett et al. (1993), male and female weevils were field collected by authors Mark and Christina Hoddle in Sumatra, Indonesia, and used for pheromone collection.

Pheromone collections and controls consisted of four treatments: (1) a sterilized mesh container only, (2) four male weevils on a food source (either sugarcane or oil palm hearts, used separately in case one stimulated pheromone production), (3) four female weevils on a food source and (4) the food source used in 2 and 3 without weevils. All treatments were placed inside heat-sterilized mesh containers, which in turn were enclosed by odorless Terinex oven bags (Terinex Ltd., Bedford, U.K.). The mesh containers held the weevils and food and prevented weevils from chewing holes in the oven bags and escaping.

Treatments 1 and 4 provided control chemical profiles of volatiles from the mesh cage and the food sources, and treatments 2 and 3 provided profiles of volatiles released by male and female weevils. An aquarium pump was used to push purified air into the oven bags over the mesh containers, food and weevils, and as the airstream exited, it was passed through activated charcoal filters, which trapped the volatiles released into the airspace of the bags by the weevils or food items (fig. 3A).

Aerations were made continuously for 3 to 4 days, and treatments were replicated four times. The trapped volatiles were eluted from the charcoal collectors and analyzed by coupled gas chromatography–mass spectrometry (GC–MS). The insect-produced compounds were tentatively identified by interpretation of their mass spectra, and these identifications were verified by comparing the GC retention times and mass spectra with those of authentic standards obtained from ChemTica.

The analyses showed that two male-specific compounds were produced by *R. vulneratus* in Sumatra, and they were conclusively identified as the two previously reported aggregation pheromone components obtained for *R. vulneratus* from Java (Hallett et al. 1993) (fig. 3B). This result raised an important question: What are the aggregation pheromones for *R. ferrugineus*? The commercially available aggregation pheromone used for *R. ferrugineus* management was identified from *R. vulneratus* (Hallett et al. 1993), and to our knowledge, the identity of the aggregation pheromone produced by *R. ferrugineus* has not yet been determined, although this species is attracted to baited traps containing ferrugineol and ferrugineone derived from *R. vulneratus*.

Field evaluations of baited traps

The attractiveness of traps loaded with fermenting bait, ethyl acetate and Ferrolure 700 mg was field-tested in the Philippines (*R. ferrugineus* was the species present at study sites on Luzon Island) and Indonesia (*R. vulneratus* was the species present on Sumatra). At the time these field studies were conducted, it was assumed that *R. ferrugineus* was the subject of this work and the only species present in both countries.

In the Philippines, three different treatments were tested for attractiveness to weevils; traps were baited with (1) fermenting dates or pieces of coconut palm heart, ethyl acetate and aggregation pheromone, (2) freshly cut coconut palm logs only and (3) a combination of treatments 1 and 2 (Hoddle and Hoddle 2011). This experiment was repeated in Sumatra and results were similar: baited pheromone traps combined with freshly cut palm logs, treatment 3, were very attractive to *R. vulneratus* (Hoddle and Hoddle 2015). The volatiles from cut palm logs likely act synergistically with the aggregation pheromones to increase attraction (Hallett et al. 1993).

A combination of traps and cut date palm trunks (date palms were used because coconut palms were not available) was tested in Laguna Beach to determine if it would result in captures of *R. vulneratus* in areas where activity was observed but no weevils had been caught in traps. Date palm sections were obtained from a commercial palm producer in Coachella Valley, California. Three sites around areas with suspected *R. vulneratus* activity in Laguna Beach were selected for weevil monitoring with sections of date palm trunks and pheromone traps.

Sections of cut apical parts of palm trunks were stacked beside *P. canariensis* palms and baited pheromone traps were deployed on top of these stacks. Traps were checked daily from June 21, 2012, to July 17, 2012, for a total of 27 consecutive days. No weevils were found in traps or log stacks. This trial was repeated Oct. 18, 2012, to Nov. 11, 2012, a 27-day period. No weevils were recovered from the second trial (see Hoddle 2012 for more details).

Palm removals, and pesticides

On Nov. 3, 2010, the infested Canary Island date palm that yielded a live male weevil on Oct. 26, 2010, was removed from Laguna Beach and disposed of in compliance with strict destruction protocols (Hoddle 2010d). No live larvae, pupae or adult weevils were found inside the trunk or petioles. This palm was the only one removed as part of the *R. vulneratus* management program.

A total of 13 palm trees were treated with broad-spectrum contact pesticides applied to foliage and/or systemic pesticides that were applied via trunk or soil injections (Hoddle 2011d; Hoddle 2011e): three *P. canariensis* (two with confirmed infestations; treated once each), five *Howea forsteriana* Becc. (suspected infestations based on visual damage assessments; treated three times from August to December 2011), one *Chamaerops* sp. (suspected; treated once) and four *Roystonea* sp. (suspected; treated twice from March to April 2012).

One *P. canariensis* with confirmed *R. vulneratus* activity was treated with pesticides Jun. 2, 2011 (Hoddle 2011e), then cut down and removed from a private residence in Laguna Beach on Mar. 27, 2013, because it was causing structural damage to an adjacent building (Hoddle 2013). The palm crown and petiole bases on individual fronds were examined for *R. vulneratus* feeding damage. There was no visual evidence of feeding damage, and no larvae, pupal cases or adults (dead or alive) were found (Hoddle 2013).

Canary Island date palm killed by *Rhynchophorus vulneratus* in Laguna Beach (note healthy Canary Island date palms in the background).

Declaration of eradication, cost

On Jan. 20, 2015, USDA-APHIS officially declared eradication of *R. ferrugineus* (i.e., *R. vulneratus*) from Laguna Beach, 3 years after the last detection of a single live weevil on Jan. 18, 2012 (El-Lissy 2015). The eradication declaration was made in accordance with European and Mediterranean Plant Protection Organization International Standards, which require a period of 3 consecutive years with no pest detections (El-Lissy 2015).

Despite significant data supporting *R. vulneratus* as the invasive weevil species in Laguna Beach (Rugman-Jones et al. 2013), USDA-APHIS states that it will "continue to refer to this detection as *Rhynchophorus ferrugineus* until additional information is available" (Molet et al. 2011, revised 2014). This stance is based on the desire of USDA-APHIS for a combined dataset of morphological and DNA information, as well as discrete species diagnoses, to resolve remaining taxonomic uncertainty (Eileen Smith, USDA-APHIS, personal communication, Mar. 31, 2015).

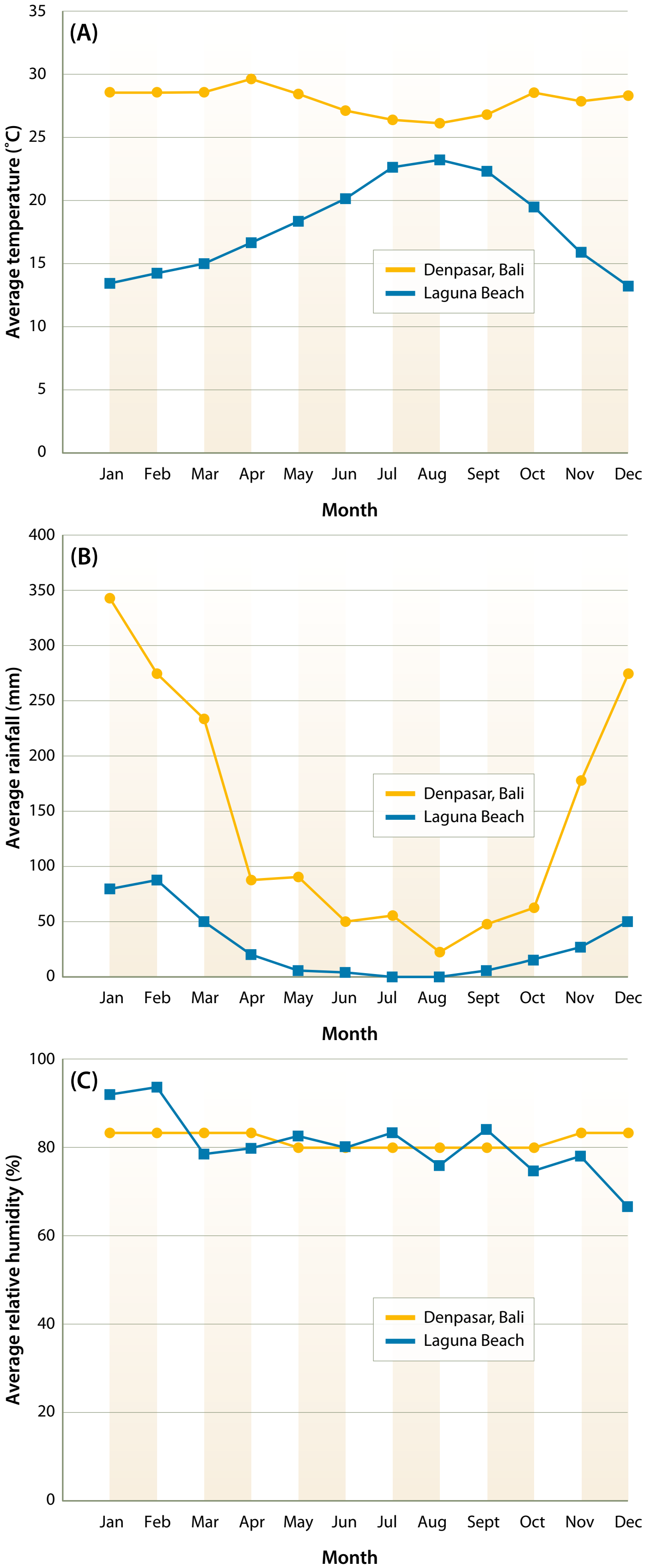

Fig. 4. Average monthly comparisons between Laguna Beach, California, and Denpasar, Bali, Indonesia for (A) temperature, (B) rainfall and (C) humidity. Sources: www.usa.com/laguna-beach-ca-weather.htm and www.weatherbase.com/weather/weather.php3?s=592525&cityname=Denpasar-Bali-Indonesia&units=metric.

The cost of the eradication of *R. vulneratus* from Laguna Beach was estimated at $1,003,646. A breakdown of estimated expenditures is provided in table 1.

Success factors

Eradication of an invasive arthropod pest depends on multiple interacting factors. Specifically, small infested areas that can be monitored with highly specific and sensitive tools (e.g., pheromone-baited traps) have higher eradication success probabilities. Furthermore, the smaller the area being treated, the less it costs to eradicate the target (Tobin et al. 2014). These factors likely contributed, in part, to the successful eradication of *R. vulneratus* from Laguna Beach.

Social, economic, regulatory and political factors also are critical components of eradication programs (Pluess et al. 2012). These may include the authority of regulatory agencies to intervene and take action on private and public lands, procurement of funds to support the project, the commitment and political will of stakeholders affected by the invasion and, very importantly, strong public support for eradication efforts (Tobin et al. 2014). The *R. vulneratus* eradication effort benefited from strong socioeconomic support.

Organisms need to maintain populations above a critical density, the Allee threshold, if they are to persist. Below this threshold, populations trend toward extinction (Liebhold and Tobin 2008; Suckling et al. 2012). Factors negatively influencing the Allee threshold and increasing extinction risk may include (1) unsuitable climate, (2) suboptimal foods, (3) low genetic

TABLE 1. Estimated costs for the program that eradicated *Rhynchophorus vulneratus* from Laguna Beach, September 2010 to January 2015

Expenditure item	Estimated cost
Labor for visual inspections of palms and monitoring of baited pheromone traps in Laguna Beach	$230,000
Bucket traps and supplies for maintaining traps (pheromones, fruit, etc.) in Laguna Beach	$32,000
Travel to monitor traps (vehicle rental and gas) in Laguna Beach	$60,000
Salary estimates for CDFA, UC and county agricultural commissioner employees involved in palm weevil monitoring, management and research	$230,000
CDFA Specialty Crop Block Grant that supported molecular analyses of weevils, testing of pheromones and trapping strategies in native and invaded ranges, and identification of aggregation pheromones collected from *R. vulneratus* in Sumatra, Indonesia	$108,446
Pesticide applications to 13 palm trees in Laguna Beach	$1,200
Four date palms used for enhanced trapping trials at Laguna Beach ($3,000 per palm)	$12,000
Outreach and extension materials and community meetings for stakeholders	$30,000
Miscellaneous costs, including rental of bucket trucks (cherry pickers) to inspect palms; palm removal, transport and disposal; cameras, binoculars; etc.	$20,000
Statewide monitoring program for invasive palm weevils in other areas of California, outside of Laguna Beach (998 traps deployed in 12 counties)	$280,000
TOTAL	**$1,003,646**

variability and (4) control tactics such as the use of pesticides. The interaction of some or all of these factors may have contributed to the successful eradication of *R. vulneratus*.

First, the climate in Laguna Beach may not have been suitable for vigorous year-round population growth of the weevil. Average monthly temperatures and rainfall are lower in Laguna Beach than in Bali, Indonesia (fig. 4), where weevils with the closest genetic match to specimens collected from Laguna Beach were found (Rugman-Jones et al. 2013). Second, low genetic variability due to the small size of the founding population (Rugman-Jones et al. 2013) may have reduced the fitness of the founding population. Third, the suitability of *Phoenix* spp. and other palm species as hosts for *R. vulneratus* is not known, and *P. canariensis* may be of marginal quality as a host. Collectively, when coupled with targeted pesticide applications to infested palms, these factors may have suppressed population growth and pushed weevil densities below the Allee threshold, resulting in the extinction of this palm pest at Laguna Beach. CA

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How many workers are employed in California agriculture?

by Philip Martin, Brandon Hooker, Muhammad Akhtar *and* Marc Stockton

In 2014, the average employment of hired workers in California crop and livestock agriculture, counting all occupations, rose by 10% to 410,900. However, although the state reports the number of jobs on farms regularly, it does not report the number of workers who fill these jobs. We analyzed all Social Security numbers reported by farm employers in 2014 and found two workers for each average or year-round equivalent farm job, making the total number of farmworkers employed in agriculture 829,300, or twice average employment. Approximately 83% of farmworkers had their maximum earnings with an agricultural employer in 2014, and almost 80% of those primary farmworkers were employed by crop support firms (392,000) or fruit and nut farms (154,000). Over 60% of all workers had only one farm employer, followed by 27% with two or more farm employers, and 35% were employed in Kern (116,000), Fresno (96,000) and Monterey (82,000) counties. These data show that California has a remarkably stable farm workforce: most farmworkers are attached to one farm employer, often a labor contractor who moves them from farm to farm.

California has led the nation in farm sales since 1950, largely because of the state's specialization in high-value fruit and vegetable crops. California's farm sales of $54 billion in 2014 included $20.8 billion worth of fruits and nuts, $8.3 billion worth of vegetables and melons and $5.4 billion worth of horticultural specialties such as greenhouse and nursery products. The value of field crops such as cotton, hay and rice was $4 billion, making crop sales of $38 billion almost three-fourths of the state's farm sales. Livestock and poultry sales were $16 billion, including $9 billion (almost 60%) from milk. Fruit, vegetable and horticultural (FVH) crops accounted for 90% of the state's crop sales and two-thirds of its farm sales.

The production of many fruits and vegetables is relatively labor intensive, with labor representing 20% to 40% of production costs. California growers reported paying $11.4 billion in wages in 2014, making labor costs over 20% of farm sales. Almost 45% of these labor costs was for support activities for crop production, primarily payments to farm labor contractors, custom harvesters and other nonfarm businesses that bring workers to farms.

Hired workers, rather than self-employed farm operators and their families, do most of the work on the state's largest farms that produce almost all labor-intensive FVH crops. Most California farmworkers were born in Mexico, and 60% of crop workers employed on the state's crop farms have been unauthorized for the past decade, according to the National Agricultural Workers Survey, which is 10 percentage points higher than the U.S. average of 50%. Farm employers say that farmworkers present seemingly valid documentation and Social Security numbers (SSNs) when they are hired, so they do not know who is unauthorized.

Several factors, including increased production of labor-intensive crops, a tightening of border controls that has slowed arrivals of new farmworkers, and proposals to give some unauthorized foreigners a temporary legal status, have intensified interest in current and future farmworkers, with farm employers arguing that there are farm labor shortages and worker advocates countering that there is only a shortage of wages to attract and retain farmworkers. While California regularly reports the number of jobs on farms across the state, it does not report

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Employment data show that most California farmworkers have only one farm employer, which suggests that the state has a stable agricultural workforce.

Jack Kelly Clark

the number of wage and salary workers who fill them. Our objective was to provide a clearer picture of California's agricultural workforce by determining the actual number of wage and salary workers in agriculture.

Data collection

The state's Employment Development Department (EDD) obtains data on farmworkers and wages paid when it collects unemployment insurance taxes from employers. Employers who pay more than $100 in quarterly wages are required to register with the EDD and pay taxes of up to 6% on the first $7,000 of each worker's earnings to cover the cost of unemployment insurance benefits for laid-off workers. (New employers pay 3.4% for a period of 2 to 3 years until EDD establishes how many claims their laid-off employees make for unemployment insurance benefits. The maximum charge is 6.2% of $7,000, or $434 a year.)

We extracted all wage and salary workers reported by California agricultural employers (North American Industry Classification System, or NAICS 11; census.gov/eos/www/naics/) in 2014 and tabulated all of their farm and nonfarm jobs and earnings in the state; we excluded wage and salary workers in forestry, fishing and hunting. This allowed us to assign workers with more than one job to their primary industry, that is, to the NAICS code of the employer(s) where they had their maximum earnings. We excluded about 800 SSNs because of apparent problems, such as excessive number of jobs reported in a quarter (e.g., more than 10 jobs).

Farm jobs and worker earnings

Average employment on the state's farms is derived from employer reports of workers on the payroll for the pay period that includes the 12th of the month. Most farmworkers are paid weekly, so an average 410,900 workers employed in 2014 means that this is the average employment of workers on agricultural payrolls during the second week of the month. Workers employed during the month but not during the payroll period that includes the 12th are not included in published average employment data because it is a monthly snapshot, summed and divided by 12 months. Our analysis, however, captures these additional workers because we obtain data on *all* wage and salary workers hired by agricultural employers at any time, including farmworkers, managers and office workers.

Figure 1 shows average employment in California agriculture since 1990. Average employment rose 10%, reflecting a decline in direct-hire employment on crop farms (NAICS 111), stable employment in animal agriculture (NAICS 112), and a 50% increase in crop support employment (NAICS 1151), most of which is with farm labor contractors. Since 2010, average employment reported by crop support establishments has been rising by 10,000 a year, so that in 2014 nonfarm crop support firms brought more workers to crop farms, an average of over 205,000, than crop farms hired directly, 175,000. In 2014, two-thirds of average employment in crop support services, 207,600, involved farm labor contractors. Very few workers are employed in livestock support services.

Average employment can be considered to be an estimate of full-time equivalent jobs, but it is not the total number of farmworkers. When average employment in California agriculture was 410,900 in 2014, there were 829,000 unique SSNs

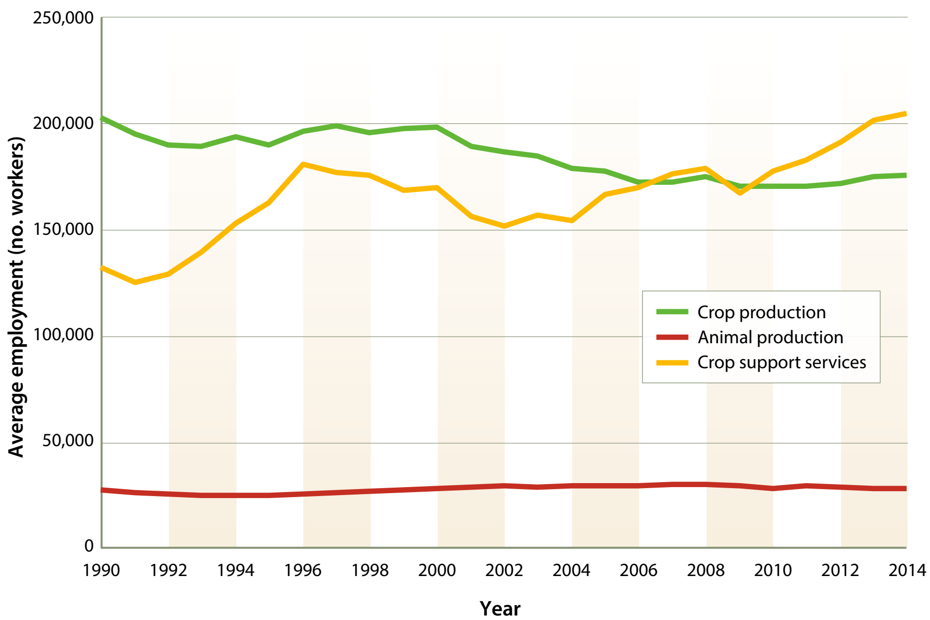


Fig. 1. Average crop, animal and crop support employment in California agriculture, 1990–2014.

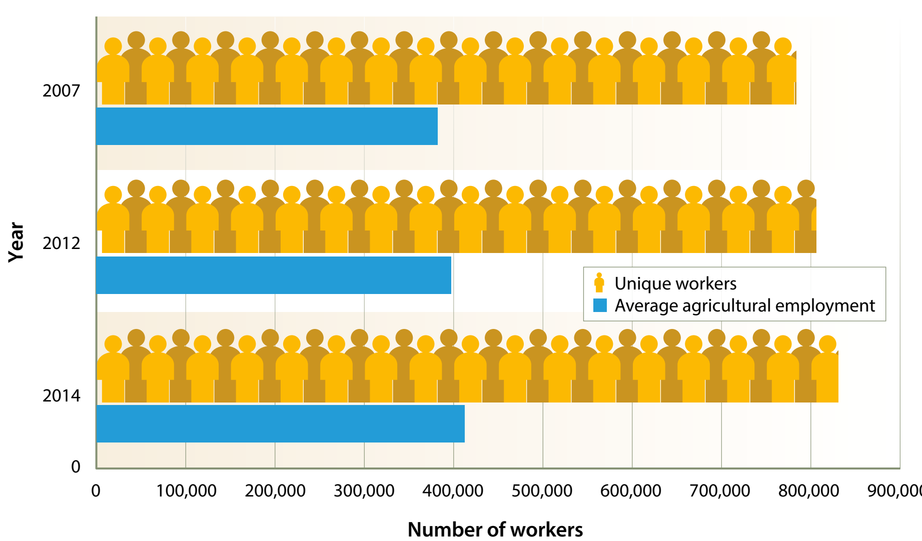


Fig. 2. Average agricultural employment and unique workers, 2007, 2012 and 2014.

reported by agricultural establishments, a two-to-one worker-to-job ratio (fig. 2). In 2012, when average employment was 395,400, there were 802,600 unique SSNs, also a two-to-one worker-to-job ratio. There was a similar two-to-one ratio of workers to average jobs in 2007.

The 829,000 people employed in agriculture during 2014 earned $11.4 billion from agricultural employers and another $4.5 billion from nonfarm employers. Average earnings for all workers with at least one farm employer were over $19,000 in 2014, while average earnings for workers who had their maximum earnings in agriculture were $16,500, up almost 8% from $15,300 in 2012.

The California jobs of the workers reported by California farm employers can be tabulated, and workers can be assigned to the NAICS or commodity in which they had the highest earnings. For example, approximately 692,000 (83%) of the 829,000 workers employed in agriculture had their highest earnings from a farm employer in 2014, and 499,000 of these primary farmworkers had only one agricultural employer (table 1).

In 2014, the crop support (NAICS 1151) and fruit and nut (NAICS 1113) sectors had the lowest average earnings, with $12,719 for crop support and $17,600 for fruits and nuts. This explains why the overall average earnings of primary farmworkers were only $16,500 even though all commodities except crop support and fruit and nut had higher average earnings, such as the $29,223 average earnings in cattle ranching.

Three sectors — crop support firms, fruit and nut farms, and vegetable and melon farms — accounted for 85% of all primary farmworkers in 2014.

Over three-fourths of the $11.4 billion in agricultural earnings were from three NAICS codes: 1151 crop support activities ($5 billion), 1113 fruits and nuts ($2.7 billion) and 1112 vegetables ($1.1 billion). Other major sources of agricultural earnings were NAICS 1114 greenhouses and nurseries ($884 million) and 1121 cattle and dairy ($737 million).

Workforce groups

By assigning all of the state's 829,300 farmworkers to the NAICS code of the employer where they had maximum earnings in 2014, we identified several groups. First, almost 692,000 (83%) of farmworkers had their maximum earnings from agricultural establishments, including (1) 392,000 (57%) whose maximum earnings were from NAICS 1151 crop support establishments, (2) 154,000 (22%) whose maximum earnings were from NAICS 1113 fruit and nut establishments and (3) 45,000 (6%) whose maximum earnings were from NAICS 1112 vegetable establishments. There are over 20 agricultural NAICS codes, but three sectors — crop support firms (often labor contractors), fruit and nut farms, and vegetable and melon farms — accounted for 85% of all primary farmworkers in 2014.

Second, almost 500,000 farmworkers, or 72% of primary farmworkers, had only one job in 2014, meaning that three-fourths of workers whose maximum earnings were from agricultural establishments worked for only one agricultural employer in California. These "one-farm employer" workers were in the same three types of establishments as all primary farmworkers: (1) 288,000 (58%) were in NAICS 1151 crop support

TABLE 1. California farmworkers and earnings, 2014

NAICS code	Category	Primary workers	Earnings ($ millions)	Average earnings ($)	Only job	Share*
	All of California agriculture	691,615	11,430	16,527	499,440	72%
1111	Oilseed and grain farming	4,587	116	25,363	3,144	69%
1112	Vegetable and melon farming	44,878	1,068	23,789	30,760	69%
1113	Fruit and tree nut farming	153,999	2,710	17,600	102,805	67%
1114	Greenhouse and nursery production	34,715	884	25,452	26,530	76%
1119	Other crop farming	19,052	446	23,414	14,244	75%
1121	Cattle ranching and farming	25,224	737	29,223	19,817	79%
1122	Hog and pig farming	132	4	26,804	109	83%
1123	Poultry and egg production	2,851	83	29,143	2,123	74%
1124	Sheep and goat farming	543	12	21,759	465	86%
1125	Animal aquaculture	441	13	30,104	324	73%
1129	Other animal production	3,069	77	25,144	2,308	75%
1151	Support activities for crop production	391,711	4,982	12,719	288,435	74%
1152	Support activities for animal production	3,156	81	25,765	2,585	82%
1153	Support activities for forestry	2,589	76	29,217	2,012	78%
	Nonfarm	137,711	4,548	33,025	—	—
	All workers with at least one agriculture job	829,326	15,978	19,266	—	—

* Percentage of workers whose maximum earnings were in this NAICS and who had only one farm job in 2014.

establishments, (2) 103,000 (21%) were in NAICS 1113 fruit and nut establishments and (3) 31,000 (6%) were in NAICS 1112 vegetable establishments.

A closer look at workers whose maximum earnings were in particular NAICS codes found that 103,000, or two-thirds of the 154,000 directly hired fruit and nut workers, were employed by just one fruit and nut establishment. Similarly, over 288,000, or almost three-fourths of the 392,000 workers whose maximum earnings were in crop support, had only one crop-support employer, although crop support employees may work on multiple farms during the year. Over three-fourths of workers in livestock production were employed by one livestock establishment.

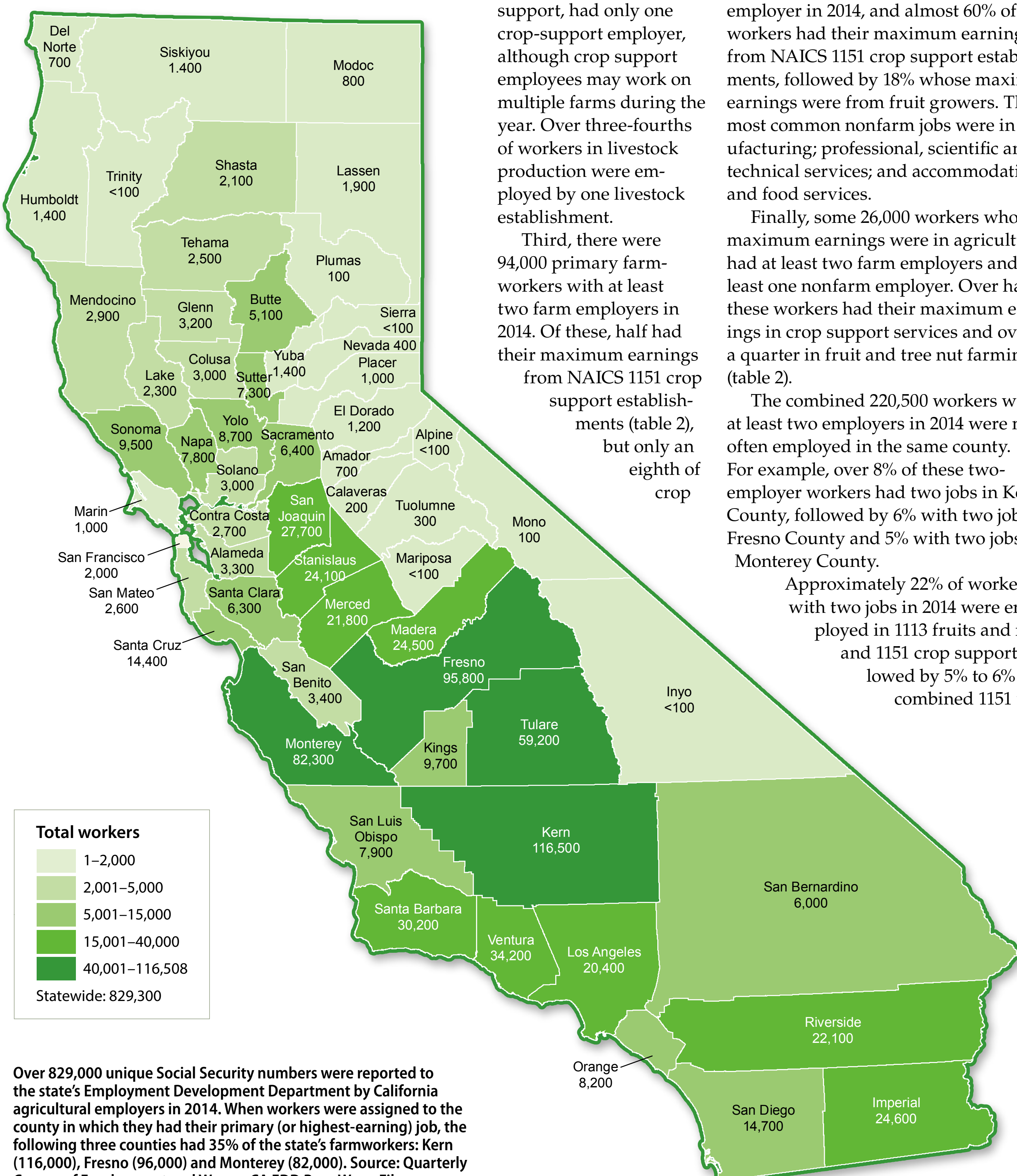
Third, there were 94,000 primary farmworkers with at least two farm employers in 2014. Of these, half had their maximum earnings from NAICS 1151 crop support establishments (table 2), but only an eighth of crop support workers had two farm employers. About 20% of those whose maximum earnings were from fruit (1113) and vegetable (1112) growers had at least two farm employers.

Almost 72,000 farmworkers had at least one farm and at least one nonfarm employer in 2014, and almost 60% of these workers had their maximum earnings from NAICS 1151 crop support establishments, followed by 18% whose maximum earnings were from fruit growers. The most common nonfarm jobs were in manufacturing; professional, scientific and technical services; and accommodation and food services.

Finally, some 26,000 workers whose maximum earnings were in agriculture had at least two farm employers and at least one nonfarm employer. Over half of these workers had their maximum earnings in crop support services and over a quarter in fruit and tree nut farming (table 2).

The combined 220,500 workers with at least two employers in 2014 were most often employed in the same county. For example, over 8% of these two-employer workers had two jobs in Kern County, followed by 6% with two jobs in Fresno County and 5% with two jobs in Monterey County.

Approximately 22% of workers with two jobs in 2014 were employed in 1113 fruits and nuts and 1151 crop support, followed by 5% to 6% who combined 1151 with



Over 829,000 unique Social Security numbers were reported to the state's Employment Development Department by California agricultural employers in 2014. When workers were assigned to the county in which they had their primary (or highest-earning) job, the following three counties had 35% of the state's farmworkers: Kern (116,000), Fresno (96,000) and Monterey (82,000). Source: Quarterly Census of Employment and Wages, CA EDD Base Wage File.

In 2014, the average earnings for workers in the fruit and tree nut farming sector were $17,600.

5613 employment services, 1113 fruits and nuts with another 1113 job, at least two 1151 crop support jobs, and 1112 vegetables with 1151 crop support.

Implications

The number of wage and salary workers employed on California farms is of great interest because of fears that farm labor shortages could reduce the state's production of labor-intensive crops. Knowing how many wage and salary workers are employed sometime during the year gives a more accurate portrait of worker earnings and mobility. In 2014, agricultural employers hired over 829,000 unique workers, which suggests that two workers filled the average year-round equivalent job, meaning that the total farm workforce was twice average farm employment.

Although the unemployment insurance data do not include the characteristics of farmworkers, they do show that most farmworkers have only one farm employer during the year, which indicates that California has a very stable agricultural workforce. An earlier study reported almost three workers for each year-round farm job in the 1990s, and a higher share of workers with more than one farm job (Khan et al. 2004). Analysis of data for 2007 and 2012 finds that the ratio had dropped to two unique workers for each average agricultural job (Hooker et al. 2015). The 2014 analysis presented here shows that this two-to-one worker-to-job ratio has remained constant. CA

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TABLE 2. Workers with two farm jobs and nonfarm jobs, 2014

NAICS code	Category	At least 2 agricultural employers	Share*	At least 1 agricultural and 1 nonagricultural employer	At least 2 agricultural employers and 1 or more nonagricultural employer
	Primary agricultural workers	94,127	100%	71,758	26,290
1111	Oilseed and grain farming	722	1%	515	206
1112	Vegetable and melon farming	7,690	8%	4,277	2,151
1113	Fruit and tree nut farming	30,291	32%	13,420	7,483
1114	Greenhouse and nursery production	2,567	3%	4,710	908
1119	Other crop farming	2,600	3%	1,643	565
1121	Cattle ranching and farming	1,869	2%	2,920	618
1122	Hog and pig farming	5	0%	15	3
1123	Poultry and egg production	161	0%	492	75
1124	Sheep and goat farming	15	0%	54	9
1125	Animal aquaculture	16	0%	91	10
1129	Other animal production	231	0%	439	91
1151	Support activities for crop production	47,555	51%	41,689	14,032
1152	Support activities for animal production	75	0%	471	25
1153	Support activities for forestry	77	0%	464	36

* Percentage of workers whose maximum earnings were in this NAICS and who had at least 2 agricultural employers in 2014.

Irrigation method does not affect wild bee pollinators of hybrid sunflower

by Hillary Sardiñas, Collette Yee *and* Claire Kremen

Irrigation method has the potential to directly or indirectly influence populations of wild bee crop pollinators nesting and foraging in irrigated crop fields. The majority of wild bee species nest in the ground, and their nests may be susceptible to flooding. In addition, their pollination of crops can be influenced by nectar quality and quantity, which are related to water availability. To determine whether different irrigation methods affect crop pollinators, we compared the number of ground-nesting bees nesting and foraging in drip- and furrow-irrigated hybrid sunflower fields in the Sacramento Valley. We found that irrigation method did not impact wild bee nesting rates or foraging bee abundance or bee species richness. These findings suggest that changing from furrow irrigation to drip irrigation to conserve water likely will not alter hybrid sunflower crop pollination.

Irrigation practices and water use efficiency are increasingly scrutinized by growers. Irrigated agriculture accounts for 80% of human-related water use in California (DWR 2013). In periods of drought, growers adopt water-saving irrigation practices at higher rates (Schuck et al. 2005). Drip irrigation, introduced to California in 1969, delivers water directly to the plant root zone, thus improving water efficiency; it is now used in approximately 40% of all irrigated fields (Taylor et al. 2014). Increases in irrigation efficiency can improve yield (Tilman et al. 2002; Wallace 2000), which is another reason growers may consider switching to drip irrigation. However, changes in irrigation practices may negatively impact other factors that determine crop success, such as pollination.

Wild bees are the most effective and abundant crop pollinators (Garibaldi et al. 2013). The majority of wild bees excavate nests beneath the soil (known as ground nesters). Irrigation has the potential to saturate nests, possibly drowning bee larvae and adults. It could also indirectly impact crop pollinators by affecting their foraging choices. Bee foraging decisions are often related to floral reward, namely nectar quantity and quality (Roubik and Buchmann 1984; Stone 1994). Nectar production is related to water availability; increased water leads to higher nectar volume expressed (e.g., Petanidou et al. 1999). Thus, an irrigation method that delivers more water, such as furrow, could make fields more attractive to wild bee pollinators, thereby increasing potential yields.

We compared the number of bees nesting and foraging in conventionally managed hybrid sunflower (*Helianthus annuus*) fields that were either furrow or drip

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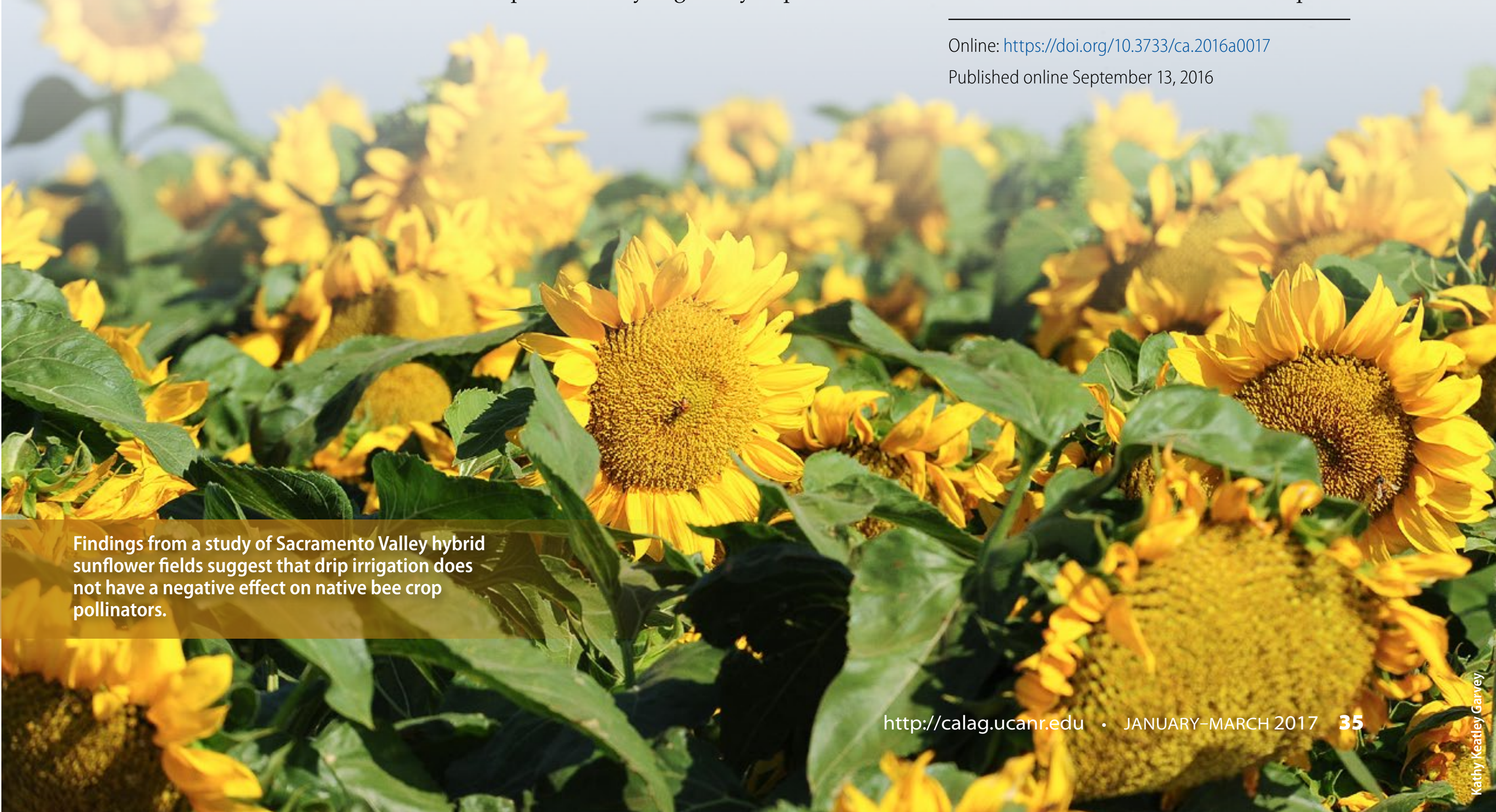


Findings from a study of Sacramento Valley hybrid sunflower fields suggest that drip irrigation does not have a negative effect on native bee crop pollinators.

Kathy Keatley Garvey

irrigated. We predicted that drip-irrigated fields would support higher numbers of nesting bees, but that more bees would forage in furrow-irrigated fields, due to indirect effects.

We also examined whether irrigation had the same effect on different bee groups. Sunflower is visited by both specialist and generalist ground-nesting native bee pollinators that nest within crop fields (Hurd et al. 1980; Kim et al. 2006; Sardiñas et al. 2016). Generalist bees visit a variety of plant species, whereas specialists collect only sunflower pollen to provision their nests. While both of these types of pollinators could be susceptible to irrigation methods, sunflower specialists are more tied to the crop and could experience potential negative effects of irrigation more strongly.

Study design

We sampled five drip- and five furrow-irrigated sites in 2013 during the summer months at peak sunflower bloom (July to August). Site types were paired by bloom time, sunflower variety and landscape context (e.g., percent natural habitat within 1 km) to reduce extraneous factors that could contribute to differences in

The stages of furrow irrigation, also known as flood irrigation: during irrigation (A), following saturation (B) and after water applied to the field has dried (C). Drip-irrigated fields lack the cracking found in furrows of flood-irrigated fields; the soil surface appears dry, even during irrigation events (D).

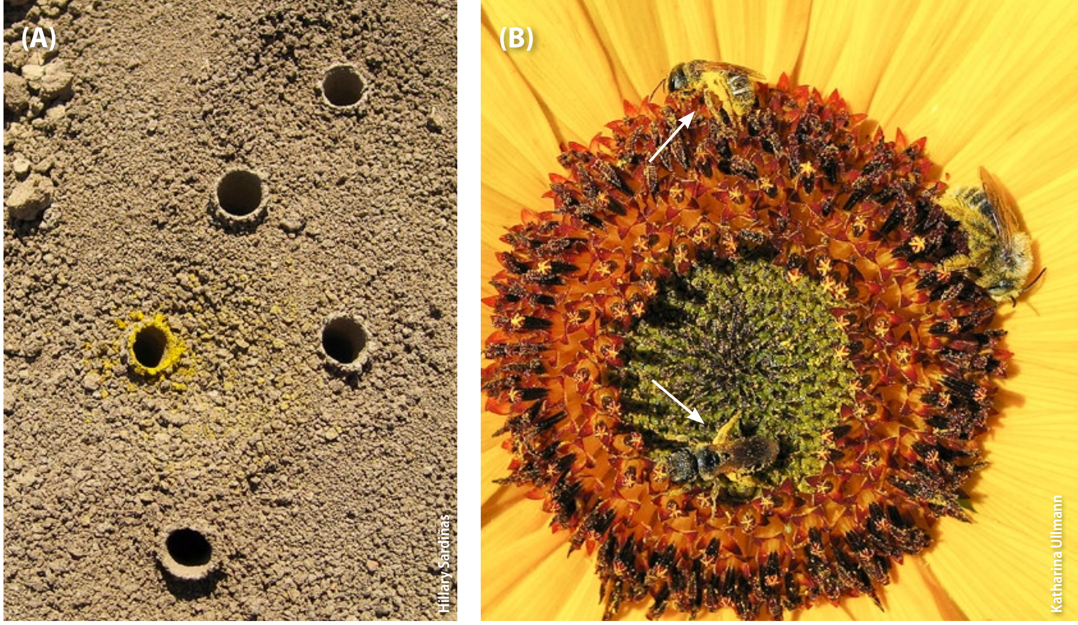
nesting and foraging patterns observed. All fields were located in Yolo County, California.

Bee sampling

We used 1.96-square-foot emergence traps (BugDorm, MegaView Science, Taiwan) to sample nesting bees (Sardiñas and Kremen 2014; Sardiñas et al. 2016). The traps have open bottoms to allow nesting bees to leave their nest. However, when they emerge, they are funneled to the top of the trap and into a kill jar. We placed the traps at dusk, after bees had returned to their nests, and weighted down the edges with soil to prevent bees from entering or exiting the trap. There were 20 traps in each field along two parallel 328-foot transects that ran into each field (fig. 1). Traps were 32.8 feet apart. Approximately 20 hours later, we removed all bees from apical kill jars (which were filled with soapy water).

The day following emergence trap sampling, we netted foraging bees visiting sunflowers for 30 minutes along each of the two transects. We set emergence traps only if weather conditions the following day were predicted to be ideal for netting: temperature > 64°F, wind speed < 5.5 mph and low cloud cover (clear skies).

All bees were pinned, then identified by Dr. Robbin Thorp, professor emeritus, UC Davis Department of Entomology. They are currently housed in UC Berkeley's Essig Museum of Invertebrate Zoology.



Nest entrances of the ground-nesting sunflower specialist bee, *Diadasia enavata* (A). Sunflower is visited by both specialist and generalist pollinators, including the generalist *Halictus ligatus* (B, arrows) and the specialist *Diadasia enavata* (B).

Vegetation

To determine whether vegetative factors influenced bee abundance or species richness, we estimated percentage sunflower bloom, stem density (count of all sunflower stems), weed density (count of all individual weeds) and weed bloom. Sunflower bloom and stem density were correlated, as were weed density and weed bloom, which allowed us to use only one metric for each category in our analyses.

Statistical analyses

We examined the effect of irrigation method on the abundance of nesting bees captured in emergence traps and foraging bees netted at blooms using a generalized linear model with a Poisson distribution in the R package lme4 (Bates et al. 2015). Independent variables were irrigation type, stem density and weed density. Site was a random effect. We repeated this analysis for species richness, which was calculated using the R package vegan (Oksanen et al. 2013). We included only female bees in our analyses of nesting rates, as male bees do not excavate nests (Kim et al. 2006).

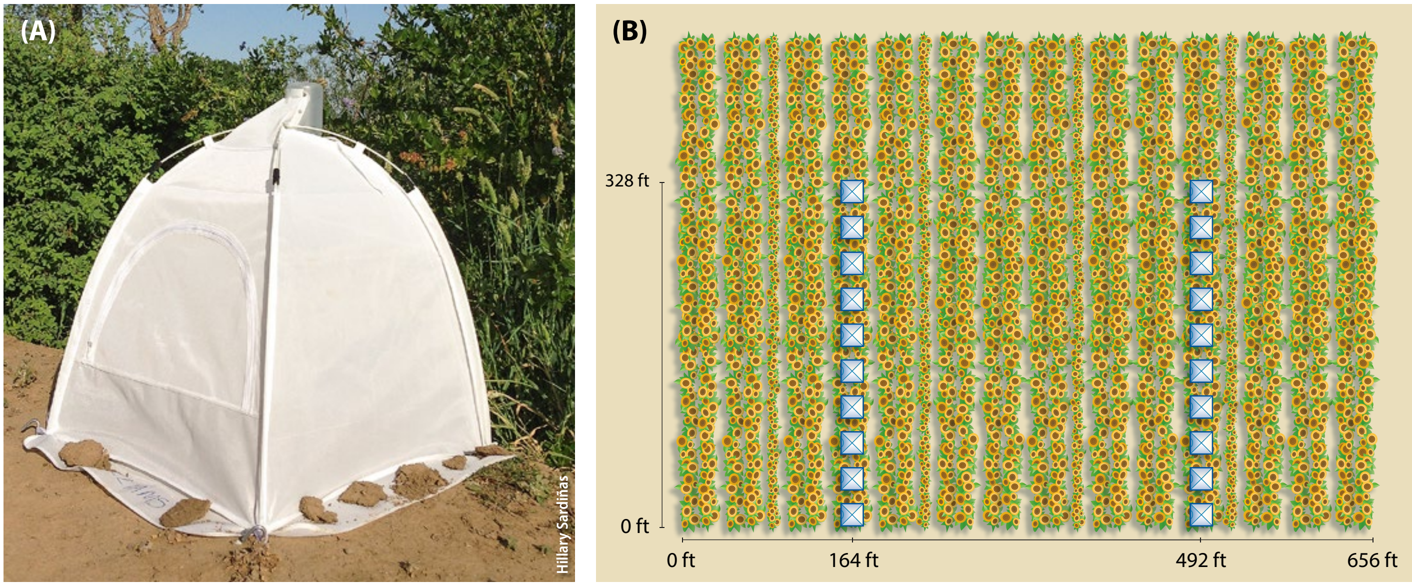


Fig. 1. Emergence traps (A) were used to collect bees nesting in sunflower fields and were placed along two parallel transects (B) running 328 feet into the fields. Transects were located 164 feet from field edges and 328 feet apart. Ten traps (white boxes, B), 32.8 feet apart, were placed along each transect.

Bee nesting and foraging counts

We collected 42 bees from six species nesting within fields and 735 bees from 14 species foraging on sunflower blooms (table 1). All of the species we collected nesting were also found foraging. The two most abundant species nesting in sunflower fields were the sunflower specialist *Melissodes agilis* and the generalist sweat bee *Lasioglossum incompletum*. These bees were among the most abundant bee species found foraging. One other species of sweat bee (*Halictus ligatus*) and three other sunflower specialist bees (*Diadasia enavata*, *M. robustior* and *Svastra obliqua expurgata*) foraged in high numbers, yet were not detected nesting within fields.

TABLE 1. Species collected nesting in sunflower fields and foraging on sunflowers

Species	Specialization	Nesting	Foraging
Bombus vosnesenskii	Generalist	0	1
Diadasia enavata	Specialist	0	53
Halictus ligatus	Generalist	1	51
Halictus tripartitus	Generalist	1	20
Lasioglossum (Dialictus) spp.	Generalist	6	1
Lasioglossum incompletum	Generalist	16	43
Megachile parallela	Specialist	0	1
Melissodes agilis	Specialist	17	393
Melissodes lupina	Specialist	0	8
Melissodes robustior	Specialist	0	63
Peoponapis prunoisa	Specialist*	0	1
Svastra obliqua expurgata	Specialist	0	88
Triepeolis concavus	Parasite	0	3
Triepeolis subnitens	Parasite	1	9
Total no. of bees		**42**	**735**
Total no. of species		**6**	**14**

* Specialist of squash, not sunflower.

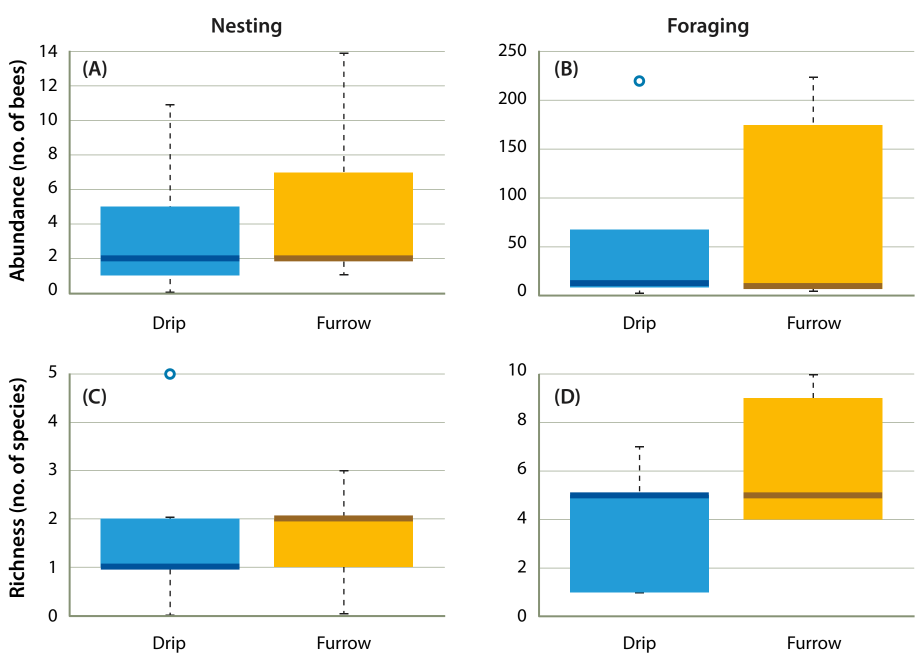


Fig. 2. Irrigation method did not affect the abundance or species richness of nesting bees (A, C) or foraging bees (B, D) in sunflower fields. Boxes are upper and lower quartiles, dark bar is the mean, whiskers show the maximum and minimum values, and points are outliers.

Bee response to irrigation method

We did not find a difference in the abundance of bees nesting in drip- versus furrow-irrigated fields (fig. 2A; $z = 0.29$, $P = 0.77$). Similarly, the species richness of nesting bees did not vary with irrigation type (fig. 2C; $z = -0.40$, $P = 0.68$). Sunflower stem density ($z = 0.71$, $P = 0.48$) and weed density ($z = -0.15$, $P = 0.85$) did not impact nesting rates (data not shown), which is not surprising given that we attempted to control for variability in bloom by sampling at peak bloom in all fields (> 90% of stems in bloom).

As with nesting rates, the abundance (fig. 2B; $z = 0.12$, $P = 0.89$) and species richness (fig. 2D; $z = 1.60$, $P = 0.11$) of native bees actively foraging on sunflower was unaffected by irrigation type. Sites that were sampled at the same time appeared to contain similar numbers of foraging bees (fig. 3) except for sites D3 and F3, where the drip-irrigated site contained almost twice as many foraging bees. However, we were unable to assess the effect of sampling date in our analyses as each site was sampled only once.

Study sample size

This study was conducted during a single year; therefore, the results reflect nesting and foraging during this one sampling season. Our sample size may not have been large enough to detect small differences in nesting rates. While the strength of the nesting results indicates that sunflower bee nesting is likely not linked to irrigation method, additional evidence from future studies could help confirm this conclusion. We collected numbers and species of bees in our netted sample that were similar to those in other studies in sunflower in our study region (Greenleaf and Kremen 2006a; Sardiñas and Kremen 2015); this similarity suggests our findings on the relationship of foraging bees to irrigation type may be robust to the effects of small study size.

Soil moisture conditions

Soil moisture has been shown to positively affect nesting (Julier and Roulston

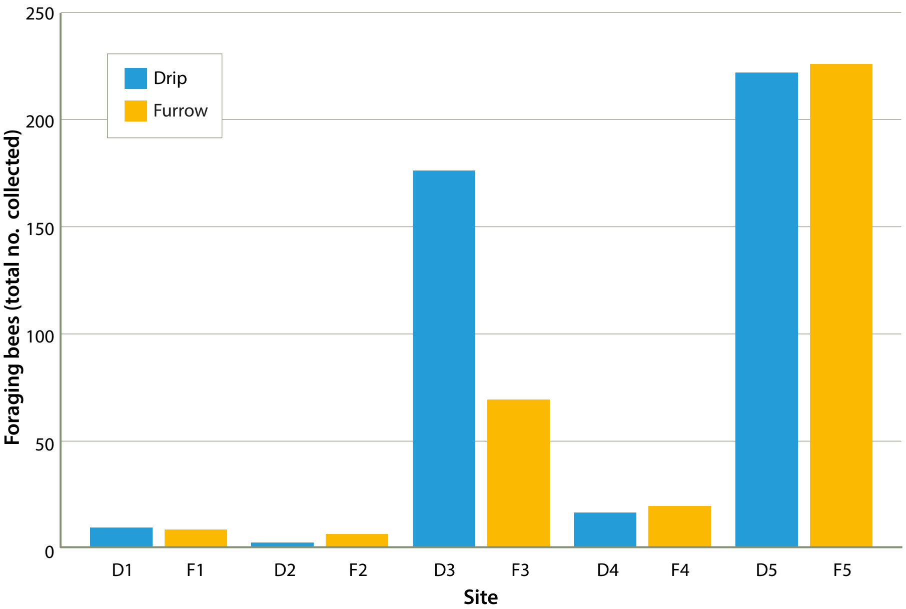


Fig. 3. Foraging bee abundance in site pairs (1–5), which were drip- (D) and furrow- (F) irrigated sunflower fields that had the same variety and bloom time.

2009; Xie et al. 2013); therefore, irrigation may help make fields attractive nest site locations for crop pollinators. Soil moisture, however, may be correlated to a number of other conditions, including soil compaction (Xie et al. 2013). In the sunflower study system, generalist wild bees have been found to nest both within crop fields as well as along un-irrigated field edges (Sardiñas et al. 2016). Soil moisture may not exert as strong of effects as other characteristics that affect nest site selection and nesting success of generalists, while sunflower specialists may be better adapted to the within field conditions where sunflowers are grown.

Bees' adaptation to inundation

The most abundant foraging and nesting sunflower specialist species, *M. agilis*, has been recorded nesting between irrigation furrows in crop fields since the early 1980s (Parker et al. 1981). The cells in their nests are lined with wax, which may have some hydrophobic properties (Cane 1981). Water-resistant wax linings have been recorded in the nests of other bee species (e.g., Rust et al. 2004).

Species whose nests are not regularly exposed to wet conditions may be able to withstand extreme conditions, such as flooding from a hurricane (Cane 1997), although some species may have local nesting aggregations wiped out by similar events if the soil structure is compromised, for example by mud slides (Fellendorf et al. 2004). The ability to withstand irrigation or natural saturation events has not been recorded for most of the bees in this study; however, the bees' presence in regularly irrigated fields indicates that irrigation may not be a factor that significantly limits or disrupts their nesting activity.

Which irrigation method is best?

Although drip irrigation is often considerably more expensive than furrow irrigation, there are numerous benefits other than water use efficiency associated with drip irrigation, including disease management and the ability to irrigate oddly shaped or uneven fields (Shock 2013). Drip irrigation, especially subsurface drip, can reduce the total amount of acre-feet applied because it reduces evaporation

In 2013, researchers sampled five drip- and five furrow-irrigated sites in Yolo County at peak sunflower bloom (July to August).

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(Ayars et al. 2015). Over 85% of processing tomato fields in California have been converted to drip irrigation systems, which has increased yields without compromising crop quality (Taylor et al. 2014). Sunflower is often rotated into fields that contained tomato the year prior because the two crops have similar row spacing. Growers leave the drip tape down (H. Sardiñas, personal observation), maximizing their investment through reuse of the drip tape.

Water efficiency is especially important in California's Central Valley, where climate change is expected to increase temperatures 2°F to 3.6°F by 2050 and the frequency, intensity and duration of summer heat waves are expected to increase (Jackson et al. 2011). The current drought is driving up the cost of water and limiting water access, leading growers to increase well drilling to obtain groundwater (Daniel Munk, UC Cooperative Extension, personal communication). Wells were expected to account for 53% of all irrigation water in 2015; however, increased rates of pumping caused by the prolonged drought has caused the water level to drop below the depth of many wells (Howitt et al. 2014); this excess pumping is also leading to land subsidence.

Drip irrigation is a viable method to combat the drought without compromising crop pollination from wild bees.

Although this study was conducted in hybrid sunflower fields, the irrigation methods applied are typical of those used in row crops throughout the Central Valley. The generalist sweat bees that nest and forage on sunflower are among the most common crop pollinators in the region, and pollinate a variety of crops from watermelon to tomato (Greenleaf and Kremen 2006b; Morandin and Kremen 2013). We would therefore expect our findings to apply to a number of different annual crop types.

The combined efficiency benefits and lack of negative effects on native bee crop pollinators indicate that drip irrigation is a viable method to combat the drought without compromising crop pollination from bees nesting within crop fields. CA

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Research Article

Wood chip denitrification bioreactors can reduce nitrate in tile drainage

by Tim Hartz, Richard Smith, Mike Cahn, Thomas Bottoms, Sebastian Castro Bustamante, Laura Tourte, Kenneth Johnson *and* Luke Coletti

Widespread contamination of surface water with nitrate-nitrogen (NO_3-N) has led to increasing regulatory pressure to minimize NO_3-N release from agricultural operations. We evaluated the use of wood chip denitrification bioreactors to remove NO_3-N from tile drain effluent on two vegetable farms in Monterey County. Across several years of operation, denitrification in the bioreactors reduced NO_3-N concentration by an average of 8 to 10 milligrams per liter (mg L^{-1}) per day during the summer and approximately 5 mg L^{-1} per day in winter. However, due to the high NO_3-N concentration in the tile drainage (60 to 190 mg L^{-1}), water discharged from the bioreactors still contained NO_3-N far above the regulatory target of < 10 mg L^{-1}. Carbon enrichment (applying soluble carbon to stimulate denitrifying bacteria) using methanol as the carbon source substantially increased denitrification, both in laboratory experiments and in the on-farm bioreactors. Using a carbon enrichment system in which methanol was proportionally injected based on tile drainage NO_3-N concentration allowed nearly complete NO_3-N removal with minimal adverse environmental effects.

Release of nitrogen (N) from agricultural fields, primarily in nitrate (NO_3^-) form, is a significant surface water quality concern across the United States. This problem is particularly acute in the Salinas and Pajaro Valleys of central coastal California. Vegetable crops such as lettuce and broccoli dominate production, representing approximately 80% of the irrigated acreage, with fields typically producing two or three crops per year. High crop value and exacting market standards for product size and color provide incentives for heavy fertilization.

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Given the sensitivity of these crops to water stress and soil salinity, irrigation is applied frequently, often with a substantial leaching fraction to minimize salt buildup. The production intensity and widespread use of tile drain systems to improve farm productivity have contributed to significant NO_3-N impairment of surface water in this region. Los Huertos et al. (2001) reported that drainage ditches receiving discharge from tile drain systems commonly had NO_3-N concentrations exceeding 70 mg L^{-1}.

U.S. Environmental Protection Agency nutrient total maximum daily load (TMDL) regulatory processes are underway to limit NO_3-N loading in both the Salinas and Pajaro River watersheds. The TMDL surface water NO_3-N target concentration in the lower Salinas River Basin ranges from the federal drinking water standard of 10 mg L^{-1} down to 1.4 mg L^{-1}, depending on location and season.

Extensive research has been conducted on fertilizer and irrigation management in the area's vegetable production system, and the potential for significant

Using carbon enrichment in wood chip bioreactors can reduce nitrate-nitrogen levels in drainage water from Salinas Valley vegetable fields. In this photo, tile drain water is pumped from a collection sump into a surface ditch that eventually drains into coastal wetlands.

Tim Hartz

improvement has been documented (Bottoms et al. 2012; Breschini and Hartz 2002a, 2002b). While more efficient fertilizer and irrigation management could substantially reduce the NO_3-N concentration of tile drainage, it is unlikely that environmental target concentrations could be consistently achieved through crop management practices alone. Some remedial treatment of tile drainage would undoubtedly be required.

Denitrification

In both terrestrial and aquatic ecosystems, a process called heterotrophic denitrification, a microbial process, converts NO_3-N to gaseous forms of N using a carbon (C) source as an electron donor and to support microbial growth (Coyne 2008). The conversion is performed by specialized bacteria under anaerobic conditions.

The possibilities of managing denitrification through the use of denitrification bioreactors have been widely studied. Bioreactors are chambers filled with carbon-rich media through which water containing NO_3-N is cycled for treatment. Bioreactors have been evaluated for remediating different types of agricultural wastewater, including tile drainage, surface runoff and greenhouse effluent (Blowes et al. 1994; Robertson et al. 2009; Robertson and Merkley 2009; Schipper, Cameron et al. 2010).

Denitrification rates achieved in bioreactors range widely (Schipper, Robertson et al. 2010). The main factors governing denitrification rates are the type of media used and the water temperature. Many types of media have been evaluated, including cardboard, straw, corncobs and green waste. However, field-scale installations have typically used wood chips; wood chips are widely available, relatively low in cost, have stable hydraulic characteristics and are long-lasting (Schipper, Robertson et al. 2010). Their main drawback is low C availability, which can limit the denitrification rate (Cameron and Schipper 2010; Warneke et al. 2011). As is the case with most biological processes, increasing water temperature increases the rate of denitrification (Schipper, Robertson et al. 2010).

Wood chip bioreactors can have potentially detrimental environmental effects, which must be weighed against the positive effect of reducing NO_3-N. The

The denitrification bioreactor was dug with a backhoe and fitted with a polyethylene liner.

release of dissolved organic carbon (DOC) and tannins during bioreactor start-up may be similar to the release from sawmills, where control measures are required (Schipper, Robertson et al. 2010). Incomplete denitrification can result in significant release of nitrous oxide (N_2O), a potent greenhouse gas. Both gaseous N_2O emission and dissolved N_2O release in bioreactor effluent can be significant (Moorman et al. 2010; Warneke et al. 2010).

In coastal California, tile drain systems may operate year-round. Tile drainage volume and NO_3-N concentration can vary widely over time, which presents a challenge to consistently effective remediation. Adjusting hydraulic residence time (HRT), the time the drainage stays in the bioreactor, is the primary tool for dealing with varying nitrate loads, but a bioreactor built to handle the average load will be either over- or underdesigned as the N load varies. An alternative technique is to add a soluble C source during times of high N loading, to augment the microbial-available C in the wood chips and increase the denitrification rate.

Carbon enrichment is commonly used in municipal wastewater treatment to stimulate denitrification. To date there have been no reports on the efficacy of C enrichment to improve the performance of wood chip bioreactors. Our research goals were to evaluate the performance of wood chip denitrification bioreactors in remediating high-nitrate tile drainage from Salinas Valley vegetable fields and to assess the potential of C enrichment to improve bioreactor performance.

Field bioreactors

Two pilot-scale denitrification bioreactors were constructed on tile-drained farms in northern Monterey County in spring 2011. Pits were dug, lined with polyethylene sheeting and filled with wood chips. The chips, which were obtained from the Monterey Regional Waste Management District, were made from untreated scrap construction wood.

The bioreactor at site 1 was 45 feet long, 5.4 feet wide and 3.8 feet deep (13.7 by 1.6 by 1.2 meters); the bioreactor at site 2 was 33 feet long, 3 feet wide and 4.5 feet deep (10.1 by 0.9 by 1.4 meters). The water-holding capacity was approximately 6 gallons per cubic foot of volume, or about 5,500 and 2,600 gallons (20.8 and 9.8 cubic meters) at sites 1 and 2, respectively. Approximately 70% of that water was free-draining, meaning 30% was absorbed by the chips. The bioreactors were not covered by tarps or soil.

Denitrification bioreactor being filled with wood chips.

Completed denitrification bioreactor.

Drainage water from the farms' tile drain systems was pumped from collection sumps into the bioreactors at a constant flow rate to achieve approximately 2 days of HRT, based on total water volume. The HRT of free-draining water was undoubtedly less than 2 days, since the water absorbed by the chips was not exchanging as quickly. The water volume entering each bioreactor was recorded using a flowmeter. Water temperature was continuously monitored by thermistors placed in the middle of each bioreactor and 2 feet from the bottom. The water drained by gravity from the bioreactor outlet into surface ditches draining the farms.

The bioreactors were operated without carbon enrichment from their construction in 2011 until fall 2013. Inlet and outlet flows were sampled an average of 2 or 3 times per week during the crop production season (March to October) and once per week during the winter. NO_3-N was determined on all samples, with nitrite-nitrogen (NO_2-N, a denitrification intermediate) and DOC analyzed periodically. NO_3-N and NO_2-N concentrations were determined using the spectrophotometric method of Doane and Horwath (2003). DOC was determined by UV-persulfate oxidation utilizing a Phoenix 8000 analyzer (Teledyne-Tekmar, Mason, OH) after filtration through 0.30-µm glass fiber filters.

Carbon enrichment studies

In 2014, six laboratory-scale bioreactors of approximately 0.5 cubic feet (14 liters) were fabricated using PVC pipe. These bioreactors were filled with aged wood chips collected from the field bioreactors. They were installed on the UC Davis campus in a temperature-controlled room maintained at 62°F (17°C) to simulate the summer temperature of tile drainage in the field bioreactors. Peristaltic pumps continuously supplied NO_3-N solution to maintain a 2-day HRT (based on total water volume), also simulating the operation of the field bioreactors.

Two of the bioreactors received only NO_3-N solution (no C enrichment), while the others received that same solution augmented by C from either methanol or glycerin (two bioreactors for each C source). These C sources were selected based on their use in the denitrification step of municipal wastewater treatment and the modest cost per unit of C. Evaluation of C enrichment effects on denitrification rate began following a 10-day acclimation period to ensure the development of a bacterial population capable of metabolizing the C source; similarly, when C enrichment levels were changed, there was a 10-day acclimation period before evaluation.

The effect of C enrichment on denitrification was evaluated over the range of 40 to 100 mg L^{-1} C for methanol and 100 to 150 mg L^{-1} C for glycerin. Daily samples were collected on 6 to 8 different days for each level of C enrichment, with NO_3-N concentration determined as previously described. Carbon enrichment effects were calculated as the reduction in NO_3-N concentration beyond that observed in the control (unenriched) bioreactors.

A subsequent laboratory experiment investigated the feasibility of achieving complete denitrification of high-nitrate water using C enrichment. An inlet NO_3-N concentration of 160 mg L^{-1} and an HRT of 2 days were maintained throughout the study to simulate conditions at the site 1 bioreactor. Two levels of C enrichment were evaluated for each C source (120 and 230 mg L^{-1} C from methanol and 160 and 320 mg L^{-1} C from glycerin); the higher levels were chosen to be adequate, based on the initial laboratory results, to allow complete denitrification. Each level of C enrichment was evaluated over a 5-week period, with samples collected on 25 days for NO_3-N and NO_2-N determination.

N_2O emission from the laboratory bioreactors was also measured. Measurements were made on 2 days for each combination of C source and concentration. Bioreactors were sealed with an airtight PVC cap, and air was circulated through the headspace of the bioreactors at a constant rate of approximately one air exchange every 2 minutes. After an hour of calibration, four headspace air samples were collected 15 minutes apart via needle and syringe and stored in evacuated glass tubes until analysis by gas chromatography.

Matching samples of outlet water were gathered for determination of dissolved N_2O. The water samples were injected into sealed glass tubes containing 2 M NaOH to stop biological activity in the water. After 24 hours of equilibration, to allow dissolved N_2O to come to equilibrium with the air in the tube, the headspace in these tubes was resampled and stored in evacuated glass tubes until analysis by gas chromatography.

The effect of C enrichment on the performance of the site 1 bioreactor was evaluated in 2015. Only methanol was evaluated in the field because of its higher efficiency (lower C:N denitrification ratio) than glycerin and our observation that the high viscosity of glycerin complicated its handling and use. Methanol was injected at a constant rate of 140 mg L^{-1} C from April 22 until May 5 to ensure establishment of bacteria capable of metabolizing methanol. The C injection rate was increased to 270 mg L^{-1} on May 5 and maintained at that level through June 17. Inlet and outlet samples were collected on 12 days during this period and analyzed for both NO_3-N and NO_2-N; DOC concentration was determined on 5 of those days.

On July 17, an optical nitrate sensor, an in-situ ultraviolet spectrophotometer (ISUS; Johnson and Coletti 2002), was installed at site 1. This sensor, designed and constructed by scientists at the Monterey Bay Aquarium Research Institute, allowed real-time NO_3-N monitoring of the tile drainage. ISUS sensors and the related SUNA (submersible UV nitrate analyzer) sensor have been shown to provide accurate NO_3-N determination in a variety of ground and surface waters (Pellerin et al. 2013; Sackmann 2011).

A C enrichment system was developed in which methanol was injected proportionally to the inlet NO_3-N concentration at a ratio of approximately 1.4:1 (C:N, on a mass basis), the ratio suggested by the laboratory experiments as being adequate to allow complete denitrification. Inlet NO_3-N concentration was determined by the ISUS sensor every 15 minutes, with that value determining the methanol injection rate.

This C enrichment system operated from Aug. 15 through Oct. 6, 2015. Inlet and outlet NO_3-N and NO_2-N concentrations were determined on samples collected on 14 days during this period, with DOC measured on 6 days. On each of 4 days, four replicate samples of outlet water were collected 15 minutes apart for measurement of dissolved N_2O. The water flow rate was increased on Sept. 17 to reduce HRT to 1.7 days; this flow rate was maintained through Oct. 6.

Field bioreactors reduce NO_3-N

Denitrification began at both sites within days of the initial filling of the bioreactors. Denitrifying bacteria are ubiquitous, and seeding of inoculum was not necessary. Water temperature in the bioreactors averaged approximately 62°F (17°C) during the summer and 55°F (13°C) during the winter (fig. 1); the water temperature pattern was consistent across years.

Inlet water typically ranged between 5 and 10 mg L^{-1} DOC. A high level of DOC was present initially in bioreactor effluent, but it declined to < 20 mg L^{-1} after several weeks of operation (fig. 2). After the first summer season of operation, outlet DOC stabilized between 10 and 15 mg L^{-1}. Bioreactor effluent was also dark colored for the first several weeks of operation, undoubtedly due to tannins leached from the wood chips. To minimize any adverse environmental effects arising from bioreactor start-up, the effluent from the initial weeks of operation might best be applied on fallow ground as pre-irrigation. Because the salinity of tile drainage can be high (it ranged from 2 to 5 dS m^{-1} at sites 1 and 2), blending with a higher-quality water source may be required.

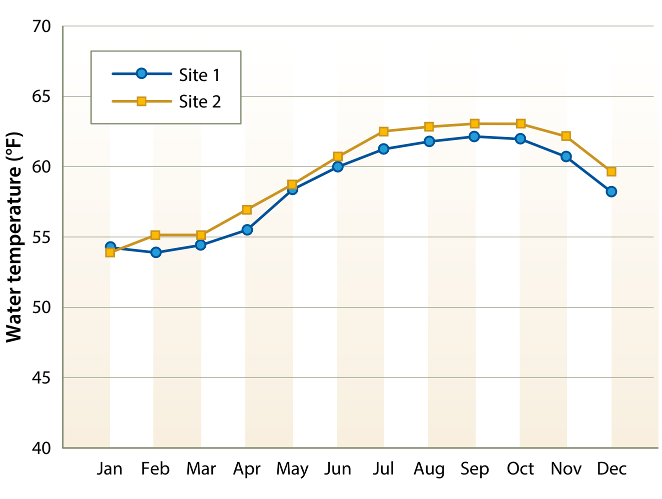

Fig. 1. Monthly mean water temperature in the bioreactors from January through December 2012.

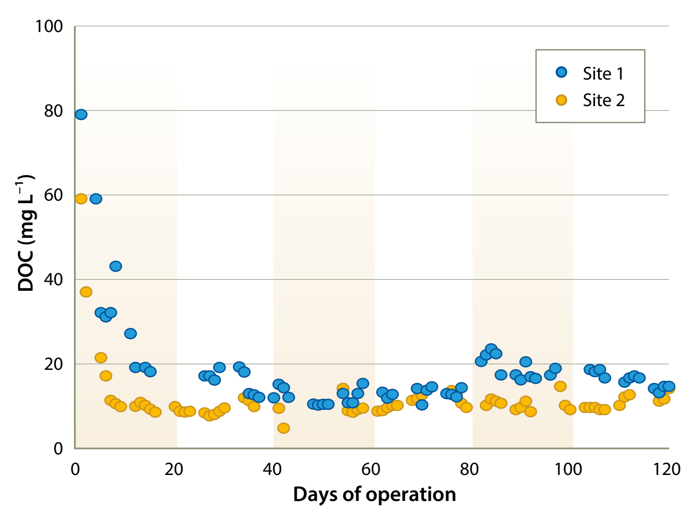

Fig. 2. Dissolved organic carbon (DOC) in bioreactor effluent in the initial 4 months of bioreactor operation.

Tile drain effluent had consistently high NO_3-N concentration, ranging between 100 and 180 mg L^{-1} at site 1, and 60 and 120 mg L^{-1} at site 2 (fig. 3). There was no clear seasonal NO_3-N trend. Denitrification rates were quite consistent between sites and across years. During the summer, NO_3-N concentration declined by an average of 8 to 10 mg L^{-1} per day of HRT (equivalent to approximately 6.4 to 8.0 g N denitrified per cubic meter of bioreactor volume per day of HRT, fig. 4). Denitrification slowed during the winter, undoubtedly due to lower water temperature; NO_3-N decreased by an average of approximately 5 mg L^{-1} per day of HRT from November through March.

At both sites, tile drainage NO_2-N was typically < 0.2 mg L^{-1}. In the initial months of operation in 2011, bioreactor treatment increased NO_2-N concentration by several mg L^{-1}, but NO_2-N in bioreactor effluent gradually declined to < 0.3 mg L^{-1} by that fall and remained below that level thereafter.

The denitrification rate observed during the summer was similar to that reported for a wood chip bioreactor treating a high-nitrate solution discharged from a greenhouse in New Zealand (Schipper, Cameron et al. 2010; Warneke et al. 2010) and higher than reported from sites treating water with lower NO_3-N (Schipper, Robertson et al. 2010). However, due to the high NO_3-N concentration of the tile drainage at these sites, water leaving the bioreactors after 2 days of HRT was often still above 100 mg L^{-1}. To reach an environmentally acceptable NO_3-N level, bioreactor treatment would have to be extended for many days, or much more rapid denitrification achieved.

We found it necessary to annually apply new wood chips at a rate of about 10% of the bioreactor volume to maintain the chip level. Most of the wood chip degradation undoubtedly occurred at the saturated/unsaturated interface, because wood chip half-life in the saturated zone has been reported to be > 30 years (Moorman et al. 2010). Chip degradation could be significantly reduced by installing an impermeable cover to separate the saturated and unsaturated zones.

TABLE 1. Effect of carbon enrichment on laboratory bioreactor performance

	Inlet (mg L^{-1})		Outlet (mg L^{-1})*		N_2O released (% of denitrified N†)	
Treatment	**NO_3-N**	**Carbon**	**NO_3-N**	**NO_2-N**	**Gaseous N_2O**	**Dissolved N_2O**
Control	160	Unenriched	151 ± 1‡	< 1	0.6 ± 0.2	11.9 ± 1.8
Methanol	160	120	34 ± 2	8 ± 0.4	1.6 ± 0.1	6.5 ± 0.8
	160	230	< 1	< 1	1.2 ± 0.1	<0.1
Glycerin	160	160	44 ± 3	3 ± 0.2	1.0 ± 0.2	11.9 ± 0.9
	160	320	< 1	< 1	1.0 ± 0.4	0.4 ± 0.1

* NO_3-N and NO_2-N concentrations are the means of two replicate columns over 25 days of sampling for each C source/C concentration combination.

† N_2O values represent the means of eight replicate measurements across 2 days of sample collection for each C source/C concentration combination.

‡ ± numbers indicate the standard error of measurement.

C enrichment removes most NO_3-N

Results from the laboratory studies confirmed that the wood chips were carbon-limited and that C enrichment dramatically increased denitrification rate. Across the range of C concentrations evaluated, there was a stable stoichiometric ratio between C enrichment and denitrification rate. That ratio was approximately 1.4:1 (C applied : N denitrified, on a mass basis) for methanol and 2.0:1 for glycerin. When C was provided at these ratios, nearly complete removal of 160 mg L^{-1} NO_3-N was achieved within 2 days of HRT (table 1).

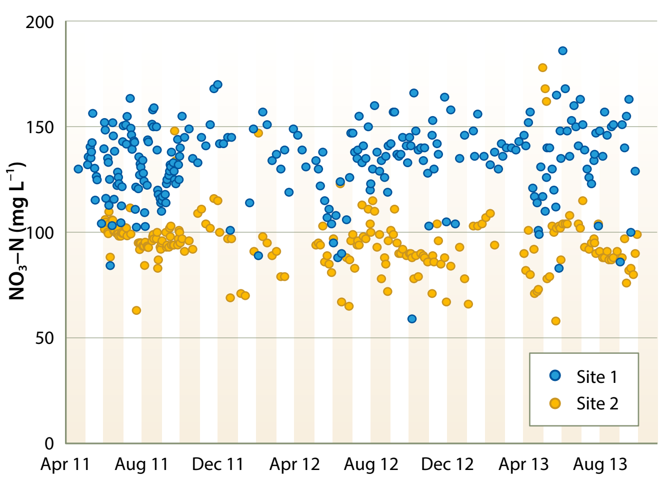

Fig. 3. NO_3-N concentration in tile drainage entering the bioreactors, 2011–2013.

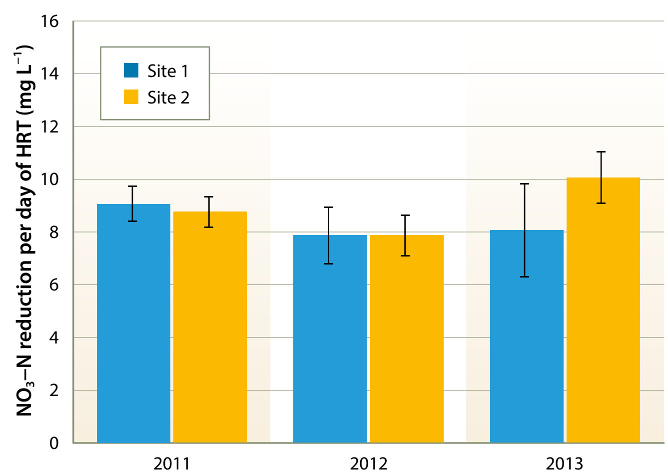

Fig. 4. Mean summer (June to September) denitrification rates achieved per day of hydraulic residence time (HRT); bars indicate standard error of measurement.

At lower levels of C enrichment, significant amounts of NO_2-N and N_2O were present in outlet water, signaling incomplete denitrification. In the unenriched control bioreactors, gaseous N_2O release was slight, but dissolved N_2O release in outlet water was substantial (when expressed as a percentage of denitrified N). A low level of C enrichment resulted in gaseous and dissolved N2O release as high as 1.6% and 11.9% of denitrified N, respectively. However, gaseous N_2O release was reduced and dissolved N_2O release nearly eliminated when C enrichment was sufficient to complete denitrification.

From May 5 through June 17, 2015, inlet NO_3-N averaged 170 mg L^{-1}, varying from 150 to 193 mg L^{-1}. Outlet water NO_3-N was consistently below 1 mg L^{-1}, with no measureable NO_2-N.

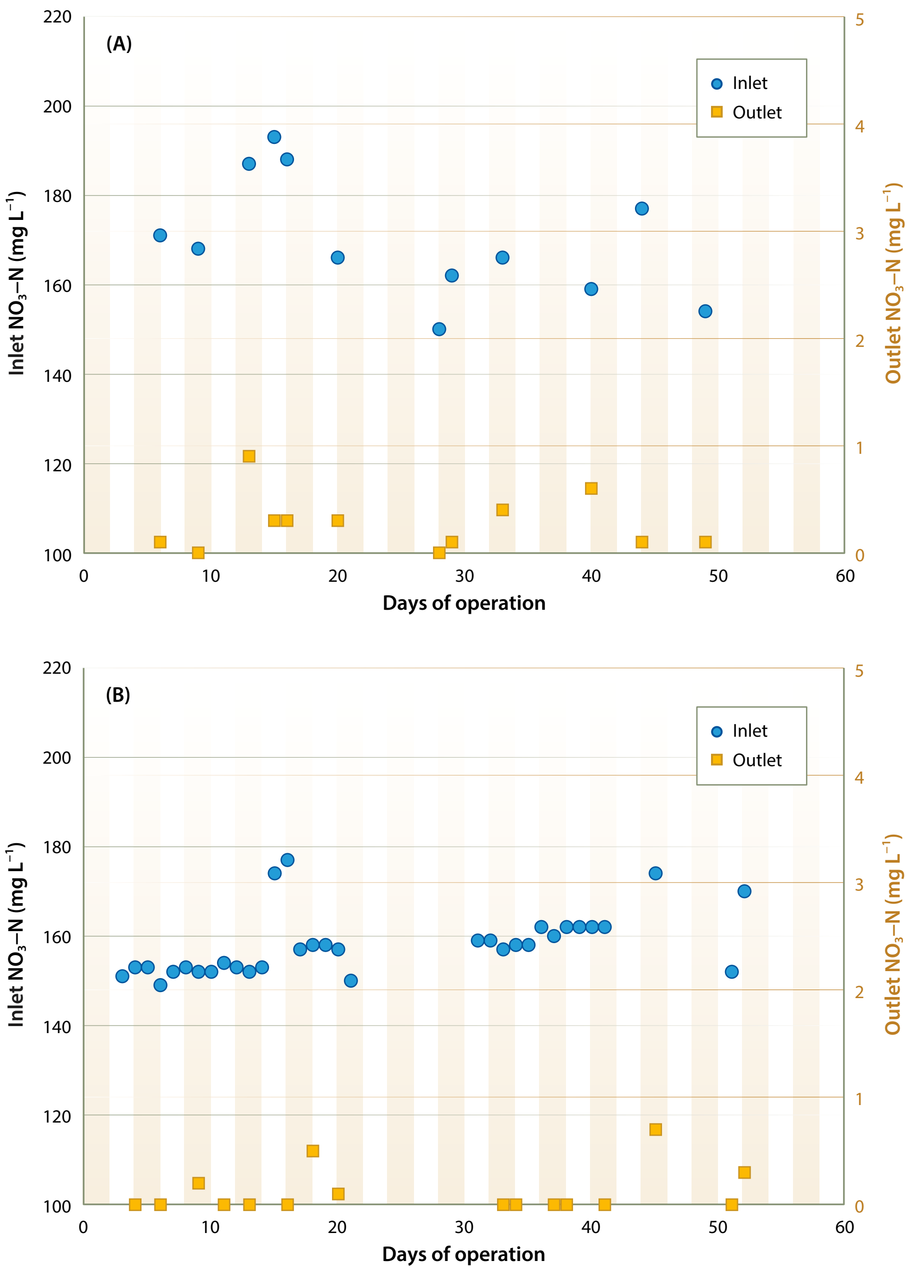

Fig. 5. Effect of carbon enrichment on bioreactor outlet NO_3-N (mg L^{-1}) at site 1; constant enrichment of 270 mg L^{-1} C (A), and proportional enrichment at a C:N ratio of 1.4:1 in inlet water (B).

C enrichment using methanol dramatically increased denitrification rate at the site 1 bioreactor. Constant enrichment at 270 mg L^{-1} C resulted in nearly complete denitrification (fig. 5A). From May 5 through June 17, 2015, inlet NO_3-N averaged 170 mg L^{-1}, varying from 150 to 193 mg L^{-1}. Outlet water NO_3-N was consistently below 1 mg L^{-1}, with no measureable NO_2-N. DOC in outlet water averaged 41 mg L^{-1} higher than inlet water across five sampling dates.

Had the bioreactor been operated without C enrichment, denitrification of approximately 15 mg L^{-1} NO_3-N would have been expected, meaning that denitrification of about 155 mg L^{-1} N could be attributed to the enrichment. Therefore, the estimated C:N ratio achieved was

$$(270 \text{ mg L}^{-1} \text{ C injected} - 41 \text{ mg L}^{-1} \text{ C in effluent}) / 155 \text{ mg L}^{-1} \text{ N denitrified} = 1.48 \text{ C:N}$$

This result was similar to the 1.4:1 C:N ratio for methanol determined in the laboratory studies.

Controlling C enrichment based on real-time NO_3-N monitoring worked well (fig. 5B). Nitrate concentrations reported by the sensor were validated by comparison of sensor values with laboratory determinations on 26 discrete samples of the inlet water; the mean difference was 1 mg L^{-1} NO_3-N. Across 7 weeks of operation, the ISUS sensor showed that inlet NO_3-N concentration varied from 57 to 184 mg L^{-1}. Proportionally injecting methanol at a 1.4:1 C:N ratio consistently reduced NO_3-N in outlet water to < 1 mg L^{-1}.

Dissolved N_2O in outlet water during the period of proportional C enrichment represented < 0.1% of denitrified N, indicating that essentially complete denitrification was achieved. There was undoubtedly significant gaseous N_2O emission still occurring along the length of the bioreactor, but this could be minimized by covering the bioreactor with a totally impermeable film (TIF), as is commonly used during soil fumigation. The use of a TIF cover would limit gaseous losses as water moves through the bioreactor, allowing sufficient time to complete the reduction of N_2O to N_2.

During the period of proportional C enrichment, outlet water DOC averaged approximately 10 mg L^{-1} higher than inlet water DOC, confirming that efficient denitrification can be achieved with C enrichment without greatly increasing DOC (and the associated increase in biochemical oxygen demand) in discharged water.

Economic feasibility

Given the high N load in tile drainage from coastal vegetable farms, a denitrification bioreactor operated in a passive mode (no C enrichment) would have to be quite large to come close to meeting the environmental target NO_3-N concentration in discharged water (< 10 mg L^{-1}). We estimated the costs of installation, operation and maintenance of a wood chip bioreactor 200 feet long, 55 feet wide and 6 feet deep (61 by 16.8 by 1.8 meters). This size was calculated to be adequate to achieve a mean discharge water NO_3-N concentration of 10 mg L^{-1} during the irrigation season from a 200-acre (80-hectare) coastal vegetable farm producing 65,000 gallons (250 cubic meters) of tile drainage daily, based on the very conservative assumption that farm management could limit tile drainage NO_3-N to 60 mg L^{-1}.

Over a projected 10-year life, the total system was estimated to cost (net present value) approximately $92,000, or about $1.50 per pound ($3.30 per kilogram) of N denitrified (Hartz et al. 2015). At higher tile drainage NO_3-N concentrations (like those observed at both field sites), the bioreactor size would have to increase, and in a passive operation mode there would be no way to effectively treat periodic fluctuations in NO_3-N load.

Carbon enrichment provides a tool for handling fluctuating N loads, and it can substantially reduce the bioreactor size requirement. Our data suggest that a bioreactor employing C enrichment could achieve complete denitrification within 1.7 days of HRT, regardless of tile drainage NO_3-N concentration. Therefore, a bioreactor 100 feet by 30 feet by 6 feet (30.5 by 9.1 by 1.8 meters) should be adequate for a 200-acre (80-hectare) farm producing 65,000 gallons (250 cubic meters) of drainage water daily.

We estimate the construction and operational costs for such a bioreactor to be approximately $33,000 over a 10-year period. Assuming complete nitrate removal and a mean inlet NO_3-N concentration of 150 mg L^{-1} (similar to site 1), this expense would equate to approximately $0.60 per pound of N denitrified, exclusive of the costs associated with C enrichment. The cost of methanol fluctuates with the price of oil, but at an estimated bulk price of $2.50 to $3.00 per gallon ($0.66 to $0.79 per liter), methanol would cost approximately $1.40 to $1.70 per pound ($3.10 to $3.70 per kilogram) of N denitrified. Currently, sensors capable of continuously measuring NO_3-N concentration are expensive; commercial NO_3-N sensors based on the ISUS technology are at least $15,000. Also, more active management would be required to keep a C enrichment system operating efficiently than to operate a bioreactor in a passive operation mode.

Clearly, C enrichment would be more expensive than passive bioreactor operation per unit of NO_3-N denitrified. However, C enrichment appears to offer the only practical way to sufficiently treat tile drainage with high but fluctuating NO_3-N to consistently meet TMDL nitrate targets. Furthermore, the ability to apply C proportionally to NO_3-N load is critical to efficient C utilization and to minimize both the emission of N_2O and dissolved C in effluent.

Remediating tile drainage using denitrification bioreactors and proportional C enrichment may be a technology more appropriately employed on an area larger than an individual farm. A larger installation could achieve an economy of scale, reducing construction, management and NO_3-N sensing costs per unit of N denitrified. CA

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Date: February 16, 2017
Time: English session, 8:00 a.m. to 11:30 a.m.; Spanish session, 12:00 p.m. to 4:00 p.m.
Location: Kearney Agricultural Research Extension Center, Parlier, CA
Contact: Maggie Reiter (563) 663-2852 or mkreiter@ucanr.edu

ANR Water Strategic Initiative Conference

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Dates: March 14–17, 2017
Time: 8:00 a.m. to 5:00 p.m.
Location: Double Tree by Hilton Ontario Airport, Ontario, CA
Contact: Program, Doug Parker doug.parker@ucop.edu or David Doll dadoll@ucanr.edu; logistics, Lauren McNees (530) 750-1257 or Danielle Palermini (530) 750-1328

Beginning Farming Academy

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Date: April 7–8, 2017
Time: 8:00 a.m. to 8:00 p.m.
Location: UC Cooperative Extension Placer/Nevada
Contact: Cindy Fake cefake@ucanr.edu