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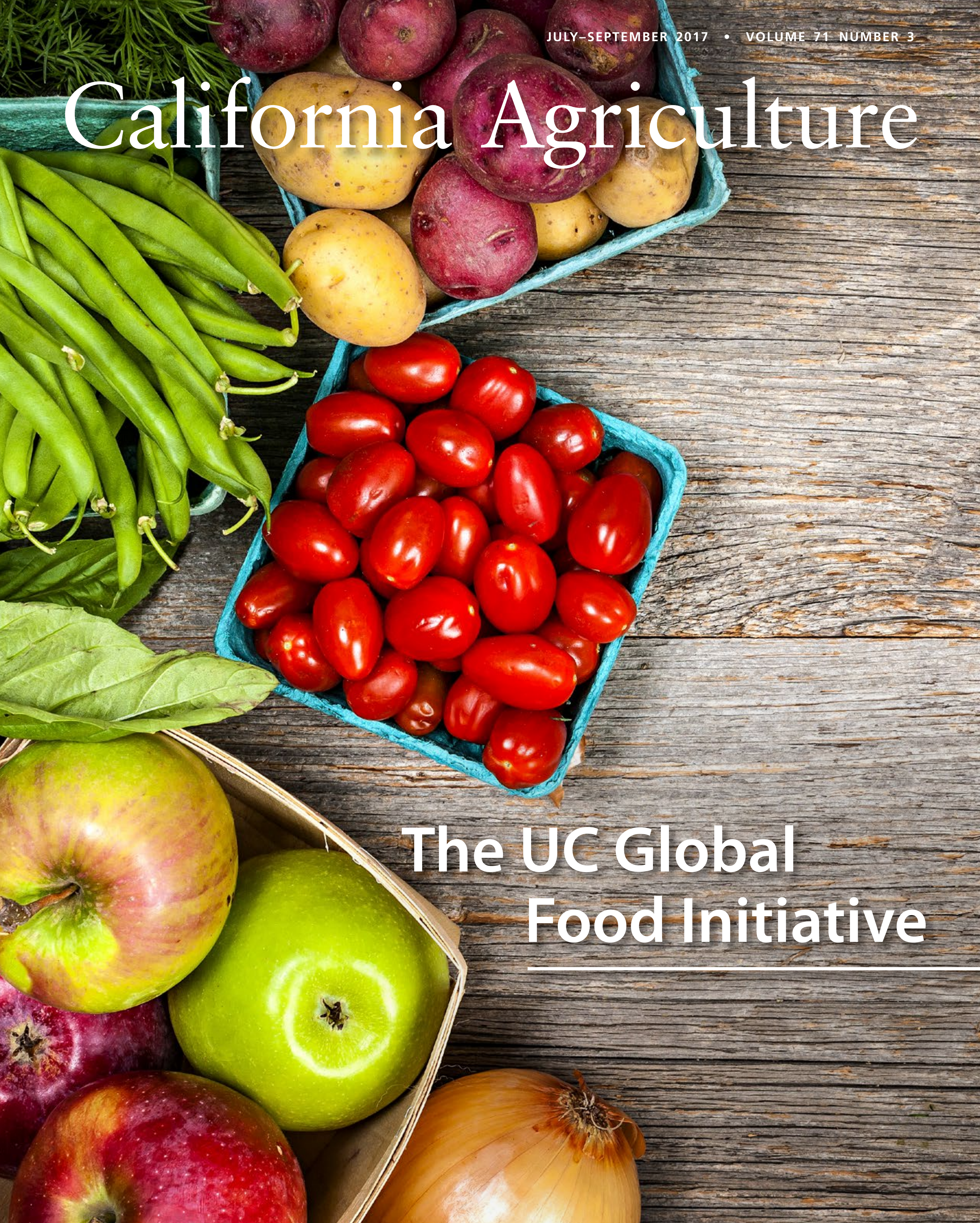
California Agriculture



The UC Global Food Initiative

California Agriculture

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Mission and audience. *California Agriculture* publishes original research and news in a form accessible to an educated but non-specialist audience. In the last readership survey, 33% of subscribers worked in agriculture, 31% were university faculty or research scientists and 19% worked in government.

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Indexing. The journal provides article metadata to major indexing services, including Thomson (Web of Science), AGRICOLA, the Directory of Open Access Journals and EBSCO (Academic Search Complete), and has high visibility on Google Scholar. All articles are posted to eScholarship, UC's open-access repository. In the 2016 Thomson JCR, the journal's 5-year impact factor was 1.0.

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Article submission and review. Guidelines for authors are here: calag.ucanr.edu/submitarticles/. The journal uses a double-blind peer-review process described at calag.ucanr.edu/About/. Roughly 50% of all submissions are rejected by the editors without peer review due to a mismatch with the journal's scope or clear weaknesses in the research. Of the subset of submissions that enter the peer-review process, roughly 60% are ultimately accepted. All accepted manuscripts are edited to ensure readability for a non-specialist audience.

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UNIVERSITY OF CALIFORNIA

University *of* California
Agriculture and Natural Resources

JULY–SEPTEMBER 2017 • VOLUME 71, NUMBER 3

The UC Global Food Initiative

Research and review articles

Cover photo by Elena Elisseeva, Adobe Stock.

EDITORIAL

UC and California food systems: Growing together through the Global Food Initiative

Janet Napolitano, President, University of California

Janet Napolitano

In the early 1900s, a young man immigrated to the United States from Italy. He mined coal in Pennsylvania to make money for a train ticket west to San Francisco. There, he dug sewer lines until he earned enough to buy 40 acres of land in the Central Valley, where he planted grapes and launched his own business.

A generation later, the man's 24-year-old son, Ernest, asked a librarian at the public library in Modesto for help. Prohibition had just been repealed, and Ernest saw a business opportunity for his family's vineyards: winemaking. But he and his brother knew nothing about making wine.

The librarian directed him to the library's basement, where he discovered a few dusty pamphlets on winemaking. The pamphlets were written by a UC Berkeley viticulture professor named Frederic Bioletti. Working off of Bioletti's pamphlets, the two brothers made their first wine that year, in 1933.

Today, E&J Gallo Winery is the largest wine producer in the world.

The will and the ingenuity to think big and take bold action has always been the hallmark of California agriculture. This success story is a prime example of the California agriculture industry's spirit of innovation, and that the connection between the industry and the University of California runs deep.

For generations, UC researchers have worked in the laboratory and in the fields, orchards and vineyards across California, striving to improve crop yields, increase efficiency, and find smarter ways to farm. Armed with UC's latest research and discoveries, California almond growers have nearly doubled their yields.

Research at the UC Davis Oakville Research Station in Napa County includes work on pests and diseases of vineyards.

Farmers have benefitted from new varieties of a range of crops, including citrus, strawberries and avocados. And UC experts have helped artisan cheesemakers develop a strong niche market within California's nation-leading dairy industry.

Today, the University of California continues to serve as a leader and a trusted partner in this progress. UC research is venturing into new frontiers, enabling California growers to better anticipate the future of agriculture, and thrive at the nexus of food, energy and water.

Both farmers and researchers are grappling with a complex challenge: how can we sustainably and nutritiously feed a growing world population — one that's expected to reach 8 billion people by 2025?

This question lies at the core of the UC Global Food Initiative, which I and the chancellors launched in 2014. And answering that question will require us once again to think big and take bold action, collectively.

The goal of the Global Food Initiative is to harness the university's vast resources and expertise to find solutions. Together, UC's 10 campuses, three national laboratories and 57 agricultural extension offices are working to develop innovative, scalable solutions to food-related problems in California, the nation and the world. We are doing this through research and public outreach, and by empowering UC students and convening working groups to tap the brainpower of UC faculty.

UC faculty members conduct groundbreaking research on sustainable agriculture, new types of crops, food-waste reduction, good nutrition and drought-friendly farming practices. Their research doesn't linger in the lab — UC experts bring the latest science and expertise to communities throughout California and beyond. They advise growers, help educate youth participating in 4-H, and work with K-12 schools to make student lunches more nutritious and sustainable.

Our Global Food Initiative student fellows are striving to create healthier, stronger food systems. More than 200 GFI fellowships have been awarded to UC graduate and undergraduate students, providing financial support to pursue food-related research, internships and projects. Through these projects, UC graduate and undergraduate students are investigating the impacts of food insecurity on homeless adults with HIV, and analyzing climate models to help provide the best available information on chill hours for Central Valley farmers.

Emily Webster, a graduate student in horticulture and agronomy at UC Davis, trains a field team of Nicaraguan farmers and university agriculture students on soil sampling protocol.

The Global Food Initiative is targeting several important campus food issues, including student food insecurity, food sourcing and food service waste.

The initiative is also helping to sponsor UC students with international fellowships to spend two to six months abroad helping partner organizations solve scientific, technological, organizational and business challenges. These graduate students are engaged in an array of regions and projects. They are helping Himalayan farmers recover from the devastating 2015 earthquake in Nepal, for example, and working with Venezuelan cacao farmers to diversify and grow higher-value crops while protecting native forests.

Here in California, UC experts helped the state weather a devastating drought. With the Sierra snowpack larger than the four previous years combined, Californians may have — temporarily — set aside their drought worries. But UC researchers are already working to understand and help prepare California for the repercussions of climate change, including drought. Specifically, they are looking at how changing climate conditions will affect California agriculture, which could have enormous economic impacts.

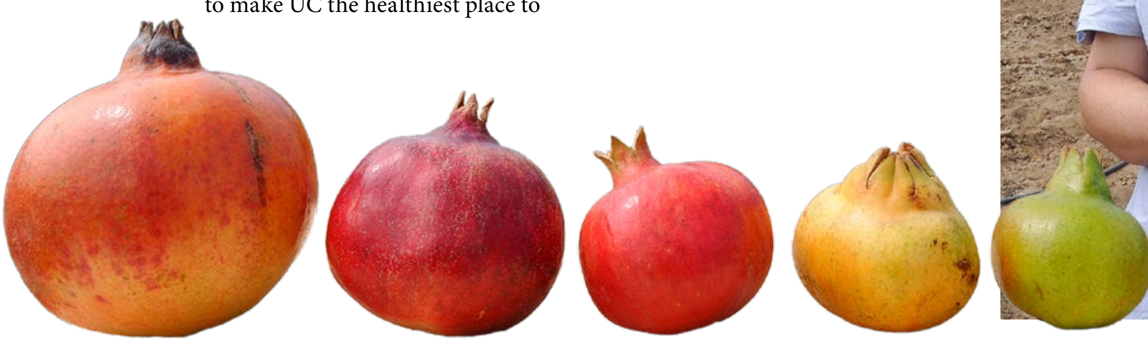
The Global Food Initiative is helping us put UC's formidable research enterprise to work on our own campuses, too. The university committed $3.3 million to ensure that UC students have access to nutritious food. We also launched the Healthy Campus Network to make UC the healthiest place to work, learn and live for students, faculty and staff. We are working to increase the availability of local produce in our campus dining halls, and we are aggressively addressing food waste, with the goal of becoming zero-waste by the year 2020.

At UC Riverside, graduate student and GFI fellow John Chater is carrying on a legacy that first took root when his grandfather began a breeding program in Camarillo with pomegranate seeds from his native Lebanon. John inherited his grandfather's passion for pomegranates. He is studying rare varieties of the fruit to better understand their suitability for commercial production in various parts of California in hopes that more people will have the chance to enjoy these types of pomegranates.

John is building on the horticultural foundation and quest for knowledge that his grandfather started. In the same way, UC research — and the UC Global Food Initiative — will continue to grow and evolve with California and its agriculture industry, helping the state tackle new problems and ensuring a safer, healthier, more nutritious, and more sustainable food system here, and far beyond the state's borders. CA

Janet Napolitano is President of the University of California system of 10 campuses, five medical centers, three affiliated national laboratories and a statewide division of agriculture and natural resources.

John Chater, a UC Riverside graduate student and Global Food Initiative Fellow, is carrying on a legacy of plant breeding work begun by his grandfather, who brought pomegranate seeds from Lebanon and launched a breeding program in Ventura County.



The UC Global Food Initiative

This special issue of *California Agriculture* features news and research articles illustrating the breadth of activities and research that make up the UC Global Food Initiative (GFI).

Launched in 2014 by President Janet Napolitano and UC's 10 chancellors, the GFI's mission is to align the university's research, outreach and internal operations to develop, demonstrate and share scalable solutions for food security, health and sustainability. The GFI is administered by the UC Office of the President and involves all 10 UC campuses, UC Agriculture and Natural Resources and Lawrence Berkeley National Laboratory.

In practice, the GFI is a collection of programs with common goals. The initiative has convened more than 20 committees made up of UC researchers, faculty, staff and students to document best practices and develop toolkits around various food issues, along with funding targeted research. It has spurred dialogue by launching the influential UC Food Observer blog; producing Mark Bittman: California Matters, a video series hosted by the renowned food writer; and hosting the inaugural California Higher Education Food Summit. And it has supported the development of UC students through more than 200 GFI fellowships, an international agricultural extension fellowship program, and the Communication, Literacy & Education for Agricultural Research (CLEAR) program, which is preparing the next generation of science communicators.

The news articles that follow highlight the work of six of the GFI's topical committees: urban agriculture and food disparities, food access and basic needs on campuses, food hub collaborative learning (connecting local growers with institutional food service), experiential learning, zero waste dining, and the international Research and Innovation Fellowship for Agriculture.

The 10 peer-reviewed articles in this issue report on a range of subjects relevant to the goals of the GFI: sustainable food production, building agricultural resilience to climate change, reducing greenhouse gas emissions from agriculture, the complexities of pest management, improving food access and reducing food insecurity on campuses and in vulnerable communities, and increasing opportunities for local sourcing of foods.

The issue was guided by *California Agriculture* Associate Editor Lorrene Ritchie, director of the UC ANR Nutrition Policy Institute, and GFI Program Manager Gale Sheean-Remotto. A panel of seven guest editors reviewed abstracts submitted in response to a call for papers for this issue: Amy Beaudreault, UC Davis World Food Center; Gail Feenstra, UC ANR / UC Davis Sustainable Agriculture Research and Education Program; Clare Gupta, UC ANR / UC Davis Department of Human Ecology; Rose Hayden-Smith, UC ANR / UCOP, founding curator of the UC Food Observer; Peter Nico, LBNL Earth and Environmental Sciences; and Michael Roberts and Tiana Carriedo, UCLA School of Law Resnick Program for Food Law and Policy.

Global ARC

Urban agriculture and food disparities

Global ARC

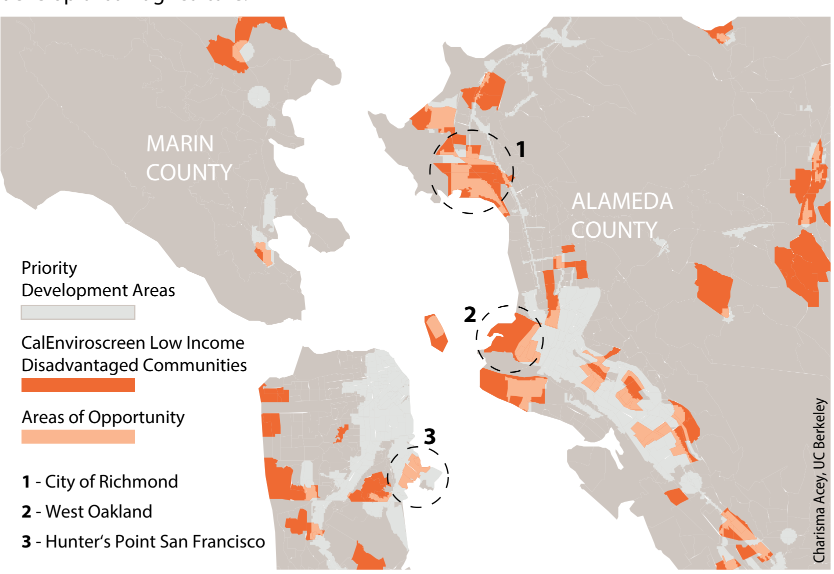
Working at the intersection of technology, civic society and sustainability to build food security and community-university connections.

Disparities in access to food have many dimensions. A "food desert" doesn't mean just the lack of a nearby supermarket. Income, education, environmental quality and political power all also influence who has access to nutritious food and who doesn't.

Urban agriculture offers multidimensional solutions to the multi-dimensional problem of food disparities. A community garden can be an additional source of food, but also a meeting place, a gateway to education and a foundation for community organizing.

Maddy Luthard from UC San Diego Roger's Community Garden leads a worm composting workshop at Ocean View Growing Grounds, in San Diego. In addition to being a source of food, community gardens can provide sites for community organizing and educational programs.

Circles in the map below highlight three prime "Food Opportunity Zones," areas where factors associated with food insecurity — such as poverty, scarce food retailers and low environmental quality — overlap with opportunities to develop urban agriculture.



The Global Food Initiative's Urban Agriculture and Food Disparities subcommittee is working on ways to help realize these diverse benefits. It is supporting mapping projects to identify needs and opportunities for urban agriculture; studies to improve understanding of how urban agriculture contributes to meeting food needs (see Rabinowitz Bussell et al., page 139); and demonstration garden spaces that provide venues for innovation, experimentation and the exchange of ideas among students, researchers and community members.

A common theme to the projects, said subcommittee member Keith Pezzoli, director of the UC San Diego Urban Studies and Planning Program, is the integration of sustainability science with applied fieldwork — co-inspired and co-led by researchers and community members. Through community-university collaboration, the participants are exploring how best to couple human and natural systems in an integrated socio-ecological approach. Green technology, equitable civic engagement, and new means for mapping and sharing knowledge are all key.

"We're merging three types of infrastructure: green, civic and cyber," he said. Here are two examples:

Mapping vulnerabilities and opportunities

Charisma Acey, professor of city and regional planning at UC Berkeley, led a GFI-funded project to map "Food Opportunity Zones," with a focus on the Bay Area city of Richmond (unpublished data). The zones are identified as the intersection of food insecurity (defined by variables like scarce food retailers, poverty and low environmental quality) and urban agriculture opportunity, such as properties that cities have designated for food production under California's 2013 Urban Agriculture Incentives Zone Act, which provides tax breaks to owners of urban parcels used to grow food.

The result is a map that highlights areas for investment in urban agriculture initiatives — and a mapping methodology that can be applied elsewhere in the state and across the country, especially where concerns about food justice are significant.

The rooted university

At Ocean View Growing Grounds, a community garden in a low-income neighborhood in southeastern San Diego, the GFI is helping to fund the establishment of a neighborhood community center built around food, nutrition and the environment. The project — a partnership of UC San Diego's Bioregional Center for Sustainability Science, Planning and Design and a local

Above and *right*, a soil workshop at Ocean View Growing Grounds, a community garden that serves as an example of the "rooted university," a place for building connections among community members and university students, staff and faculty.

nonprofit organization, the Global Action Research Center — is designed to be an example of the "rooted university," a platform for building connections between community members and the students, staff and faculty of the university.

"It's the place where science and the residents come together," said Pezzoli.

Pezzoli and Zack Osborn, a UC San Diego research associate, plan to extend to Ocean View Growing Grounds a program already established at Roger's Community Garden on the UC San Diego campus.

There, students experiment with new ways to bring technology to gardening — installing digesters to produce biogas from campus food waste, for instance, and incorporating small-scale aquaculture systems into the garden, utilizing nutrients in the fish waste to grow plants. Both involve sophisticated sensors and control systems, Osborn said, and offer challenges to science and engineering students who might not be interested in old-fashioned manual vegetable cultivation.

Bringing that energy to a neighborhood garden, Pezzoli hopes, will foster an exchange of ideas between the community and the university.

"The experimentation happening on campus gets connected to local neighborhoods," he said. "This enables the university to be more rooted in the neighborhoods, creating a bi-directional flow of ideas and knowledge that inspires innovation and problem-solving." CA

—Editors

Preparing a potato box at Ocean View Growing Grounds.

Increasing experiential learning opportunities in food and agriculture

A new report from the Global Food Initiative identifies hands-on learning opportunities for UC students.

"Seeing what you're learning and learning it by doing. Tell 'em we got dreams and goals we're pursuing. Tell 'em we're choosing to make a change right here."

— *Can UC* music video, produced by UC Santa Cruz Students including David Robles (center), Aubrey Wilson (right) and Alyssa Billys (left)

Can UC, a hip-hop music video made by students at UC Santa Cruz, is one of 12 UC student videos supported by the GFI subcommittee on experiential learning in food and agriculture. Against a backdrop of the UCSC farm and Chadwick garden, it presents students' visions and solidarity efforts to bring about a more just and sustainable food system, through their education. And it shows the enthusiasm for and value of experiential learning (i.e., learning that is hands-on, reflective and action producing).

The subcommittee set out to identify and increase experiential learning opportunities in food and agriculture for UC students and make them more accessible, while sharing lessons learned and best practices. The project was highly collaborative across UC campuses, coordinated by co-leaders from UC Berkeley (Berkeley Food Institute), UC Davis (Agriculture Sustainability Institute), UC Santa Cruz (Center for Agroecology and Food Systems) and UC Cooperative Extension.

As a first step, the subcommittee inventoried the existing opportunities. The directory, compiled in fall 2015 from a survey of all UC campuses, details over 200 courses with experiential learning components, such as labs or field classes. It also identifies more than 150 food and agriculture programs, including, for example, the UC Davis Honey and Pollination Center

Jonathan Fong

Student managers at the Berkeley Student Food Collective, a nonprofit, student-led grocery store that offers experiential learning internship programs and employment.

and the Food Law Society at UC Los Angeles, along with numerous internship programs and student-led groups. The directory is a living document on the web, for use by students, educators, researchers, administrators and others interested in learning about and using experiential learning to teach agriculture and food systems.

Drawing from the survey data, the subcommittee produced a report, *From the Ground Up: Experiential Learning in Food and Agriculture Systems at the University of California*. It includes a pedagogical framing of experiential learning approaches, a summary of lessons learned about effective practices, challenges and needs, and 12 case studies. The case studies show a wide range of content areas and program type, from the UC Merced Campus Garden, where solar-related projects have made the garden almost self-sustaining; to UC San Diego's Taste Buds partnership with an executive chef and nutritionist who present hands-on educational sessions for the community; and the UCLA's Swipe Out Hunger project, which started as a student club in 2009, with students donating unused food points, or swipes, from their meal plans to students and community members in need, and is now a national nonprofit. Best practices are identified in each case study. At the top of the list of challenges the projects face is unstable funding.

As a second step, the subcommittee invited student teams to submit proposals to create videos highlighting food and agriculture experiential learning opportunities on their campuses. Video recording equipment was provided to each team, and 12 videos were completed. The videos are a kaleidoscope of innovation, community empowerment and actions toward environmental and food justice. For example, students at UC Riverside, where almost one in three students lacks the money to acquire adequate food, produced *Food Insecurity* on an undocumented student's struggle to gain access to educational opportunities and resources, including food; students at UC Berkeley produced a video on their Compost Alliance, an innovative program that reduced food waste, through a partnership between students and staff.

To facilitate discussion and exchange of information, the subcommittee took a third step and held

Opposite page: The subcommittee identified over 200 UC courses with experiential learning components, such as this UC Berkeley course on campus landscape ecology.

half-day workshops last spring at UC Davis and UCLA, to bring the experiential learning community together from the 10 campuses. In July, it co-organized the Sustainable Agriculture Education Association national conference at UC Santa Cruz, which was attended by almost 400 people.

Next on the agenda, with new funding from the Global Food Initiative, is strengthening the UC garden-based programs by contributing funding and increasing collaboration and knowledge exchange among those programs. One of the outcomes will be best practices toolkits online, accessible to campuses worldwide.

The subcommittee is working alongside a dynamic, rapidly expanding student movement. “It’s remarkable how many students have become engaged in experiential learning — through UC classes, student-led groups and programs such as campus gardens and farms,” says subcommittee co-leader Ann Thrupp, executive director of the UC Berkeley Food Institute. For example, there are now at least 19 food and agriculture student-led groups at UC Berkeley — double the number when the subcommittee’s survey was completed. “The food movement is mushrooming at Berkeley and on all campuses,” says Thrupp. CA

—Editors

Student staff members and interns harvest produce at the UC Santa Cruz Center for Agroecology and Sustainable Food Systems farm.

UC GLOBAL FOOD INITIATIVE UPDATE

Moving toward zero waste dining

A new toolkit helps food service operators identify opportunities to reduce waste.

Elëna Zhukova

UC Merced student Andrew De Los Santos empties a campus waste bin into a hopper. A conveyor belt carries the materials to a sorting line for separation into recycling, compost and landfill channels.

One aim of the Global Food Initiative is to use UC campuses as testing grounds for improvements in the ways that large food supply chains and waste streams are managed. New methods and tools developed within the university can then be shared with other institutions to achieve broader-scale impacts.

The waste audit toolkit developed by the Zero Waste Dining subcommittee is an example. The subcommittee — made up of Sean Murray, associate director for campus dining at UC Merced, and Tyson Monagle, a sustainability steward with Aramark who works in partnership with UC Irvine Hospitality & Dining — developed a simple spreadsheet-based tool to help foodservice operators gather the data needed to assess the current state of their waste streams: how much waste is produced in various categories, and how much is being recycled, composted or landfilled.

The tool is designed to support campus food service operations as they work to develop strategies to meet UC's 2020 systemwide goal of having just 5% of campus waste streams, by weight, sent to landfills (this level of diversion is considered "zero waste", even though some waste, mainly items that are not readily recyclable, will continue to be landfilled).

"Food service operators are worried that tracking this kind of information takes too much time," said Monagle. "This is about showing that it is simple and easy to do," and putting into place systems that allow all food service operators to track waste periodically, he said. While a number of dining operations within the UC system already collect such data, Monagle said, many don't — particularly smaller-scale ones with more limited resources.

Documenting the components of food service waste streams helps to identify what waste-reduction strategies are needed. Steps can range from signage and education campaigns to clarify to diners and staff about what can and can't be composted and recycled, to changes in the types of carry-out containers provided, to sourcing more food items in bulk to reduce single-serve packaging.

"It's a lot of little things," said Murray.

Another benefit of looking closely at food service waste streams is that it encourages operators to scrutinize all of their sourcing and food-preparation processes, which can lead to reductions in the amount of food waste that is generated in the first place (as opposed to just making sure that what is wasted gets composted). A colossal amount of food is wasted worldwide each year — about 70 billion pounds in the United States alone, or 40% of what we produce — and that waste is a major source of avoidable greenhouse gas emissions. A recent UC video (bit.ly/2pipfTX) called food waste "the world's dumbest environmental problem."

In March, Monagle presented the waste audit toolkit at a meeting in Ohio of Presidents United to Solve Hunger (PUSH), a consortium of university leaders that works on food security issues, including waste.

"One of the great things was realizing how many people there are out there that want to use this toolkit," he said. "We come at it from within UC, which is already driving very hard toward sustainability. But there are people from all over, who might not be at the same step yet." CA

—Editors

UC GLOBAL FOOD INITIATIVE UPDATE

Ensuring basic access to food for UC students

Each campus is working toward food security for all by 2020.

"Most of these students didn't grow up hungry or homeless," said Canedo. "Thinking these are only the low-income students, the Pell grant or undocumented students — that's false."

In summer 2014, Ruben E. Canedo, recipient of the prestigious Regents' and Chancellor's Scholarship when he was a student at UC Berkeley, was asked by the UC Office of the President to co-facilitate the coordination of food pantries on UC campuses. Just one semester later, when it became clear to Canedo and campus leaders that many UC students had inadequate resources for food, that focus widened to urgently addressing food insecurity at the university level. Since then UC has strongly committed to advancing food security and also security in other basic needs, such as housing, for all UC students.

In 2015, the first-ever UC Student Food Access and Security Study (bit.ly/29Lcdpr) of students at all 10 campuses, developed by UC ANR's Nutrition Policy Institute as part of the Global Food Initiative, found that 19% of student respondents experienced very low food security, which the U.S. Department of Agriculture (USDA) defines as experiencing reduced food intake due to limited resources. An additional 23% had low food security, defined as reduced quality, variety or desirability of diet, with little or no indication of reduced food intake (see Watson et al., p. 130).

Canedo, director of equity initiatives at UC Berkeley's Division of Equity and Inclusion, is co-chair of the UC Global Food Initiative Basic Needs Access and Security subcommittee. He and Tim Galarneau, community-engaged education coordinator at UC Santa Cruz's Center for Agroecology and Sustainable Food Systems, each coordinate five UC campus committees, where student, staff, faculty, administrators and community leaders are building strategies for addressing student basic needs.

The subcommittee has made significant progress, with basic needs committees in place on all 10 campuses, and partnerships established with the California state universities and community colleges and with local and national experts on food and housing to facilitate research and plan preventative strategies. The extensive data that UC has collected on students'

UC campuses such as UC Berkeley are working to increase the availability of nutritious and sustainable food to students.

Eliëna Zhukova

struggles in meeting their basic needs sets the university in the lead nationally on this issue. In 2016, the UC systemwide student experience surveys were updated by UCOP's Institutional Research and Academic Planning unit to include both food and housing security questions, which will produce ongoing student data and show the impact of the university's efforts.

This summer the subcommittee will launch a best practices toolkit. It will highlight campus education and community engagement programs, such as the UC Davis CalFresh Project, and give details on how they work, their challenges and lessons learned. Also described will be campus food access models, including the UC Los Angeles Farmers Market Gleaning Program, and policy and institutional practices, such as the UC Irvine Food Pantry Usage and Tracking process. Sharing information from so many campus projects will benefit universities and colleges across the nation looking to address basic needs.

Sorting produce for the farmers market at UC Merced.

The ultimate goal, said Galarneau, is to "inform a sea change across the United States in how higher education approaches the basic needs of students." The solution is not a provision of services limited to food pantries, but a system shift so that basic needs are ensured from the start. "This struggling of students is happening at too high a rate, so we must make structural changes," Canedo said.

According to the 2015 UC Student Food Access and Security Study, most food-insecure students (57%) did not report experiencing food insecurity as children. "Most of these students didn't grow up hungry or homeless," said Canedo. "Thinking these are only the low-income students, the Pell grant or undocumented students — that's false. We have students from working-class and middle-class families who become food insecure as college students. We also have students who come from wealthy families who are cut off from support due to being LGBT+ or choosing a different faith or religion. For these students, the challenges are new, and they are embarrassed and unprepared to seek help."

Guided by the survey findings, President Napolitano allocated more than $377,000 per campus in funding for the 2 years 2016–2018. The funding supports campus efforts to develop programs such as food trainings, emergency aid, food pantries, curricular and research alignment and an effective communication and marketing plan to reach target students.

Canedo quickly has become a national expert on student basic needs; he knows the crisis through his work with campus students, the data, and personally. He experienced food insecurity himself even with that scholarship and would have had periods of homelessness if his mentors had not helped him. Galarneau, a former UC student leader with a focus on sustainability and social justice, has expertise in university food service policy. Together, and with the support from the Global Food Initiative, they are "twisting up a strong rope of support for students across the UC," said Galarneau, and galvanizing support for other students in California and nationally. CA

—Editors

UC GLOBAL FOOD INITIATIVE UPDATE

Extending agricultural knowledge globally

An international agricultural fellowship program has supported graduate students working in 24 countries — conducting research, providing training, overseeing field trials and more.

Through the Research and Innovation Fellowship for Agriculture (RIFA) program, the GFI has, over 2 years, supported 40 graduate students from across the UC system in conducting sustainable international agricultural development projects with host organizations around the world.

The fellowship program, initiated with funding from the U.S. Agency for International Development (USAID), links graduate students possessing significant international experience with development projects based at universities, research institutions and nongovernmental organizations in host countries. They carry out their work with the close mentorship of UC faculty.

Within their projects, fellows conduct research, provide training, oversee field trials, introduce new technologies and practices, monitor and evaluate projects and programs, and help to design new initiatives.

"RIFA fellows play a key role in the GFI by taking research to action," said founding director G. David Miller. The RIFA program is based in the International Program Office of the College of Agriculture and Environmental Science at UC Davis. Projects run for 2 to 6 months with fellows continuing to provide support even upon their return to the United States. The fellowship covers travel and health-related costs, and provides a small stipend for living expenses.

RIFA has supported work in 24 countries by a total of 80 students (half funded by GFI, half by USAID and other sources; there were 11 students in 2015, 26 in 2016 and 39 in 2017). The program recruits from all the UC campuses and beyond and has fostered many collaborations between UC faculty and host organizations. The host organization initiates the request for collaboration and then, over several months, a project is agreed upon with a clear set of measurable objectives.

USAID funding is no longer available for the fellowships, but GFI funding will continue to support the program through 2018; Miller said he is also working on making the program sustainable by building an endowment. This has already begun with the support of donors James and Rita Seiber of Davis, who funded an additional three fellows in 2016 and have made a commitment to continue to fund one RIFA fellow per year.

The map shows the countries where students have worked, and some examples of their projects. CA

—*Editors*

Fellow **Emily Webster**, a graduate student in horticulture and agronomy at UC Davis, worked with the International Center for Tropical Agriculture (CIAT) in Colombia and Nicaragua to compare the dynamics of soil macrofauna in silvopastoral systems with those in traditional pasture systems and quantify impacts on ecosystem services.

Kate Polakiewicz, a UC Davis graduate student in international agricultural development, led a study in Honduras, Guatemala and Mexico with Catholic Relief Services and the Tropical Agricultural Research and Higher Education Center to understand how soil fertility management interacts with coffee leaf rust, a devastating disease. Kate was recognized for her work as one of the GFI 30 under 30 winners (bit.ly/2tzfRwl) and, after graduation, was hired by CRS to continue work on the project.

Ihab Anwar, CARE International, Egypt

Stephanie Webb, an environmental studies Ph.D. student at UC Santa Cruz, worked with WorldFish in Egypt to conduct rapid commodity chain assessments of the farmed tilapia industry, interviewing famers, brokers, wholesalers and retailers. She also conducted a sensory science experiment to test consumer acceptability and use of small-farmed tilapia to evaluate consumer behavior and potential markets for Egyptian farmed tilapia.

Kaitlyn Le Baudour and husband **Jonathan Yates**, both international agricultural development graduate students at UC Davis, worked with the NGO Aythos in Nepal to help rural farmers establish better land management practices through the use of biopesticides and the application of new composting techniques.

Jonathan Yates

Hanyuan Jiang, a graduate student at UC Davis in international agricultural development, worked with Ifugao State University in the Philippines to help with a local farmer-training program to utilize knowledge and skills of local natural resources to reconstruct traditional rice-paddy landscapes. (more: bit.ly/2ttsJUK and bit.ly/2vSVz2A)

Roberson Guay Addug

Hanyuan Jiang

UC Riverside environmental engineering graduate student **Pedro Piqueras** worked with the Council of Scientific and Industrial Research in South Africa to quantify and characterize air pollutants in South Africa, helping to improve the understanding of their impacts on local crop yields.

Pedro Piqueras

Pedro Piqueras

Food hubs: The logistics of local

David Matheson Photography

UCSB Office of Public Affairs and Communications

Locally grown peaches are served in the dining commons at UC Santa Barbara.

Connecting small farms with big buyers — like UC campuses.

Demand for locally grown food is gaining traction, including among larger institutional buyers like UC campuses. This trend is creating sales opportunities for smaller-scale farms that would otherwise focus on direct market channels such as farmers markets and sales to restaurants.

But high-volume institutional customers often have needs — such as for consistent, large deliveries of produce — that an individual small farm can't meet.

"Food hubs" aim to bridge that gap — and GFI-funded projects run by the UC Sustainable Agriculture Research and Education Program (SAREP) are helping them do it.

Food hubs are designed to enable small and mid-scale farms to efficiently reach larger and more distant market channels like campuses and school districts, hospitals and corporate kitchens. Rather than an individual farm assuming responsibility for sales and deliveries, it can sell to a food hub, which aggregates, markets and delivers produce from many farms in a region. A key detail is that, unlike many mainstream wholesalers, food hubs identify the farms they source from by name and location. That's critical when selling to customers who are prioritizing local food.

Food hubs vary in scale from sizable, established produce businesses, like Veritable Vegetable in San Francisco and Coke Farm in San Juan Bautista, to smaller organizations, some of which are funded in part by grants.

Food hubs are often mission-driven and seek to support sustainable and equitable food systems. They generally support higher product pricing for growers, provide a variety of support services to growers, and emphasize connecting farms and customers within a region. Some also work to improve food access for low-income communities; for example, Mandela Foods Distribution, a Mandela MarketPlace social enterprise, supplies fresh fruits and vegetables that are distributed

Opposite page: Veritable Vegetable CEO Mary Jane Evans inside the company's distribution center in San Francisco. Food hubs can help connect small and mid-scale farms with institutional buyers.

Mandela MarketPlace

Mandela Foods Distribution in Oakland supplies fresh fruits and vegetables to corner stores and community produce stands in low-income neighborhoods.

A Veritable Vegetable truck picks up boxes of freshly harvested organic lettuce from J.E. Perry Farms in Fremont.

to community produce stands and corner stores in low-income neighborhoods in Oakland.

The number of food hubs nationally has grown rapidly, from 105 to 302 over 7 years, according to a 2014 survey (ERS 2015). But there has been little regional-level information available about them: how many farms and customers they serve, what obstacles they face, and whether they are in a position to serve institutional customers.

In 2015 SAREP established a 2-year pilot project to study and support a group of seven small and mid-sized food hubs in California. The study collected data on the operations of the food hubs, connected them with each other and with more established food hubs, and provided training and support.

One of the inspirations for the project, said SAREP Deputy Director Gail Feenstra, was the fact that food hubs (with some exceptions) didn't appear to be capitalizing on the opportunity presented by the UC system's sustainable food procurement mandate — 20% of food from local or other sustainable sources by 2020.

Boxes of melons from Full Belly Farm in Yolo County are loaded into Capay Valley Farm Shop's truck. The truck collects produce from multiple farms in the region for delivery to buyers in the Bay Area.

"We saw a place where the food hubs could really fill an important role in helping campuses source directly from local farms," Feenstra said. "But that wasn't happening as much as we thought it would."

The project identified several barriers around connecting food hubs with large institutional buyers. A common problem was difficulty meeting food-safety standards, which include third-party audits of both farms and food hubs. The smaller food hubs also lacked the scale and logistical sophistication to reliably meet the needs of large customers.

However, small food hubs clearly show promise. The GFI report from the Small Growers Subcommittee, *Facilitating Small Growers' Ability to do Business with UC*, documents how UC Santa Barbara Residential Dining Services has already exceeded the sustainable purchasing goal, in large part due to its relationship with Harvest Santa Barbara, a relatively small food hub.

Feenstra and Gwenael Engelskirchen, a sustainable supply chain analyst with SAREP, also identified a number of strengths of the smaller regional food hubs, including their direct relationships with farms and customers, product quality and freshness, source identification, responsiveness to consumer needs, and accountability to producers in terms of product pricing and logistical support. One hub, for instance, offers a rural climate-controlled produce drop-off location that saves local farms a long trip to an urban distribution hub. Most offer one or more support services such as crop planning, food-safety trainings, trucking services and use of storage facilities, often free of charge.

The UC SAREP project produced a video on food hub best practices as well as a report on lessons learned from the pilot network. It also led to a grant from the California Department of Food and Agriculture to support food-safety training for the growers that supply these hubs. Going forward, Feenstra said, the project will broaden the network to include a larger cohort of food hubs in California and define a set of goals and objectives for the network. The project was also granted continued funding through the GFI to continue conversations with university buyers to better understand how to work within their pricing, ordering, logistical and certification requirements and leverage technical assistance to help food hubs meet those requirements. CA

—*Editors*

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RESEARCH BRIEF

Hedgerow benefits align with food production and sustainability goals

Adoption of hedgerows on California farms shows benefits and a return on investment in 7 to 16 years.

by Rachael F. Long, Kelly Garbach and Lora A. Morandin

Abstract

Restoring hedgerows, or other field edge plantings, to provide habitat for bees and other beneficial insects on farms is needed to sustain global food production in intensive agricultural systems. To date, the creation of hedgerows and other restored habitat areas on California farms remains low, in part because of a lack of information and outreach that addresses the benefits of field edge habitat, and growers' concerns about its effect on crop production and wildlife intrusion. Field studies in the Sacramento Valley highlighted that hedgerows can enhance pest control and pollination in crops, resulting in a return on investment within 7 to 16 years, without negatively impacting food safety. To encourage hedgerow and other restoration practices that enhance farm sustainability, increased outreach, technical guidance, and continued policy support for conservation programs in agriculture are imperative.

Intensive, homogeneous agricultural lands are highly productive and efficient for meeting global food production demands. However, these fields often have little surrounding natural habitat, which has led to a loss of biodiversity and ecosystem services on farms (MEA 2005), including a reduction of pollinators and other beneficial insects (Zhang et al. 2007). As a result, external inputs, such as honey bee hives and pesticides, are increasingly needed to keep farms profitable, causing widespread concern that our farming systems are not sustainable (Hobbs 2007; Tilman 1999).

Restoring field edges, by creating hedgerows or other habitat plantings, diversifies farms without taking land out of production (Long and Anderson 2010; Williams et al. 2015). Benefits include wildlife habitat creation (Heath et al. 2017), water quality protection (Long et al. 2010) and increased pollination and pest control by beneficial insects (Morandin et al. 2016). Despite the documented benefits, resources (UC IPM 2017), and support for conservation programs through the Agricultural Act of 2014, commonly known as the Farm Bill (NRCS 2017; USDA 2017), field edge habitat restoration on farms remains low.

Adoption of restoration practices is explained in part by landholders' experience with the potential benefits (e.g., wildlife habitat, aesthetics, increased beneficial insects such as natural enemies and bees) and their concerns about habitat plantings (e.g., regulations, equipment movement limitations, potentially increased presence of weeds, rodents and insect pests). The low implementation of restoration highlights the need for technical and financial assistance in local farming communities through conservation programs, such as those in the Farm Bill (Garbach and Long 2017).

UC Agriculture and Natural Resources, UC Berkeley, UC Davis and local conservation groups have

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A hedgerow bordering an almond orchard in Yolo County has been planted with native flowering shrubs and a forb understory of annual and perennial wildflowers. Hedgerows support bees and other pollinators as well as the natural enemies of pest insects and mites.

Katharina Ullmann, Xerces Society

Will Suckow

The flowers of toyon, a native shrub, are a nectar source for beneficial insects. The berries are favored by birds, including insectivorous birds that feed on crop pests.

been studying hedgerows in the Sacramento Valley for two decades. Research projects have examined pest control, pollination, wildlife, and food safety in row crops and orchards, with and without hedgerows. The results showed field edge habitat provides significant benefits from beneficial insects and poses low risks to crop production from insect pests and rodents (Morandin et al. 2016; Sellers et al. 2016). However, this information alone has not proved sufficient for increasing hedgerow adoption. Garbach and Long (2017) found that hedgerow adoption was highest where there was both agency support (e.g., from Natural Resources Conservation Service) and peer-to-peer support from growers with experience in field edge plantings. Efforts to increase the use of hedgerows on farms may also benefit from strategic support for social learning (e.g., peer-to-peer communication) that highlights the potential benefits and addresses growers' concerns about field edge habitat (Garbach and Long 2017).

Hedgerows data

We synthesized data from our studies in hedgerows and adjacent crops on the provision of two ecosystem services — pollination provided by native bees and pest control by natural enemies. We considered these data within a framework of crop production, wildlife habitat and food safety using processing tomatoes and walnuts as model systems.

We evaluated farm hedgerows near Sacramento in the Central Valley that were 10 to 20 years old during our study years, about 1,000 feet long and 15 feet wide, and planted with California native flowering shrubs and perennial grasses (Long and Anderson 2010). We compared these to conventionally managed field edge cropping systems, which were mowed, disked or sprayed with herbicides to control weeds, though some residual weeds were always present.

Improved pest control and pollination

Natural enemy insect numbers were higher in the hedgerows than in the conventionally managed field edges and insect crop pests were lower. Hedgerows also exported natural enemies into adjacent crops, where they provided biocontrol of insect pests (Long et al. 1998; Morandin et al. 2011, 2014). Tomato crops with hedgerows required less input of insecticides than those without them. Considering only the reduction in insecticide treatments, and a cost of $4,000 for hedgerow installation and establishment (Long and Anderson 2010), profit was realized after 16 years (Morandin et al. 2016; fig. 1).

Native bee abundance and diversity were higher in the hedgerows than in the conventionally managed field edges (Morandin and Kremen 2013). Hedgerows also exported native bees into adjacent tomato crops, where sentinel canola (potted plants used to assess pollination effects) had greater bee abundance than sentinel canola plants adjacent to conventionally managed field edges. Hedgerow profit from pollination enhancement in canola and enhanced biocontrol of insect pests was realized after 7 years (Morandin et al. 2016; fig. 1). Our profit

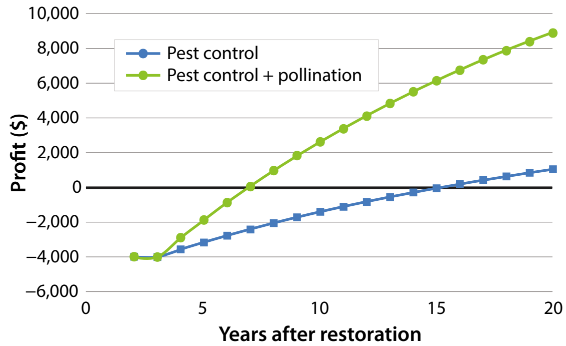

Fig. 1. Hedgerow restoration studies showed the value of hedgerows in terms of their pest control and pollination benefits in rotational cropping systems (from Morandin et al 2016).

Will Suckow

Author Rachael Long and grower Justin Rominger walk a hedgerow adjacent to a tomato field in Yolo County. Research suggests that hedgerow adoption is positively influenced by technical support from conservation agencies as well as by grower-to-grower communication.

model can be adapted to different rotational cropping systems.

Minimal impacts on wildlife, food safety

Remote cameras and live trapping of rodents in hedgerows and conventionally managed field edges documented that hedgerows did not generally result in greater mammalian wildlife incursion into field interiors at the walnut and tomato study sites. However, cottontail rabbits were more numerous in the hedgerows, and when they move into adjacent crops they can damage seedling stands.

Hedgerows did not have any noticeable impact on foodborne pathogen prevalence, including *Salmonella* (< 1% of rodents tested positive in walnuts and 0% in tomatoes) and *E. coli* O157 (0% of rodents in both tomatoes and walnuts) (Sellers et al. 2016). Hedgerows are generally too narrow relative to the larger landscape to have significant influence on vertebrate pests in adjacent crops. These data support other UC studies documenting minimal impacts of field edge habitat and associated wildlife on farms and food safety issues (Jay-Russell 2013; Karp et al. 2015).

The case for hedgerows

There is increasing pressure on farmland to meet the projected increases in the global demand for food, and also pressure to protect limited natural resources (Foley et al. 2011). Hedgerows provide a tool for integrating habitat, conservation and farm production goals without taking land out of production. Our studies showed they can reduce growers' reliance on crop inputs, such as honey bees and insecticides, and support food production. Similarly, global studies on the value of habitat on farms have found benefits to pollination and pest control (Garibaldi et al. 2011; Holland et al. 2017; Kennedy et al. 2013). Research on other benefits associated with field edge habitat, such as more insectivorous birds (Garfinkel and Johnson 2015) and water quality enhancement (Long et al. 2010), might provide an even more comprehensive case for why field edges should be more widely considered and restored to increase farm sustainability.

Farmers and landowners familiar with these benefits were more likely to plant hedgerows on their farms (Garbach and Long 2017). This suggests that farmer perceptions and actions to plant hedgerows can be positively influenced by outreach from conservation agencies (e.g., NRCS) that focus on technical support for field edge plantings. Support from agencies that target early adopters and create demonstration hedgerows is important for the sharing of information from farmer to farmer and neighbor to neighbor to support field edge restoration. Enhancing biodiversity is critical for building resilience in our farming systems to help reduce our reliance on external inputs for crop production. CA

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Above, bees visit wildflowers in a hedgerow: a honey bee on elegant clarkia (*Clarkia unguiculata*) and a bumble bee on California phacelia (*Phacelia californica*).

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RESEARCH BRIEF

Long-term agricultural experiments inform the development of climate-smart agricultural practices

Studying cropping systems over decades illuminates slow-changing but important effects on soil carbon, soil biota, water holding capacity and more.

by Kristina Wolf, Israel Herrera, Thomas P. Tomich and Kate Scow

Abstract

California's Mediterranean agro-ecosystems are a major source of U.S. fruits and vegetables, and vulnerable to future extremes of precipitation and temperature brought on by climate change, including increased drought and flooding, and more intense and longer heat waves. To develop resilience to these threats, strategies are necessary for climate-smart management of soil and water. Long-term, large-scale, replicated ecological experiments provide unique testbeds for studying such questions. At the UC Davis Russell Ranch Sustainable Agriculture Facility (RRSAF), the 100-year Century Experiment, initiated in 1992, is investigating the effects of multiple farming practices in a farm-scale replicated study of 10 row crop cropping systems. It includes different fertility management systems: organic, conventional and hybrid (conventional plus winter cover crop) systems; different crops: wheat, tomatoes, corn, alfalfa, cover crops and grasslands; and different irrigation systems: rainfed, flood irrigated and drip irrigated. We briefly describe and report on a selection of long-term experiments conducted at RRSAF investigating soil management and irrigation practices, which are an important focus for developing climate-smart strategies in Mediterranean systems. For example, long-term monitoring of soil carbon content revealed that most crop systems have experienced a small increase in soil carbon since 1993, and increases in organically managed plots were substantially higher. As RRSAF continues to build upon this rich dataset from one of a very few long-term row crop experiments in Mediterranean ecosystems, it provides a testbed for identifying climate-smart solutions for these agronomically important ecosystems.

Agricultural productivity in the United States has increased dramatically over the last few decades, but in the face of climate change current management practices might not sustain current levels of production (Gregory et al. 2005; Lobell et al. 2008). Some practices that achieve high crop yields and profit — for example, minimal use of crop rotations, high rates of fertilizer and pesticide inputs, minimal carbon inputs and soil disturbance — also result in degradation of ecosystem processes on which agricultural systems rely. Such degradation can reduce resilience, making these systems more vulnerable to high temperatures and uncertainty in water supply, resulting in lower productivity in times of extreme weather conditions, such as prolonged drought (Tilman et al. 2002).

Climate-smart agriculture means increasing resiliency to extreme and unpredictable weather patterns induced by climate change by following three principles: (1) developing agricultural cropping systems that are productively resilient in the face of climate change; (2) reducing greenhouse gas emissions attributable to agriculture to further reduce contributions to global warming; and (3) proactively and adaptively managing farms in a way to buffer farm productivity and profitability against the negative effects of climate change.

To make informed, evidence-based management decisions under new climate change regimes, data is

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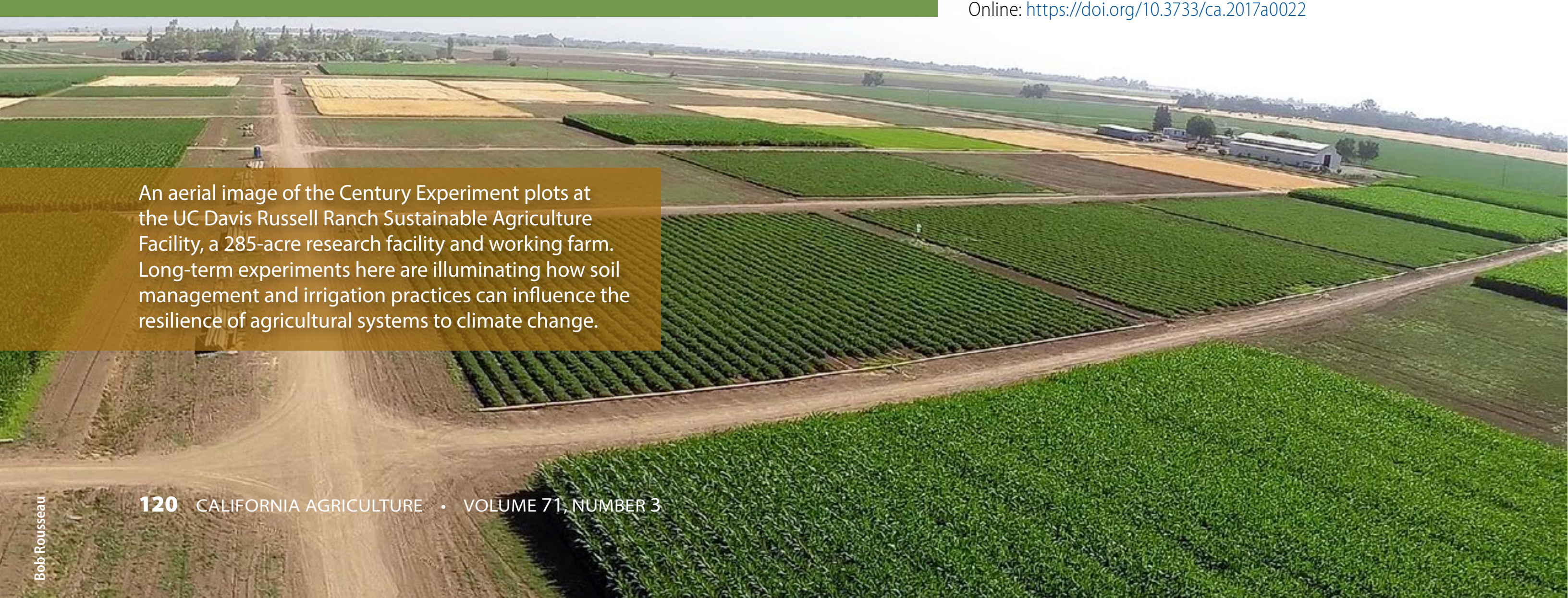

An aerial image of the Century Experiment plots at the UC Davis Russell Ranch Sustainable Agriculture Facility, a 285-acre research facility and working farm. Long-term experiments here are illuminating how soil management and irrigation practices can influence the resilience of agricultural systems to climate change.

Bob Rousseau

needed from long-term agricultural experiments, few of which exist. As weather and climate patterns change, repeated measurements over decades can reveal what may be slow but incremental changes in crop yield and quality, as well as soil quality and biodiversity (Rasmussen et al. 1998).

Century Experiment at RRSAF

A long-term agricultural experiment, known as the Century Experiment, is underway at the Russell Ranch Sustainable Agriculture Facility (RRSAF), a unit of the Agricultural Sustainability Institute at UC Davis. RRSAF is a 285-acre research facility and working farm where, under realistic commercial-scale conditions, controlled long-term experiments are testing a variety of crop systems and management practices related to fertility and nutrient management, irrigation and water use, energy use, greenhouse gases and soil health.

The Century Experiment was designed as a 100-year replicated experiment. It was initiated in 1992, when environmental and soil conditions were monitored as a baseline prior to installation in 1993 of 10 cropping systems across 72 one-acre plots; since then, one additional cropping system and restored native grassland reference plots have been introduced (table 1, fig. 1).

Soil and plant samples are collected regularly and analyzed, and subsampled for archive and future analysis. Crop yield and quality are measured annually at harvest. Energy use, inputs and outputs are monitored for all equipment and groundwater pumping throughout the year.

The interior of each 1-acre plot in the Century Experiment is maintained consistently for collection of the long-term dataset. Microplots and strips within each plot are available for additional experimental investigations, which have included the impacts of different fertilizers or crop varieties, pest management practices, tillage practices and soil amendments.

RRSAF research is also conducted in additional plots that are not part of the Century Experiment to focus on questions that explore practices that may ultimately be adopted within the main experiment. This research includes targeted investigations of soil amendments, irrigation frequency and type, and new crop varieties, and it permits side-by-side comparisons of management history on the effectiveness of different practices. UC and UC Agriculture and Natural Resources researchers and the RRSAF team collaborate regularly with local growers, as well as with researchers from other institutions throughout the United States and around the world, so that the research addresses local issues and also has broader relevance for agriculture in Mediterranean climates worldwide.

TABLE 1. Cropping rotations in 100-year study at Russell Ranch Sustainable Agriculture Facility

System	Crop rotation	Replications	Winter cover crop (WCC)?*	Irrigation†	Fertilizer source	Pesticide management
Organic tomato-corn	Tomato-corn	Six	Yes	Irrigated	Compost and WCC	Organic methods
Transitional tomato-corn‡	Tomato-corn	Three	Yes	Irrigated	Compost and WCC	Organic methods
Legume tomato-corn	Tomato-corn	Six	Yes	Irrigated	Mineral fertilizer and WCC	Conventional methods
Conventional tomato-corn	Tomato-corn	Six	No	Irrigated	Fertilizer	Conventional methods
Conventional wheat-tomato	Wheat-tomato	Six	No	Supplemental§ when wheat; irrigated fully when tomato	Fertilizer	Conventional methods
Alfalfa-tomato-corn¶	Alfalfa-alfalfa-alfalfa-tomato-corn-tomato	Six	No	Irrigated	Mineral fertilizer	Conventional methods
Wheat-fallow	Wheat-fallow	Six	No	Supplemental§	Fertilizer	Conventional methods
Wheat-fallow	Wheat-fallow	Six	No	Rainfed	Fertilizer	Conventional methods
Wheat-fallow	Wheat-fallow	Six	No	Supplemental§	None	Conventional methods
Wheat-fallow	Wheat-fallow	Six	No	Rainfed	None	Conventional methods
Wheat-legume	Wheat-legume	Six	Yes	Rainfed	WCC	Conventional methods
Native grass (reference system)	Perennial native grasses planted in 2012	Three	No	Rainfed	None	None

* The WCC is a bell bean, lana vetch and oat seed mix.

† Irrigation prior to 2014 was applied by flood (wheat) or furrow (tomato, corn). In 2015, subsurface drip irrigation (SSDI) was installed in tomato-corn plots. Alfalfa is irrigated by check-flood, and irrigated wheat by furrow-flood if needed.

‡ The transitional system was located in three unassigned plots prior to 1999 when it was converted to a tomato-corn rotation. It was managed as a tomato-corn system similar to farmers converting from conventional to organic, was managed with fully organic methods by 2000, and certified organic by 2001. It has been managed like the organic tomato-corn system since.

§ Wheat receives supplemental irrigation in plots that are not rainfed only when needed in excessively dry years, and at most two times in the winter, but in general receives no additional irrigation.

¶ All crop systems are 2-year rotations, except for alfalfa-tomato-corn, which is a 6-year rotation of 3 years alfalfa, followed by tomato-corn-tomato.

Soil chemistry, biology changes

Maintaining healthy soils is a key to climate-smart agriculture. Properties such as porosity, water retention, drainage capacity, carbon sequestration, organic matter content and biodiversity all help to confer resilience to new pest and disease pressures and to extremes in temperature and water availability (Borron 2006; Dick 1992; Pretty 2008). The California Department of Food and Agriculture's Healthy Soils Initiative, launched in 2016, reflects the state's commitment to improve the quality of managed soils (CDFA 2016). Encouraging best practices for maintaining healthy soils will increase biodiversity as well as beneficial physical and chemical properties of soil. Improving these properties will, in turn, confer resilience of agro-ecosystems to uncertainties in climate, including unpredictable rainfall patterns, new extremes in temperature and unexpected shifts in the distribution of pests and diseases (Borron 2006; Pretty 2008).

Intensive soil sampling is a key part of the Century Experiment. Plots are sampled at least once every 10 years to as deep as 3 meters (9.8 feet) in eight depth intervals, and a number of chemical and physical properties are measured. After 20 years, cropping systems, with few exceptions (e.g., unfertilized wheat-fallow), either maintained or increased total soil carbon content to a depth of 2 meters (6.5 feet). Soil carbon increased significantly more in the organic tomato-corn system than it did in any other crops and management systems. Soil infiltration rates and aggregate stability were also greater in the organic than conventional tomato-corn system. This research also identified specific soil fractions where early changes in carbon sequestration can be detected, to help predict which practices promote increases or decreases in soil carbon.

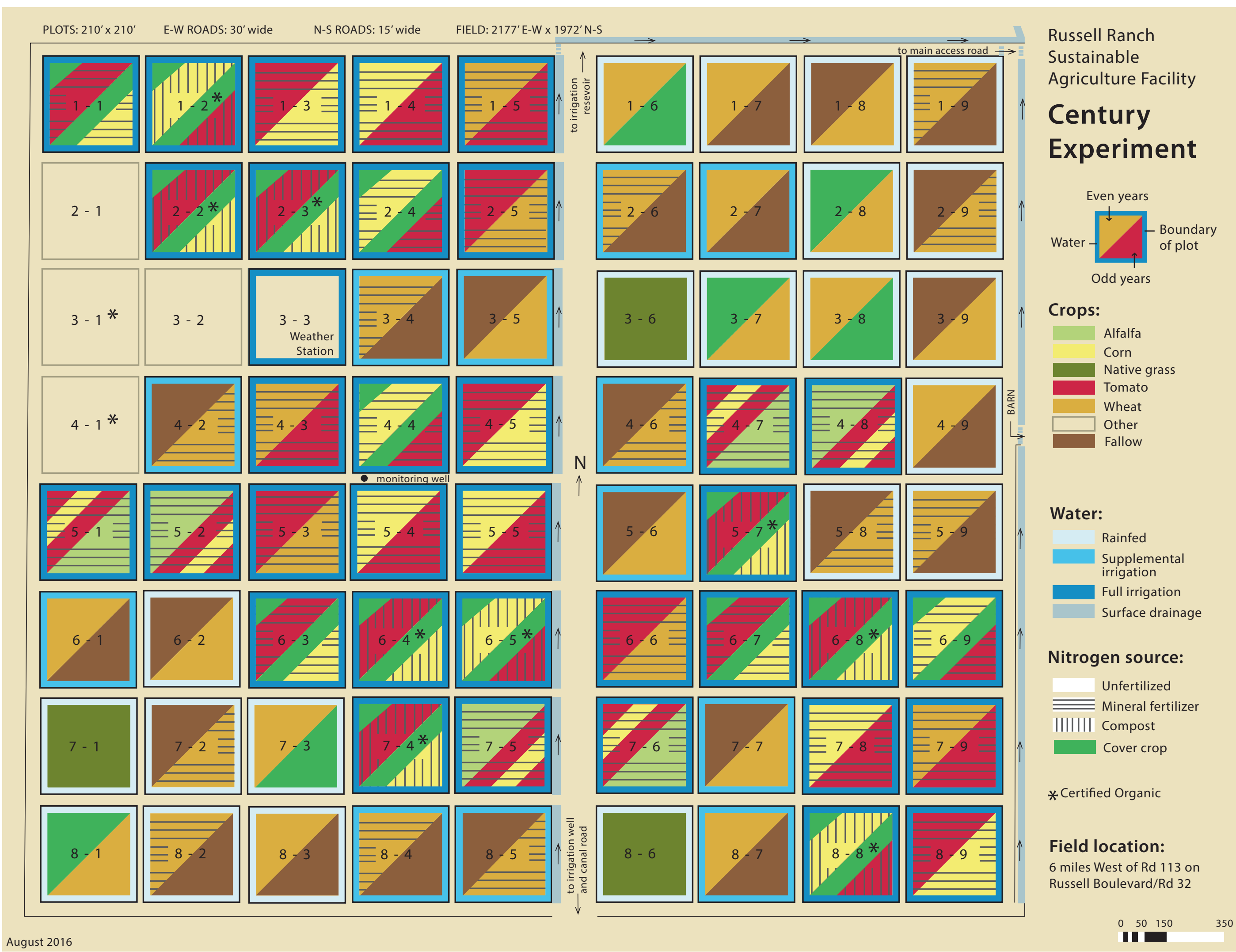

Fig. 1. Experimental design of the Century Experiment at the Russell Ranch Sustainable Agriculture Facility, showing the 1-acre treatments in year 25 of the planned 100-year experiment. "Even and odd years" in the legend (upper right) refers to the sequence of crop harvest and does not apply to the 6-year alfalfa-corn-tomato rotation, which began in 2012. All crop systems are 2-year rotations, except for alfalfa-tomato-corn, which is a 6-year rotation: 3 years of alfalfa followed by tomato-corn-tomato. Cover crops are grown either as part of a two-year rotation with wheat (in the "wheat-legume" rotations) or as a winter crop in the tomato-corn rotation. Numbers within plots are identification numbers. See table 1 for further information.

Changes in soil biology were evident as well: microbial biomass was 40% higher in soils in organic than in conventional tomato-corn rotations, and microbial community composition under organic and conventional management was distinctly different. More in-depth analyses of the soil biota, including sequencing of soil microbial communities and measuring abundance of mycorrhizal fungi, are underway.

Amendment, cover crop effects

Use of agricultural and food wastes, and cover crops, can reduce dependency on synthetic fertilizers that rely on fossil fuels and generate greenhouse gases in their synthesis. Also, use of soil organic amendments helps organic and conventional growers to "close the loop" by reducing energy and environmental costs of waste disposal, and recycling valuable nutrients back into the soil. At RRSAF, composted poultry manure and winter cover crops provide sufficient nitrogen and other nutrients to the organic tomato-corn rotation. Organic tomato yields for 20 years under furrow irrigation were not significantly different from conventional tomato yields.

Soil amendments and winter cover crops have led to increased soil carbon sequestration, higher infiltration rates and greater aggregate stability in the organic system compared to the conventional systems; however, these benefits may be of limited interest to growers if yields are substantially reduced. A challenge is how to combine use of organic inputs with subsurface drip irrigation (SSDI) for organic systems. Organic relies on solid sources of fertility, for example, cover crops and compost, that cannot be delivered in the drip line, and that rely on microbial activity to convert them into plant-available forms. In SSDI systems, only a limited area of the bed is wetted and microbial activity may be reduced. Researchers at RRSAF are investigating the feasibility of using different combinations and forms of solid and liquid organic amendments in organic tomato-corn rotations. This is particularly timely as interest in organic farming and products increases (Jerkins and Ory 2016).


Agricultural Sustainability Institute at UC Davis

Planting tomatoes in soil with cover crop residue still present. The use of cover crops and soil amendments in Century Experiment plots has led to increased soil carbon sequestration, higher infiltration rates and greater aggregate stability in the organic systems compared to conventional systems. Such soil properties can help crop systems withstand the temperature extremes and pest and disease pressures that may occur as the climate changes.

In 2012, a long-term experiment was initiated with the soil amendment biochar, a form of charcoal made from pyrolysis of organic waste materials. Application of biochar to tomato-corn rotations at 10 tons per hectare resulted in corn yields increasing in year 2 by approximately 8%, but no other yield effects were observed over 4 years (Griffin et al. 2017). Biochar had no impact, however, on soil water retention. These results underscore the importance of being able to draw conclusions based on long-term research, and the experiment continues to be monitored.

Water management

Water quantity and quality are critical concerns for climate-smart agriculture in chronically drought-afflicted California (Dettinger et al. 2015; Mann and Gleick 2015). SSDI may increase crop yields, reduce weed pressure and improve water management in conventionally managed systems (Ayars et al. 2015), but the trade-offs associated with other impacts of SSDI, such as changes to soil moisture patterns, reduced microbial activity, altered accumulation of salts and reduced groundwater recharge, have received little attention. At RRSAF, researchers are comparing effects of furrow versus drip irrigation on crop yields, root growth, microbial communities and soil structure. Many changes, such as soil aggregate structure, are not evident immediately and require long-term experiments to understand and resolve.


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Samples of biofertilizer in its various stages, from raw waste to fertilizer. Using cover crops and composted agricultural and food wastes lessens dependency on synthetic fertilizers, reduces waste disposal costs and recycles valuable nutrients back into the soil.

Irrigation scheduling is another focus of water management at RRSAF. Different methods and associated technologies (some commercially available) have been compared for estimating irrigation needs, including methods based on evapotranspiration (ET), soil moisture sensors, plant water status and remote-sensing data. In tomatoes, an ET-based method was found to better predict crop water needs than soil sensor–based methods.

Other research at RRSAF

Research projects at RRSAF have also addressed other aspects of climate-smart agriculture. These include development of farm equipment that reduces soil disturbance and energy consumption; application of sensor technology (soil and water sensors, airborne imaging spectrometers) in collaboration with NASA's Jet Propulsion Laboratory to support data-driven management choices in response to climate variation; and comparison of the efficacy of smart water meters in groundwater wells and irrigation systems.

Other investigations have measured the feasibility of using dairy and food waste biodigestate (product of anaerobic bioreactors) that can help offset consumption of fossil-fuel based fertilizers; tracking changes in wheat cellulose via isotopic methods to monitor plant responses to climate change; and measuring lower greenhouse gas emissions under SSDI than furrow irrigation. New varieties of climate-smart crops, such as perennial wheat, are being evaluated for their yield and resilience in California's Mediterranean climate.

In its 20 years, the Century Experiment has demonstrated a unique value in generating climate-smart data — for example, which practices enhance carbon sequestration in California row crop soils, how irrigation can be managed to reduce greenhouse gas emissions, and what sensors help most in reducing water consumption. Future research will address how soil biodiversity, such as the symbiotic mycorrhizal fungi, can be harnessed to reduce water and nutrient inputs, and increase crop resilience. Researchers exploring mechanisms driving short- and long-term responses to global change can guide the development of decision support models that incorporate economic, agronomic, ecological and social trade-offs and provide support for decision-makers — growers, policymakers, researchers — to make management decisions in the face of increasing climate uncertainty. CA

Researchers at RRSAF are evaluating new varieties of climate-smart crops, such as perennial wheat, for their yield and resilience in California's Mediterranean climate. Here, students hand harvest wheat for data collection.


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RESEARCH BRIEF

Getting the farm to the school: Increasing direct, local procurement in Yolo County schools

Data on in-season produce purchases and a collection of "forager" services support direct and seasonal sales from farms to schools.

by Gail Feenstra, Shosha Capps, Kristy Lyn Levings, Elaine James, Mary Laurie, Mitchell Maniti and Emma Lee

Abstract

Since 2012, the UC Sustainable Agriculture Research and Education Program (SAREP) has worked with the Yolo County Department of Agriculture to support farm to school activities in Yolo County. In 2015, SAREP partnered with the Yolo County Department of Agriculture to deepen engagement with Yolo County growers and increase direct sales to Yolo County schools. SAREP tracked the volumes and prices of produce purchased by five school districts for the 2014–2015 baseline year and the 2015–2016 school year. Analysis was completed for three school districts for common produce items purchased, increases in in-season purchasing and direct grower versus distributor sales. For these districts, 17 produce items were in the top 10 for at least one of the districts; the five most common were apples, bananas, lettuce, oranges and strawberries, four of which are available locally for some or all of the school year. Districts purchased between 50% and 75% of their produce in season by the end of year two. All districts increased their purchases directly from growers. Findings suggest how services for growers and school food buyers can contribute to more local procurement.

Farm to school programs bring food from regional farms to school cafeterias, support school gardens and promote food literacy. These programs have grown exponentially since the late 1990s, with more than 42,500 schools participating nationwide in 2014. In California, 55% of all school districts surveyed in 2013–2014 participated, representing 5,400 schools with 3 million children. Participating schools invested $167 million in local food (as defined by their districts), with the average school district spending 15% of its food budget on local products (USDA FNS 2015).

The goal of the project described here was to build the capacity of local growers in and around Yolo County to sell more products directly to school food service buyers. Such sales can have several benefits for growers, including diversifying and expanding their markets as well as potentially receiving higher prices than wholesale distributors offer. For school food service buyers, purchasing direct from growers helps

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Workers prepare fresh salads in the Davis Joint Unified School District central kitchen. Although direct sales can help growers expand their markets and in some cases receive higher prices, developing long-term purchasing relationships with school food service buyers has remained a challenge.

Will Suckow

The Yolo County Department of Agriculture has hosted a series of Marketplace Exchanges, economic matchmaking events similar in structure to speed dating. At the meeting above, in Woodland in November 2014, growers were paired with buyers, such as school food service purchasers, for a series of 5-minute conversations.

to meet the typical goals of farm to school programs, including increasing documented spending in the local agricultural economy and enabling the identification and promotion of local growers on school menus, websites and newsletters or in the cafeteria.

The alternative way for growers to sell to institutional buyers is through a distributor. This is the way that most fresh produce is purchased for school cafeterias. Most produce distributors do not provide farm-of-origin information (though some do). Distributors generally offer a selection of produce from many farms, near and far, at competitive prices, as well as greater convenience and more frequent deliveries compared to direct sales from farms.

For school food service buyers who want to support local growers through direct purchases, developing long-term, sustainable purchasing relationships has remained a challenge. Issues that are difficult for food service include drafting bidding language to give preference to regional produce, increased labor costs related to sourcing and cooking produce provided directly from a farm, delivery logistics, and pricing. For growers, difficulties include being able to provide consistent volumes over time, lack of long-term contracts, food safety and Good Agricultural Practices (GAP) certification requirements (voluntary audits that verify that fruits and vegetables are produced, packed, handled and stored as safely as possible to minimize risks of microbial food safety hazards), and adequate prices (Conner et al. 2011; Feenstra and Ohmart 2012; Izumi et al. 2009; Marshall et al. 2012).

In Yolo County, the county agricultural commissioner's office (Yolo County Department of Agriculture) and UC Agriculture and Natural Resources Sustainable Agriculture Research and Education Program (SAREP) have partnered to support farm to school activities since 2012, with a particular focus on increasing direct local produce purchasing by county school districts. Activities have included (1) professional development to help school food service staff incorporate more California specialty crops into school menus, (2) grower trainings on the logistics of selling to schools, (3) networking events to connect local growers and school food buyers, (4) evaluation of procurement practices and impacts, and (5) educational tours for policy- and decision-makers.

While this project focused on direct sales from farms to schools, we note that the goals of farm to school programs also may be achieved by sourcing produce from distributors that track farm-of-origin information. Some of the information collected for this project — in particular the data on seasonal produce — is also relevant to the procurement of local produce through a distributor.

Project description

In 2015, a new project was initiated with U.S. Department of Agriculture funding to focus on gathering school district purchasing data that would be meaningful to local growers (aggregated as pounds of produce rather than number of servings) to help them better assess what they might sell directly to schools and at what prices. The project also included individualized help for growers and school food service buyers in navigating logistics such as food safety certification, delivery options, seasonal pricing and learning about the farms and products through farm tours. This assistance can be valuable to some school food service buyers and growers, especially those just getting started in farm-to-school purchasing. The project had the following goals: (1) analyze, over two school years, the produce purchasing patterns of five school districts in Yolo County (Davis Joint Unified School District, Esparto Unified School District, Woodland Joint Unified School District, Washington Unified School District and River Delta Unified School District), (2) translate crop purchasing data into yield and acreage terms that are more useful for growers, (3) provide training for growers to acquire GAP certification, and (4) provide farm to school "forager services" (see sidebar).

The project evaluation described here focuses on analyzing produce sales data over a 2-year period. We did not formally evaluate other elements of the forager services such as the farm tours or GAP trainings. We hypothesized that all support services, including grower trainings and forager services, would influence

Forager services

Chef and restauranteur Alice Waters popularized the use of the term "forager" in connection with direct sales from farms. At Waters' pioneering farm-to-table restaurant in Berkeley, Chez Panisse, the forager is the staff member responsible for sourcing ingredients from local farms. Today, some school districts and other institutional buyers have generalized the term to include a range of services such as helping to identify local farms from which to source products, facilitating sales through sharing farm produce availability listings, organizing farm tours for food service directors, and helping growers collect needed documents such as tax forms, proof of liability insurance, and food safety certifications. For the project described in this article, forager services were provided by the Yolo County Department of Agriculture.

purchasing decisions and therefore be reflected in changes in the data.

Produce purchasing patterns were analyzed for each district based on distributors' and growers' invoices for two school years: 2014–2015 (before the project started) and 2015–2016 (during the project). Funding was not available to analyze more years although it would have been interesting to see if longer term trends could be identified. Invoice data was summarized by pounds purchased, price paid, date (month and school year), supplier and whether the produce item was purchased in or out of its local season.

This data was used in three ways. First, it was analyzed to determine the most common produce purchases, the amount purchased in and out of season, and the average price paid per pound. Second, the number of pounds purchased was translated into yield and acreage (using data from the Yolo County Department of Agriculture) to assist growers in evaluating their capacity to meet school food service buyers' needs in the future and to make cropping decisions. Third, the data was analyzed to identify changes from pre-project purchasing (year 1) to intervention purchasing (year 2) in terms of in-season buying and purchases directly from growers. In-season purchases were defined following seasonality charts developed by the Center for Urban Education About Sustainable Agriculture (CUESA 2016).

In the next section, we summarize trends in crops purchased, seasonal purchasing and direct purchasing for three of the school districts — Davis, Woodland and Esparto — the districts for which data analysis was complete at the time of this writing. We do not include translation of this data into yields and acreage.

Common crops

Seventeen produce items, as shown in table 1, were in the top 10 (by dollars spent) for at least one of the three school districts in one of the two school years. Five — apples, bananas, lettuce, oranges and strawberries — show up in the top 10 at least four times. The top 10 produce items for each district account for the majority of all expenditures (62% to 94% of total expenditures).

TABLE 1. The top 10 produce items purchased in each school district, by total dollar value

Crop*†	Davis		Woodland		Esparto		Average price/lb
	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16	
Apple-whole	■	■	■	■	■	■	$0.63
Apple-sliced			■	■			$1.74
Banana	■		■	■	■	■	$0.52
Carrot-carrotini					■	■	$1.28
Carrot-peeled		■			■		$0.88
Carrot-snack pack				■			$1.80
Celery	■	■			■		$1.73
Cucumber	■						$0.63
Grape		■	■	■			$1.36
Jicama					■	■	$2.14
Kiwi		■	■		■		$1.25
Lettuce-baby						■	$1.95
Lettuce-green leaf						■	$1.95
Lettuce-little gem						■	$3.70
Lettuce-chopped romaine	■	■	■	■			$1.82
Lettuce-shredded/tossed			■	■	■		$0.79
Orange-whole	■	■	■		■	■	$0.48
Orange-sliced				■			$1.75
Pineapple-whole‡							$0.72
Pineapple-spears/chunk			■				$4.17
Plum	■	■					$0.94
Spinach						■	$1.67
Strawberry	■		■	■		■	$2.25
Tangerine	■	■		■			$0.78
Tomato	■	■					$1.39
Expenditures for top 10 crops	$39,410	$48,827	$177,321	$135,610	$13,522	$14,548	
Total produce expenditures	$48,619	$55,336	$246,934	$219,782	$14,359	$16,853	
Top 10 as percent of total	**81%**	**88%**	**72%**	**62%**	**94%**	**86%**	

* Red highlighting means this crop showed up in the top 10 at least four times.
† Bold highlighting means this crop was purchased directly from growers for at least one school district.
‡ Whole pineapple was not in the top 10 for any school, but was included to provide complete pricing data for pineapple in both a processed and unprocessed form.

On an educational tour for elected officials and government staff, a food service director explains the contents of a grab-and-go salad for students.

UC Sustainable Agriculture Research and Education program

Seasonal purchasing

Purchases of produce items during the months in which they are locally in season suggest opportunities for increased regional procurement. Table 2 shows the amount and percentage of seasonal purchases made by each district. In Davis, about 75% of all produce was purchased in season in both years. The percentage of produce purchased in season decreased slightly from 78% to 75% in the second year (2015–16). Inspection of the data shows this may partially be due to much larger purchases of whole apples and tangerines out of season in 2015–16. Woodland's purchases show a substantial increase in the percentage of produce purchased in season (from 48% to 65%), mostly due to a very large decrease in the purchase of pineapple spears (which are always considered out of season in Northern California) in 2015–2016. Esparto increased its percentage of in-season purchasing from about 46% to 51%. This is partially due to large increases in local products purchased in season in the second year (oranges, strawberries, lettuce, spinach, carrots).

TABLE 2. Seasonality* of school district produce purchases

Amount purchased	Davis		Woodland		Esparto	
	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16
Total purchases	$48,619	$55,336	$246,934	$219,782	$14,359	$16,853
Total in season	$37,862	$41,559	$119,527	$142,339	$6,563	$8,540
Total out of season	$10,757	$13,777	$127,407	$77,443	$7,796	$8,313
% In season	77.9%	75.1%	48.4%	64.7%	45.7%	50.7%

* Seasonality defined by CUESA seasonality charts (CUESA 2016).

Direct purchasing

Table 3 shows that all school districts increased the percentage of purchases directly from growers, although the increase was small for Woodland. Since Woodland was the biggest of the three districts, even 2.6% of total purchases amounted to $5,793, the largest dollar amount spent with local growers in all three districts. The types of crops purchased directly from local growers for at least two school districts included lettuce, onions, watermelons, carrots and tangerines.

TABLE 3. School district produce purchases from distributors and direct from farms

Amount purchased	Davis		Woodland		Esparto	
	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16
Total purchases	$48,619	$55,336	$246,934	$219,782	$14,359	$16,853
Total direct purchases	$0	$4,185	$4,053	$5,793	$747	$2,832
Total distributor purchases	$48,619	$51,151	$242,881	$213,990	$13,612	$14,021
% Direct	0.0%	7.6%	1.6%	2.6%	5.2%	16.8%
Items purchased direct from farms	n/a	Cherry tomato Kiwi Lettuce Onion Watermelon	Cabbage Cucumber Eggplant Lettuce Melon Onion Bell pepper Tomato Turnip Watermelon	Cabbage Carrot Lettuce Mandarin Persimmon Tomato	Asparagus Lettuce Orange	Carrot Cauliflower Lettuce Onion Orange Potato Spinach Strawberry Tangerine

Opportunities for direct sales

Yolo County schools purchase many of the same crops. Five crops are in the top 10 for at least two districts (apples, bananas, oranges, strawberries and romaine lettuce). With the exception of bananas, all of these items can be sourced locally. If local growers are interested in exploring sales with schools, these popular produce items could be the focus of future planning. Three (lettuce, oranges and strawberries) were already being purchased locally during the pre-project or project phases (see table 1).

Yolo County school districts purchase between half and three-quarters of their produce in season, in part due to long regional growing seasons for many commonly purchased crops. However, it is possible to increase that percentage further by intentionally buying more products in season and replacing items that cannot be

Purchases of produce items during the months in which they are locally in season suggest opportunities for increased regional procurement.

grown locally (such as bananas and pineapple) with locally available alternatives. A more robust forager program could help school food service staff develop a greater awareness of when particular crops are in season (when they are also cheapest) and how to incorporate them into menus, which would boost seasonal sales for growers to local buyers. Additionally, a guidebook about using California specialty crops, developed through a recent California Department of Food and Agriculture grant with Yolo County, is available on SAREP's website for school food service buyers to use (Evans and Brennan 2015).

Direct purchasing from local growers in Yolo County increased in all three districts. The percentage increase was substantial in Davis (increase from from 0% to 8%) and in Esparto (increase from 5% to 17%). The crops listed in table 3 might be a good place to start if more growers are interested in supplying produce directly to school districts. However, all these districts still make most of their produce purchases through produce distributors, so it will be important to include distributors in efforts to increase in-season and regional purchasing in addition to building direct relationships with growers.

School food service and grower education and the "foraging" services offered as part of this project appear to have had a positive impact on regional and direct procurement, according to the forager, particularly in the Esparto school district (pers. comm., Kristy Levings, Yolo County Dept. of Agriculture). Our data, at least for Esparto, supports this assertion. Additional factors that may have influenced the shifts seen in one or more districts include increased funds available to the food service directors through this project or other sources, and increased support and encouragement from local district administrators. Observational evidence from this project suggests that several factors need to be in place for successful direct procurement to take place. These may include supportive leadership at all levels in the school district, adequate funding, willing and enthusiastic food service staff and growers, and marketing to children and families.

Supporting local procurement

The data presented here can help support school food service buyers and growers to better meet challenges related to local procurement. Growers can better assess the feasibility of selling to a school district if they know which crops are most commonly purchased, at what price, and how much the district is spending. In collaboration with the Yolo County Department of Agriculture, school buyers can use their seasonal purchasing patterns to identify opportunities to increase local, in-season purchasing both through their produce distributor and directly from regional farms.

Support programs that help prepare growers to sell to institutional markets and prepare school food service buyers to identify and buy from local growers are also important elements of building successful relationships. Some school districts are likely to benefit from these services more than others depending on their initial capacity (infrastructure, knowledge, staff time) and experience, and level of support from district leadership. CA

UC Sustainable Agriculture Research and Education program

Preparing meals from scratch has helped some schools increase their use of local produce. All three of the Yolo County school districts studied for this project increased their direct purchases from the previous year.

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RESEARCH ARTICLE

College students identify university support for basic needs and life skills as key ingredient in addressing food insecurity on campus

Food insecurity is a persistent stressor for some students; food literacy may help improve student well-being.

by Tyler D. Watson*, Hannah Malan*, Deborah Glik and Suzanna M. Martinez

Abstract

A recent University of California (UC) systemwide survey showed that 42% of UC college students experience food insecurity, consistent with other studies among U.S. college students. As part of UC's efforts to understand and address student food insecurity, we conducted 11 focus group interviews across four student subpopulations at UC Los Angeles (n = 82). We explored student experiences, perceptions and concerns related to both food insecurity and food literacy, which may help protect students against food insecurity. Themes around food insecurity included student awareness about food insecurity, cost of university attendance, food insecurity consequences, and coping strategies. Themes around food literacy included existing knowledge and skills, enjoyment and social cohesion, and learning in the dining halls. Unifying themes included the campus food environment not meeting student needs, a desire for practical financial and food literacy "life skills" training, and skepticism about the university's commitment to adequately address student basic needs. The results of this study broadly suggest there is opportunity for the university to address student food insecurity through providing food literacy training, among other strategies.

Food insecurity, the uncertain or limited ability to get adequate food due to lack of financial resources, is a persistent problem in the United States. The U.S. Department of Agriculture (USDA) estimated that 13% of U.S. households were food insecure in 2015 (Coleman-Jensen et al. 2016). Food insecurity is linked to several physical and mental health problems, such as poor self-reported health, poor diet quality, obesity, diabetes, depression and anxiety (Gundersen and Ziliak 2015; Seligman and Schillinger 2010).

Since the Great Recession in 2008, a rapidly growing number of U.S. studies have documented student food insecurity. Among college students, it is estimated that food insecurity ranges from 14% to 72% (Chaparro et al. 2009; Dubick et al. 2016; Freudenberg et al. 2011; Gaines et al. 2014; Goldrick-Rab et al. 2015; Hanna 2014; Maroto and Snelling 2015; Martinez et al. 2016; Morris et al. 2016; Patton-Lopez et al. 2014). Several recent studies showed that food-insecure students were more likely to self-report being in fair or poor health, experience depressive symptoms, and perform lower academically than food-secure peers (Freudenberg

* These authors contributed equally to this work.

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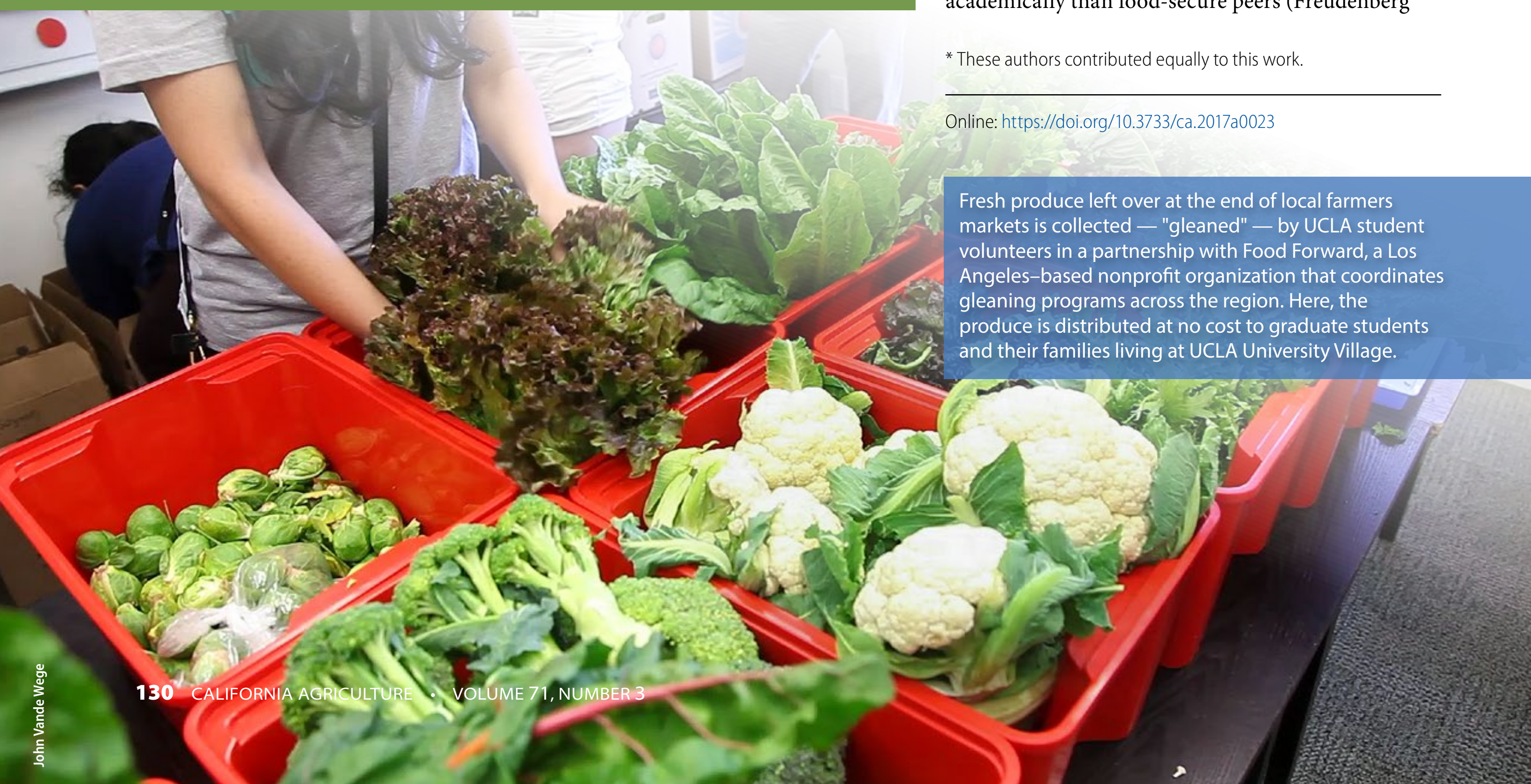

Fresh produce left over at the end of local farmers markets is collected — "gleaned" — by UCLA student volunteers in a partnership with Food Forward, a Los Angeles–based nonprofit organization that coordinates gleaning programs across the region. Here, the produce is distributed at no cost to graduate students and their families living at UCLA University Village.

John Vande Wege

et al. 2011; Martinez et al. 2016; Patton-Lopez et al. 2014). The scale of food insecurity among students documented since the Great Recession suggests that it may be attributed to the rising cost of attendance (tuition and fees, books and supplies, housing and food, transportation, and personal expenses) and inadequate financial aid to meet basic needs, namely housing and food.

A recent UC Student Food Access and Security Study reported that 42% of UC students have experienced food insecurity (Martinez et al. 2016). That study was funded by the UC Global Food Initiative (GFI), which had as one of its goals to identify and address food insecurity across the UC system. Also with support from the GFI, we undertook our qualitative research on student food insecurity to help contextualize the issue for UC. A secondary goal was to contribute to the GFI's understanding of food literacy among college students, and to help identify opportunities to advance food literacy across the UC system. Recently, food literacy has been conceptualized as a protective factor against both food insecurity and obesogenic environments (Cullerton et al. 2012, unpublished). Although the research is nascent, promoting food literacy among college students may be an appropriate strategy to help protect students from food insecurity.

Our study used qualitative research methods to (1) better understand how students perceive, experience and cope with food insecurity, and (2) explore opportunities to address food insecurity by improving food literacy among college students.

Food literacy

Food literacy can be understood through the four domains established by Vidgen and Gallegos (2014) — food planning and management, selection, preparation, and eating. These domains are contextual in nature; that is, diet quality depends not only on the individual but also on the environment in which the individual lives. Like the expanded view of health literacy, food literacy can be viewed broadly as a skill set, which individuals use to navigate their food environment to enhance their well-being (Massey et al. 2012; Palumbo 2016).

Focus groups

We conducted 11 focus group discussions between March and June 2016 with 82 students enrolled at University of California, Los Angeles (UCLA). Students were recruited to ensure representation from four subpopulations: residential undergraduates (living on campus with a meal plan), nonresidential undergraduates (living off campus), graduate/professional students, and students using free food resources (e.g., Community Programs Office [CPO] Food Closet).

The first three subpopulations were recruited via emails sent out by Residential Life staff and academic department administrators. To purposively sample students using free food resources (used as a proxy for food insecurity), we obtained referrals from food program leaders and included both undergraduate and graduate students. Interested students completed an online screener so we could select a diverse student sample based on the following characteristics: gender, race/ethnicity, international student status, major/department, and year in school.

Students were assigned to appropriate focus groups to maximize homogeneity among participants. We held three focus groups with residential undergraduates, three with nonresidential undergraduates, three with graduate/professional students, and two with students using free food resources. Participation was incentivized with dinner at the focus group location and a $30 honorarium paid via electronic transfer to students' university ID card at the conclusion of participation. The study was approved by the Institutional Review Board at UCLA.

The interview guide was informed primarily by the qualitative literature and by our practical research goals; it was reviewed by UCLA faculty and GFI leaders, including a student food insecurity expert. The script was pilot-tested with a group of eight UCLA students and modified to improve conversational flow.

Focus group interviews were conducted in English, with five to 10 participants. Upon arrival, students were asked to read and sign informed-consent documents and complete a brief survey with demographic and food insecurity questions, including the USDA six-item food security short form survey module (USDA 2012). Focus group interviews were 90 minutes long and were facilitated by two authors (T.W. and H.M.). Facilitators used a semistructured interview guide, with the questions in the first half dedicated to food literacy and in the second half to food security (fig. 1). All discussions were audio-recorded.

Fig. 1. Focus group questions used to guide discussions with students about food literacy and food insecurity at UCLA.

Food literacy

- Where do you usually eat or get food?
- What is most important to you when deciding what and where to eat?
- Now that you're a UCLA student, how are your food choices different than they were growing up?
- Over the course of your life, how have you learned about food and nutrition?
- Can you think of any examples of when you've gotten mixed messages about food?
- What do you think about receiving training or education around food as a UCLA student?
- What would it mean for someone to be food literate?
- Would you consider yourself to be food literate? Why or why not?

Food security

- Please describe what you know about student food insecurity at UCLA.
- Why do you think some students are food insecure at UCLA? Please feel free to share your personal experiences or experiences of your peers.
- How does the cost of living, including tuition, housing and meal plan, supplies, etc., impact your access to food?
- If you receive financial aid, how does this impact your access to food?
- If you or another student you know has experienced food insecurity, how were you or someone you know affected?
- Do you know about any campus resources available to UCLA students in need of food?
- What are some solutions that could be implemented at UCLA to help overcome student food insecurity?

Analytic strategy

We tabulated student characteristics for all 82 students. Food insecurity was assessed using the scoring criteria from the USDA six-item food security short form.

TABLE 1. Sociodemographic characteristics of UCLA student focus group participants (n = 82) and the UCLA student body

	Focus group students		UCLA student body*
	n	%	%
Gender			
Female	50	61%	53%
Male	31	38%	47%
Gender nonconforming	1	1%	—
Race/ethnicity			
Asian or Pacific Islander	27	33%	35%
Hispanic or Latino	23	28%	20%
White	15	18%	35%
Biracial or multiracial	7	9%	—
Black or African-American	5	6%	5%
Other	5	6%	4%
International student status			
Domestic	77	94%	85%
International	5	6%	15%
Year in school			
1st year undergraduate	12	15%	13%
2nd year undergraduate	7	9%	13%
3rd year undergraduate	19	23%	19%
4th year undergraduate	14	17%	18%
5th year or more undergraduate	5	6%	5%
Total undergraduate	57	70%	68%
Recently completed undergraduate	1	1%	—
Graduate or professional	24	29%	32%
Living situation			
Other off-campus housing	46	56%	60%
Campus	25	30%	27%
Off-campus university housing	11	13%	13%
Receiving financial aid†			
Yes	64	78%	65%‡
No	18	22%	35%‡
Food security status			
Food secure	38	46%	60%
Food insecure	44	54%	40%
Low food security	26	32%	23%
Very low food security	18	22%	16%

Note: Percentages may not add up to 100 due to rounding.

* Sources: Martinez et al. 2016 (campus-specific data for UCLA); UCLA 2015a, 2015b; UCLA Office of Academic Planning and Budget, personal communication, 2017.

† Students receiving any financial aid, including grants, loans, and scholarships.

‡ Percentages available for undergraduate students only.

Each focus group audio recording was divided into two files, one consisting of the discussion on food literacy and the other of the discussion on food security. All audio files were transcribed verbatim by GMR Transcription Service. Two authors (T.W. and H.M.) employed an integrated approach using an inductive (ground-up) development of codes and themes and a deductive framework for organizing the codes according to the literature and interview guide. This involved an initial identification of themes directly following each session, as well as multiple reviews of the session notes, audio recordings, and written transcriptions.

After finalizing the coding schemes, two authors (T.W. and H.M.) used Atlas.ti Version 1.0.48 (2013, Scientific Software Development GmbH, Berlin) to code quotations within the transcripts. Different codes could be applied to the same segment of dialogue. Both authors (T.W. and H.M.) coded all transcripts and reached consensus on coding discrepancies. Ten themes were identified.

Low and very low food security

Participant characteristics are presented in table 1. According to survey responses to the USDA six-item food security survey module (USDA 2012), 44 participants, or about 54%, were classified as food insecure: 32% experienced low food security (defined as reduced diet quality, variety, or desirability) and 22% experienced very low food security (defined as skipping or reducing the size of meals).

Students who had experienced food insecurity reported they often relied on campus free food resources. One such resource, the UCLA Community Programs Office Food Closet (above), takes food donations and provides free food to any UCLA student in need.

Food insecurity themes

The focus groups discussed several themes around food insecurity, including student awareness, cost of university attendance, consequences, and coping. Illustrative student quotes are presented in figure 2.

Awareness of food insecurity

Students were very aware of socioeconomic inequality among students, which included the ability to afford food. Students did not use the term "food insecurity," but most had heard of the term and were aware of its approximate definition. Many students had either experienced food insecurity or knew that it existed among their peers. However, students spoke about food insecurity as an invisible issue on campus that was not openly discussed, and they expressed a desire for spaces to openly discuss food insecurity and other basic needs issues (i.e., housing and finances).

Students recognized the end of the academic quarter, academic breaks/holidays, and summer as times when they were more likely to experience food insecurity. Undocumented, commuter and international students were identified as highly vulnerable to food insecurity. Many students had heard about the CPO Food Closet but generally were not aware of other campus food resources unless they had personally used them. Students wanted more awareness and outreach around existing free food resources for struggling students.


Chidera Izuchukwu

Cost of attendance

Students described the high cost of attendance (tuition and fees, books and supplies, housing and food, transportation, and personal expenses) as the primary cause

Fig. 2. Themes and quotes around food insecurity among focus group participants (n = 82).

Themes around food security	Quotes
Awareness	"Food insecurity isn't something that is very obvious because . . . you can't always tell who's food insecure and who knows exactly where their next meal is coming from." — Undergraduate student "I think that term [food insecurity] is something that you wouldn't necessarily see, because food insecurity isn't something that a lot of people are very willing to openly discuss." — Graduate student "I've heard [of] it. I don't use it. It feels kind of weird to like intellectualize this process that just comes down to like, I'm hungry, and I don't have money to buy food, you know." — Undergraduate student
Cost of attendance	"I try to allocate [my refund check] for housing because housing is like really, really important, but what's left over is like nothing for food." — Undergraduate student "You're getting aid . . . but at the same time, cost of living is going up . . . and the financial aid is not keeping up with all that." — Undergraduate student "UCLA does not pay for housing or meal plans, which does not make sense. If the school recognizes you can't afford to pay tuition, then it doesn't make sense that it expects you to be able to afford housing and meal plans." — Undergraduate student "There's nothing normal about being a starving grad student. We make sacrifices, the opportunity cost of going to school is, okay, we could have been in the workforce . . . I think it's more difficult to finance graduate school than undergrad." — Graduate student
Consequences of food insecurity	"I think 'getting by' is a pretty good description as opposed to excelling, which we can all do if we were properly fueled, but sometimes we're not." — Undergraduate student "Food is always on my mind like, 'What am I going to eat? Do I have enough money? Maybe I should just skip a meal today so I can have enough food for dinner.' Yeah, it's always on my mind." — Undergraduate student "The physiological effects of having poor quality of food really affects the way you think and the way you function as a student . . . because good grades, ultimately, is a function of how well you are getting your physiological needs met." — Undergraduate student "I'll just go hungry because the main goal was to get to UCLA and get my degree and make my parents proud. I can forego some meals. I know I'm still going to survive." — Undergraduate student
Coping with food insecurity	"So I would have to buy . . . ramen and things like that so I can make sure that I have somewhere to live and I have electricity and things like that." — Undergraduate student "I think an indirect effect that [food insecurity] has on academics is just the fact that people might feel obligated to sacrifice some of their academics to go work a secondary — a part-time — job, just to be able to afford food." — Undergraduate student "[When I meal-prep for the week, my roommates] tell me, 'Don't you get tired of eating the same thing in the week?' I'm like, 'Yeah, but I get full, then it's good.' And then I'm like, 'Hunger is the best condiment. It tastes good.'" — Undergraduate student

of food insecurity either personally or among their peers. They were particularly concerned about high tuition and fees and high rents in nearby neighborhoods. For many students, financial aid was not sufficient to cover the cost of attendance, and students often prioritized food last. Many students expressed concern about not having enough money to absorb unexpected costs such as medical bills.

In general, students did not feel confident budgeting, especially because they received their financial aid disbursement in a single payment per academic quarter. There was a range of viewpoints on the acceptability of loans, with some students accepting they would have a heavy loan burden after graduation and others unwilling to accept any student loans. Graduate students generally felt they had less financial support from the university than undergraduate students had, despite often having additional financial responsibilities such as a spouse and dependents.

Consequences of food insecurity

Many students reported choosing cheaper, less nutritious foods and skipping meals. For struggling students, worrying about food was a persistent stressor that negatively impacted their academic performance. Some students reported spending a substantial amount of time and energy worrying about getting enough food or where their next meal would come from. They reported both mental and physical health impacts, including stress, inability to focus on their work, fatigue and lack of energy, irregular sleep patterns, irritability, depression, headaches, and weight gain linked to inadequate food intake. Students also described missing out on social opportunities, such as eating with friends in the dining halls or at restaurants due to financial constraints (e.g., running out of meal swipes or wanting to save money).

Coping with food insecurity

A majority of students attended events on and near campus to get free food. Students who had experienced food insecurity reported they often relied on campus free food resources to help them get by, especially the CPO Food Closet and 580 Café, a nearby community study space that offers free snacks and meals for students. A few students discussed preparing inexpensive staple foods, such as beans and rice, or snacking on granola bars to get through the day. Some students talked about working part-time jobs to help afford food and other expenses, but this caused more stress, which impacted academic performance. Students were hesitant to ask for help, but often relied on friends for assistance. For example, "swiping" friends with campus IDs into campus dining halls was a common strategy to help friends living both on and off campus. Some students normalized the struggle to eat as part of the college experience.

Fig. 3. Themes and quotes around food literacy among focus group participants (n = 82).

Themes around food literacy	Quotes
Existing food knowledge and skills	"I learned from my mom and my parents, originally, but I'm still learning, you know. You see things in the dining hall . . . people in the dining hall, and your friends kind of influence what you eat too." — Undergraduate student "I don't think there is anybody or anything [at UCLA] telling us to eat healthy . . . people who are eating healthy learned from somewhere else, or learned previously." — Undergraduate student "[Meal prepping] saves a lot of money and also time . . . it's really convenient to just have it there for you instead of having to be hungry and then worry about what you're going to eat or how much money you're going to spend." — Undergraduate student "I think that's a struggle for many of us . . . trying to find a [balance] between eating healthy, but at the same time on a budget . . . I don't know how." — Undergraduate student
Enjoyment and social cohesion through food	"I really enjoy having the freedom of choosing what I eat and deciding for myself what I wanna eat and how I want to prepare my food." — Undergraduate student "Food is such a social thing too. No one wants to say, 'Oh, I can't go out just to be with my friends just because I don't want to spend money.' No one wants to say that." — Undergraduate student "The reason why [580 Café is] so special to me is because there's a sense of community . . . I sit down. I see friendly faces. I can talk to Jeanne. Jeanne hugs everybody. And so it's more personal and intimate. And that's what eating is supposed to be." — Graduate student
Learning in the dining halls	"It's exciting to me . . . there's so many foods that I've tried here that I never had at home . . . I tried [quinoa] for the first time and I tried way more vegetables and fruits so . . . it's a learning experience." — Undergraduate student "My first year I was like, 'Oh, I'm gonna be healthy.' So I went [to the dining hall] and they don't have soda there, so I was like, 'Oh, okay. I won't drink soda.'" — Undergraduate student "I remember freshman year, I was so mind-blown by this concept of all-you-can-eat, all-you-can-drink, whenever, wherever. So, at dining halls, I would religiously get Coca-Cola . . . Thankfully, I eased off on that. But, I do remember the transition from being regulated on what I eat to . . . complete freedom. That really impacted my choices." — Undergraduate student

Food literacy themes

Students discussed several themes around food literacy, including existing knowledge and skills, enjoyment and social cohesion, and learning in the dining halls. Illustrative student quotes are presented in figure 3.

Food knowledge and skills

Students identified numerous sources of food knowledge and skills, most often mentioning family, peers, news media, and UCLA courses. They also mentioned entertainment media (e.g., cooking shows), social media (e.g., Yelp, Facebook), smartphone applications (e.g., MyFitnessPal), scientific journals, UCLA resources (e.g., dietician), public health campaigns, advertising, travel, and K-12 education.

Students described family customs and culture as the foundation of food literacy and said they continued to develop their food knowledge and skills. Many discussed learning about food by observing others in the dining halls, discussing peers' dietary habits, and cooking with friends and roommates. Students commonly reported watching food documentaries and cooking shows, and many reported searching online for recipes, nutrition, and other food-related information. Although students cited UCLA courses as a credible and influential source of academic information about food, the large majority of students said they received little or no practical skills-based training from UCLA. Few students mentioned learning about food and nutrition as part of their K-12 education.

Students discussed their confidence and ability with respect to the food literacy domains of planning, selecting, preparing, and eating food. Many students described strategies for protecting diet quality and reducing costs. For some students, this meant prioritizing time to eat in the dining hall, while for others it involved prepping meals on Sundays or finding free food resources on campus. Others said they felt overwhelmed or time restricted and thus were less able to balance their resources with their nutritional needs. They reported skipping meals or choosing less preferable (e.g., unhealthy, low-quality, not filling) foods.

Food enjoyment, social cohesion

Students referred to cooking and eating as a way to bond and express love. They also discussed college and early adulthood as an exciting and formative time in which they were able to determine their own food preferences and priorities, explore new cuisines, and build community through food. Some students said they enjoyed cooking as a way to relax, relieve stress, and be creative.

The majority of students reported spending time dining, discussing, and preparing food socially with their peers. They explained that sharing food can be a positive way for students to come together in a stressful and competitive university environment. Bonding over food and cooking was even mentioned as an opportunity to build friendships. Students struggling with food insecurity said resources that supported family-style eating provided the added value of social interaction and support.

Learning in the dining halls

Residential undergraduates (with campus-provided meal plans) discussed how the food and beverages offered in the dining halls not only expanded their knowledge of healthy food but also "nudged" them into healthful habits. They said signage and menu labeling improved their awareness of nutrition and sustainability issues. However, many students expressed challenges with transitioning to a new food environment and a desire for culturally familiar food described as "comfortable." Students explained that their new independence combined with an overabundance of food in dining halls required learning and effort to self-regulate eating behaviors.

The university's role

Students discussed several themes that overlapped both food insecurity and food literacy. Unifying themes included the campus food environment not meeting student needs, a desire for practical financial and food literacy "life skills" training, and skepticism about the university's commitment to adequately address student basic needs. Illustrative student quotes are presented in figure 4.

Fig. 4. Themes and quotes around the role of the university among focus group participants (n = 82).

Themes around the role of the university	Quotes
Campus food environment	"I feel like [commuter students] would rather starve until they go back to their room or to their apartments to not pay for food here [on campus]." — Undergraduate student "I have 11 Regular — the cheapest meal plan. I just can't afford anything else. So, I try to limit myself. If I'm going to stay over the weekend, I'm not going to eat dinner today, and I'll just have cereal, or yogurt, or something." — Undergraduate student "Dining halls waste a lot of food, and I've seen them throw it away. And it's ridiculous." — Undergraduate student
Life skills in college	"I'm surprised we have all these GE requirements, but there's nothing about food. That's one of my pet peeves. What about food, and what about financial wellness?" — Undergraduate student "I just think more along the lines of cooking . . . It would just be better to know simple, fast ways to make certain foods without it being very time consuming and it can still be healthy for you at the same time." — Undergraduate student "I think it would be helpful if students were taught how to better allocate their money . . . [and given] cooking lessons, how to cook simple." — Undergraduate student "I can't afford to eat 100% right every day." — Undergraduate student
Addressing basic needs	"We're so much more than students, so the fact that this university focuses more on academic rigor and being competitive and thinking about the future and not really how to take care of yourselves now, it really affects you a lot." — Undergraduate student "There's so much money here [UCLA], all this research, all that's going on. I think hunger shouldn't really be a problem at an institution like UCLA, you know? We pride ourselves in being the best, but we can't even feed our own people." — Undergraduate student "A less obvious impact of food insecurity in the context of an institution [is] definitely disaffection from the institution, itself . . . It undermines the confidence that we have in the mission of this sort of institution — this sort of space." — Undergraduate student "It seems unfair that we're thrown into such a competitive environment with such unequal opportunities. It's not a level playing field, which I knew coming in, but it's definitely been reinforced." — Undergraduate student

Campus food environment

Many students living in campus residence halls had positive comments about the quality of the food in the dining halls but expressed concerns about the tiered meal plan structure — having a meal plan did not guarantee food security. Students discussed choosing meal plans based on their financial means and not on nutritional needs. For instance, some students reported buying the most limited meal plan (11 meals per week) because it was the cheapest option. Students also reported they lacked access to kitchen space to prepare food to supplement meal plans or cook with friends. A majority of students also perceived large amounts of food waste on campus and felt that some food, especially in the dining halls, could be recovered and redirected to students in need.

Beyond the dining halls, students overwhelmingly said that food on and near campus did not meet their needs. Food perceived to be healthy was often cited as expensive or not "filling" (e.g., salads). Food that was affordable and "filling" was often perceived as unhealthy and low quality (e.g., $1 beefy burrito). Consequently, many students brought food from home, bought less preferable foods, found free food options, or skipped meals. Many students were willing to travel beyond the surrounding campus neighborhood to find affordable and culturally appropriate food outlets (e.g., Asian markets, discount stores).

Through the UCLA Farmers Market Gleaning Program, students volunteer with Food Forward, a Los Angeles-based nonprofit organization that collects produce from local farmers markets, *below*, that would otherwise go to waste and distributes it to people in need through food pantries, shelters, senior homes and other channels. The program was started in 2015 by author Tyler Watson and undergraduate student Savannah Gardner, *left*, in collaboration with the student group Swipe Out Hunger. It now delivers more than 400 pounds of fresh produce to UCLA students each week and also hosts cooking and nutrition demonstrations.

Life skills in college

Students identified college as an appropriate place to learn practical life skills, including food planning and preparation. They said that food-related issues became more salient in college, and they expressed the need for the university to provide additional food education and training. Many students wanted to learn to budget and cook simple nutritious meals. They were frustrated with intellectually knowing the "right choice" but not having the skills or resources to act on that knowledge.

Students discussed various formats for receiving practical food instruction, ranging from a required general education course to pop-up cooking demonstrations on campus. Many students said they thought a practical one-unit undergraduate life skills course should be required to both support health-promoting behaviors among students and demonstrate the university's commitment to student well-being. Students identified the transition from living in university residence halls to living off campus as a critical time to receive this instruction.

Addressing basic needs

Many students were skeptical of the university's commitment to adequately and effectively address student basic needs. A prevailing attitude was that the university placed too much importance on academic performance and research efforts and not enough on prioritizing struggling students and a holistic student experience. Students discussed key areas in which the university was not addressing their needs: inadequate financial aid allocations, unaffordable housing costs, inflexible meal plans, high food costs on campus, and lack of opportunities to learn life skills, including financial and food literacy. Many students did not believe the university would address these needs, which negatively affected their sense of belonging at the university. Some students were hopeful about the increasing awareness of student food insecurity and other struggles such as homelessness.

UCLA tuition and living costs

UCLA undergraduate student tuition and fees ($12,836 for the 2016–2017 academic year) are now twice what they were in 2006–2007 in absolute dollars, largely as a result of state funding cuts to the UC during the Great Recession (Mitchell et al. 2014; UCLA 2016; UCOP

2016). Following a 6-year tuition freeze, UC Regents have voted to increase tuition and fees by 2.5% for the 2017–2018 academic year (UC Board of Regents 2017; UCOP 2016).

In addition to rising tuition and fees, UCLA is located in one of the highest-cost-of-living regions in Los Angeles (Apartment List Inc. 2017). According to the 2016 UC Cost of Attendance Survey, UCLA students living in a one-bedroom apartment without roommates paid $1,342 per month, and students with one roommate paid $951 per month. The all-student rent average was $840 (ranging from zero to six-plus roommates), making it the second-highest rent average in the UC system, below only UC Berkeley (UCOP 2017).

Many students receiving financial aid felt the support was insufficient to meet the cost of attendance, currently estimated at $34,088 at UCLA (UCLA 2016). Their concern is consistent with Kelchen et al. (2014), who found that over half of U.S. postsecondary institutions underestimated 9-month living cost allowances for students living off campus by an average of $3,000, assuming a single-efficiency apartment. These student concerns about actual cost of attendance led to improvements in how the UC system asked students about their cost of living in the 2016 UC Cost of Attendance Survey. Specifically, the question of food expenses in the last month was updated to food expenses in the last week based on student and staff input (Ruben Canedo, UC Basic Needs Co-Chair, personal communication, Mar. 15, 2017).

Food insecurity normalized

Taken together with the UC Student Food Access and Security Study, the findings from our study suggest that students across the UC system struggle to meet their basic needs, and food is the easiest thing to sacrifice. It is possible that struggling with food insecurity in higher education settings has been normalized among students, which may help explain why, until recently, the issue has been unacknowledged and therefore largely unaddressed.

Students in this study described struggling to afford food as a persistent stressor that affected both academic performance and mental and physical health, which is consistent with the literature (Freudenberg et al. 2011; Gundersen and Ziliak 2015; Martinez et al. 2016; Patton-Lopez et al. 2014; Seligman and Schillinger 2010). A recent UC study found that students experiencing food insecurity were twice as likely to have feelings of depression than their food-secure counterparts (Ritchie and Martinez 2016). In our study, students felt they missed out on social opportunities, such as dining with peers, which are important for building social ties in a college environment (Umberson and Montez 2010). Limited opportunities to create social ties in college may affect a sense of belonging and increase a student's intention to drop out of college (Langhout et al. 2009).

Food training, cooking skills

A majority of students in our study discussed wanting more training and skills around food preparation and budgeting. The UC Student Food Access and Security Study also found that across the UC system students wanted university assistance with learning to cook cheap, healthful meals and to budget with limited resources (Martinez et al. 2016). Previous research suggests people with high or moderate levels of cooking, food preparation, and financial skills are less likely to experience food insecurity than people with lower skill levels (Gorton et al. 2009).

A majority of students discussed wanting more training and skills around food preparation and budgeting.

College may be a critical time for developing food literacy, as 57% of food insecure UC students reported that they were new to experiencing food insecurity (Martinez et al. 2016). Also, improving food literacy could help address the widely held student perception that healthy food is more expensive. Several UC campuses have launched academic and community programs to increase student food literacy and improve student food security.

Limitations

This study had several limitations. We used convenience and purposive sampling to recruit focus group participants, which may limit generalizability to broader student populations. Participants were more likely to be female, minority race/ethnicity and receiving financial aid than the general student population. Because two focus groups intentionally included students who use free food resources, the overall proportion of study participants who had experienced food insecurity (54%) was higher than in the UC Student Food Access and Security Study (42%) (Martinez et al. 2016); however, the prevalence of food insecurity among students in the other nine focus groups was 39%. Additionally, study participants may have been more interested in and aware of food issues. Lastly, it is important to consider issues of conformity and censoring within focus group


Hannah Malan

With support from the UCLA Healthy Campus Initiative and David Geffen School of Medicine, a teaching kitchen pilot program was launched in spring 2017 for students in health-related fields. Based on the high level of interest and positive feedback, organizers hope to expand the program.

studies. Despite efforts to maximize homogeneity within groups and the apparent range of experiences and opinions heard, some students may have been inclined to match their experiences to those already stated or refrain from sharing unpopular attitudes or beliefs (Morse 1994).

Statewide challenge

Meeting student basic needs is gaining recognition as a major challenge across institutions of public higher education of all sizes, and efforts are under way to comprehensively work toward student basic needs security. With support from the UC Global Food Initiative, all 10 UC campuses are conducting academic and administrative research; implementing both short-term (e.g., food pantries) and long-term (e.g., Supplemental Nutrition Assistance Program, SNAP, registration) services; improving systems practices (e.g., contracts with food vendors); and leading policy advocacy across campus, UC system, and state government levels. In 2017, the institutions of higher education in California — UC, state universities, and community colleges — formalized a partnership to develop statewide policy solutions to improve the lives of their students. Further research is needed to better understand the student experience of food insecurity and to assess the feasibility and effectiveness of interventions aimed at reducing food insecurity among college students nationwide. CA

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RESEARCH ARTICLE

UC pursues rooted research with a nonprofit, links the many benefits of community gardens

A study of eight San Diego County community gardens demonstrates their role in gardeners' health and well-being and community development.

by Mirle Rabinowitz Bussell, James Bliesner and Keith Pezzoli

Abstract

The informal economy, healthy food options and alternative urban food systems are interconnected in important ways. To better understand these connections, and explore a rooted university approach to working with communities, we collaborated with the San Diego Community Garden Network to analyze the production, distribution and consumption of produce from eight community gardens in San Diego County. The project engaged UC San Diego researchers and students with county residents and community-based organizations to develop a survey together. Interviews with the gardeners and data from the completed survey document the ways in which community gardens contribute to individual and household health, well-being and community development. They suggest that despite perceptions that community gardens have marginal commercial capacity, they have the potential to contribute in meaningful ways to community development, particularly in low-income neighborhoods.

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The informal economy, healthy food options and alternative urban food systems are interconnected in important ways. To better understand these connections, we analyzed the production, distribution and consumption of urban agricultural products in several low-income San Diego neighborhoods with a focus on community gardens.

Community gardens play a critical role in alternative food systems since they typically operate in socially disadvantaged areas and serve to enhance the economic, social and nutritional needs of local residents. Integrating knowledge about food systems, health and ecology with knowledge about labor force dynamics and grassroots community development creates actionable theory suggesting new pathways for jointly improving social and economic conditions in the context of urban food systems. In this paper, we define the informal economy as economic transactions that are not regulated by the state and are primarily completed through cash transactions (Castells and Portes 1989; Hart 1973).

Under the authors' supervision, UC San Diego students administer a survey at City Heights Community Garden in San Diego on the role of community gardens in alternative food systems. In an earlier study in this neighborhood, the authors found a robust informal economy operating among community gardeners.

Jim Bliesner

Our research project further enhanced our understanding of the merits of the "rooted university," a university that invests a significant amount of its attention and resources in place-based education, integrative research and community engagement. It engaged university researchers with residents and community organizations in a place-based (rooted), mutually beneficial exploration seeking ways to link community gardens, grassroots community development and access to healthy food. Following Ferguson and Dickens (1999), we define community development as a place-based comprehensive effort that produces assets in five forms: physical, social, intellectual/human capital, political and financial.

With funding from the UC Global Food Initiative and in collaboration with the San Diego Community Garden Network, we administered a survey to 120 community gardeners at eight gardens throughout San Diego County. Undergraduate students in the Urban Studies and Planning Program at UC San Diego helped design and conduct the survey as part of a field research practicum course created expressly for this project.

The New Roots Fresh Farm Community Garden, in El Cajon, provides garden plots to new refugees, who use them for small business farming.

Urban food systems

In understanding how food gets from farm to table, it is critical that both formal and alternative urban food systems are clearly outlined and their relationship to one another acknowledged. The academic literature on urban agriculture is rapidly expanding (Golden 2013) and informed our research. Studies have identified the complexity and hybridity that exist in local food supply chain relationships between producers, processors, distributors and retailers in both alternative and formal systems (Mount 2010).

According to a University of Missouri urban agriculture report, a food system includes the following eight components: growing, harvesting, processing, packaging, distributing, marketing, consuming and disposing of food (Hendrickson and Porth 2012). When these components are integrated to benefit the environmental, economic, social and nutritional health of a specific geographic area, an alternative community food system is formed (Garrett and Feenstra 1999). This framework of an alternative community food system is often used interchangeably with the concepts of informal, local or regional food systems; scholars have found the boundaries between them difficult to delineate. For example, while the congressional definition of "local" is "less than 400 miles from its origin" (Hendrickson and Porth 2012; Hicks and Seidl 2008), these geographic constraints are limiting in some contexts. Other studies have found that given this ambiguity there is no generally accepted definition of local food (Martinez et al. 2010).

In a formal food system, the previously mentioned eight components typically involve larger corporations, a considerable amount of administrative oversight and a highly organized, profit-maximizing approach to production and distribution. A large majority of the food most people in the United States eat comes from this type of formal source. Yet the formal food system has left considerable gaps for many segments of the U.S. population.

Food deserts, as defined by the U.S. Department of Agriculture, are areas devoid of fresh fruits, vegetables and generally healthy food options. Food deserts are often found in impoverished areas that lack access to farmers markets, grocery stores and other healthy food providers (Gallagher 2010). Alternative urban food systems attempt to accommodate for these gaps by offering food security, food proximity, food self-reliance and food sustainability. These efforts often create value (e.g., noncommodified mutual aid networks) that lies outside of, but supports in significant ways, the formal market economy. By encouraging local growth and consumption of produce, the alternative urban food system has the potential to fill in the gaps that the formal food system has created.

Alternative urban food systems, in particular community gardens, are designed to "enhance the environmental, economic, social and nutritional health of the residents within a particular place" (Maryland-National Capital Park and Planning Commission 2012). Usually they operate in the context of socially disadvantaged areas and marginal populations, and serve as alternative economic systems. In alternative food systems, the emphasis is on building community relationships in the food system that can enhance health, society and the environment. Communities have alternative food economies for different reasons: educating and promoting healthy practices, alleviating food insecurity, substituting store-bought food, fostering community building, rehabilitation training and therapy,

The study survey showed that 70% of gardeners with plots at the New Roots Fresh Farm Community Garden spend more than 10 hours a week there.

and local food sources for business (McCormack et al. 2010). Within these alternative food systems, urban agriculture plays an important role.

Urban agriculture can be defined as the production, distribution and marketing of food beyond home consumption and educational purposes “within the cores of metropolitan areas and at their edges” (Golden 2013). What differentiates urban agriculture from other forms of agriculture is its integration within the urban ecosystem. Direct linkages to the city, its resources, policies and inhabitants signify urban agriculture as an embedded system within the city (RUAF Foundation n.d.). The ecosystem of urban agriculture includes, but is not limited to, microfarms, community gardens, community farms and institutional farms and gardens (Cohen and Sanghvi 2012). We turned our focus to community gardens.

Community gardens

The literature on community gardens highlights their numerous benefits to individuals, including increased consumption of fresh vegetables (Armstrong 2000; Blair et al. 1991; McCormack et al. 2010), psychological well-being (Kaplan 1973; Ulrich 1981) and savings on food costs (Hlubik et al. 1994). Their connections to individual health and well-being have also been explored (Armstrong 2000), and the positive effects of exercise associated with community gardens are documented (Blair et al. 1991; Hlubik et al. 1994).

In addition to the benefits to individuals, community gardens also have the potential to serve as a catalyst for collective approaches to effective public health strategies (Armstrong 2000; Speer and Hughey 1995). They may also serve as a vehicle for community organizing or increase community capacity (Lillie-Blanton and Hoffman 1995).

Community gardens also contribute to community development. Whether serving as catalysts for positive community change (Holland 2004) or community interaction and socializing (Patel 1991; Saldivar-Tanaka and Krasny 2004; Teig et al. 2009), they have been shown to have a positive impact on citizen engagement, collaborative decision-making and activism (Glover et al. 2005; Patel 1991; Travaline and Hunold 2010).

Economic impacts

Despite a robust literature on other dimensions of alternative urban food systems, considerably less is known about their economic impacts (Golden 2013; O’Hara and Pirog 2013). We do know that components of alternative urban food systems can serve as a mechanism for job training and employment for both adults and youth (Kobayashi et al. 2010; Metcalf and Widener 2011). In some instances, this may include the incubation of new businesses (Bregendahl and Flora 2006; Feenstra and Lewis 1999).

At the individual and household level, activities that take place in the alternative urban food system can provide savings on food expenditures. For example, farmers markets and community supported agriculture

A gardener works in the shade at Tijuana River Valley Community Garden. The study survey collected information on what factors draw people to community gardening, including social, well-being and economic reasons.

(CSA) frequently provide cost savings (Cooley and Lass 1998; Park et al. 2011) and so too do community gardens. Studies have documented the frequency with which community gardeners cite the direct correlation between their community gardening and lower grocery bills (Blair et al. 1991; Patel 1991). However, little is known about the other means through which community gardening promotes economic benefits. The informal channels of barter and food exchange are of particular interest to our project because of the pervasiveness of the informal economy in low-income communities.

Earlier survey, new survey

This project builds on our previous research completed in 2013, when we collaborated with a community-based organization to analyze the informal economy in City Heights, one of San Diego's most ethnically, racially and linguistically diverse communities (Rabinowitz Bussell and Bliesner 2013). Our research identified a robust informal economy, characterized by a wide-scale reliance on cash transactions, which played a significant role for local consumers and producers. A survey of over 100 residents found that food-related transactions, such as buying and selling produce or prepared foods made at home, were a major factor in strategies local residents used to increase their household income or engage with the informal economy. The implication was that an alternative urban food system existed and served as the primary source of this economic engagement.

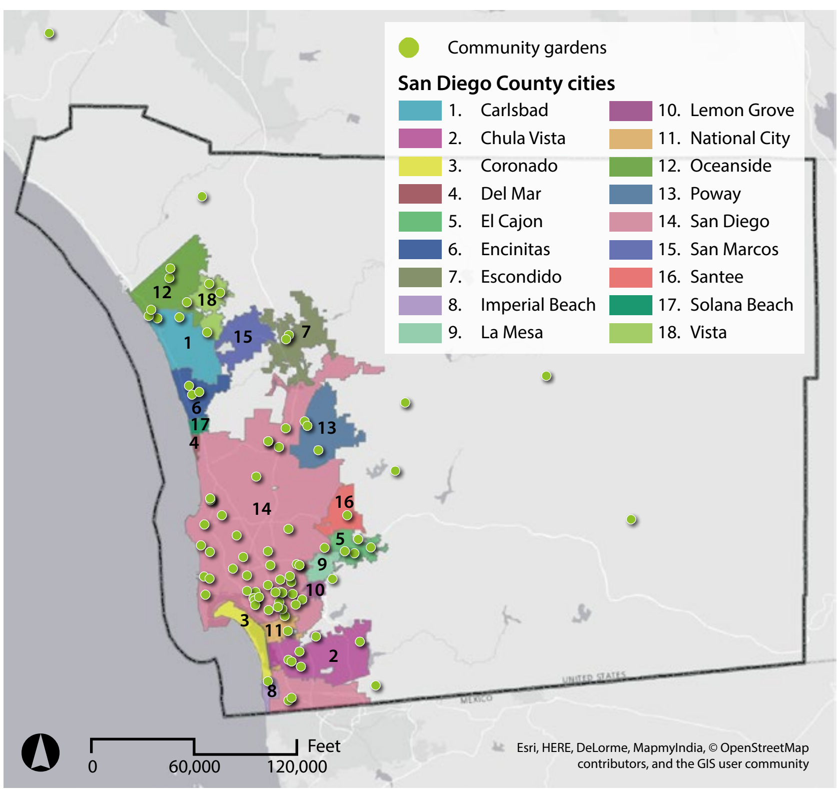

Fig. 1. The San Diego Community Garden Network. Map created by Arturo Tovar-Villalobos.

Preliminary analysis showed that it could be effective to not only look at the structure and dynamics of the City Heights food system but to put it in the context of the larger countywide emerging alternative food system. We hypothesized that our findings were not unique to City Heights and that similar systems likely existed in other low-income, racially and ethnically diverse neighborhoods in San Diego.

With funding from the UC Global Food Initiative in 2015, we administered another survey, this time at eight different community garden sites throughout San Diego County. The survey (http://ucanr.edu/u.cfm?id=177) was designed to better understand the reasons why people pursue community gardening and to discern whether low-income community gardeners are motivated by perceived or actual economic benefits. Toward this end, the survey collected data on the factors that draw people to community gardening, including social, well-being and economic reasons. The survey also included questions about the types and volume of produce commonly grown as well as other questions that sought to discern the adequacy of the community gardens in meeting the needs of their gardeners. Under our supervision, the survey was administered by a group of nine undergraduate students from the Urban Studies and Planning Program at UC San Diego, who received specialized training on survey design, administration and research protocols. Prior to commencing the research, the proposal was reviewed and approved by UC San Diego's Human Research Protections Program.

We created the survey and research design in close collaboration with the San Diego Community Garden Network (SDCGN). SDCGN supports community gardens with the larger goal of enhancing food security, promoting sustainability, and fostering social capital enhancement through community-based educational opportunities and community building. The network involves over 88 community gardens located throughout the region but primarily in urban areas, with a significant number located in low-income communities (fig. 1).

Its deep knowledge of San Diego's community garden ecosystem made it an ideal collaborator for this project as we sought to investigate a compelling research question within the framework of strengthening our capacity as a rooted university. The rooted university is one that invests a significant amount of attention and resources in place-based education, integrative research and community engagement. This approach is geared to understanding and improving how local-global forces interact and shape the human-natural environments we inhabit (Pezzoli et al. 2014). It is further premised on the belief that it is possible for scholars to become engaged in civic matters and public scholarship in ways that add value and contribute substantively to academic discourse and at the same time yield benefits to civic life (Peters et al. 2003).

The survey was administered to 120 community gardeners at eight sites. The sites were strategically selected in consultation with the SDCGN based on several criteria. We sought to include sites that represented both socioeconomic and geographic diversity, with a primary emphasis on gardens in low-income communities. We included larger, more mature community gardens as well as younger and smaller gardens. As shown in figure 2, the sites included rural and urban locations, small and larger gardens, and represented in the final analysis a representatively diverse population.

Respondents ranged in age, with the majority, 76.6%, between 30 and 79. They were ethnically diverse; 40% were Caucasian, 23.3% Hispanic or Latino, 6.7% African-American, 7.5% Asian, 6.7% African, 5% Middle Eastern and 5% other ethnicities (fig. 3). The majority of the respondents were members of large households, with 51% living in households of three or more people. Employment status was also diverse, and a relatively large percentage, 36.7%, were retired. The majority of the respondents had relatively low levels of educational attainment; only 16.6% had completed a bachelor's or postgraduate degree, 45% had a high school degree but no further education.

Community gardens surveyed

Name	**Calavera Schoolhouse Community Garden**
Location	City of Carlsbad
Sponsor	City of Carlsbad
# of garden plots	28
Waiting list status	N/A
Name	**City Heights Community Garden**
Location	City Heights
Sponsor	Price Charities
# of garden plots	31
Waiting list status	Long wait
Name	**City of Carlsbad, Harold E. Smerdu Community Garden**
Location	City of Carlsbad
Sponsor	City of Carlsbad
# of garden plots	48
Waiting list status	Long wait
Name	**Linda Vista Community Garden at Bayside**
Location	Linda Vista
Sponsor	Bayside Community Center
# of garden plots	N/A
Waiting list status	N/A
Name	**Mosaic Community Garden of Chula Vista**
Location	City of Chula Vista
Sponsor	Gracia y Paz Covenant Church and the San Diego Community Garden Network
# of garden plots	N/A
Waiting list status	N/A
Name	**Mt Hope Community Garden**
Location	Mt Hope (SE San Diego)
Sponsor	Project New Village
# of garden plots	60
Waiting list status	N/A
Name	**New Roots Fresh Farm Community Garden**
Location	City of El Cajon
Sponsor	International Rescue Committee and Kaiser Permanente
# of garden plots	45
Waiting list status	N/A
Name	**Tijuana River Valley Community Garden**
Location	Tijuana River Valley
Sponsor	Resource Conservation District
# of garden plots	136
Waiting list status	Long wait

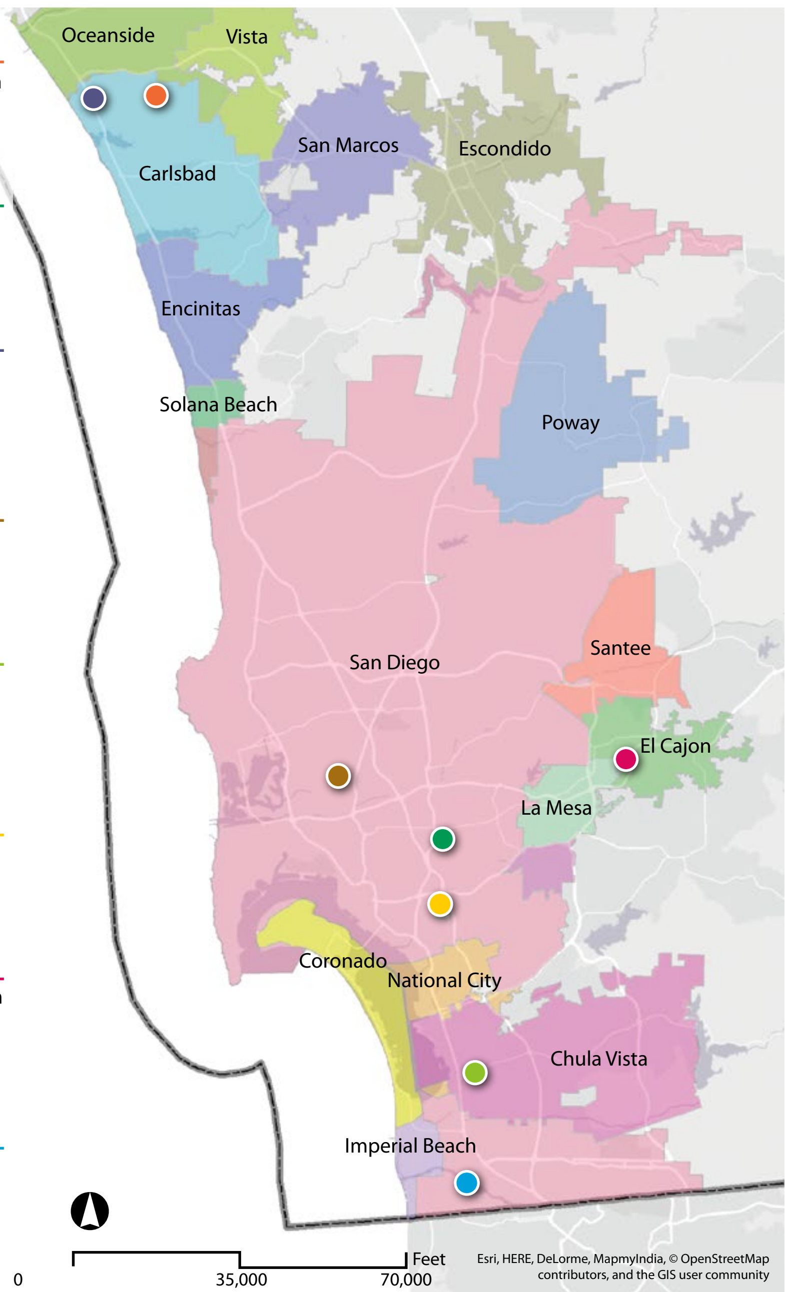

Fig. 2. Surveyed community gardens. Map created by Arturo Tovar-Villalobos.

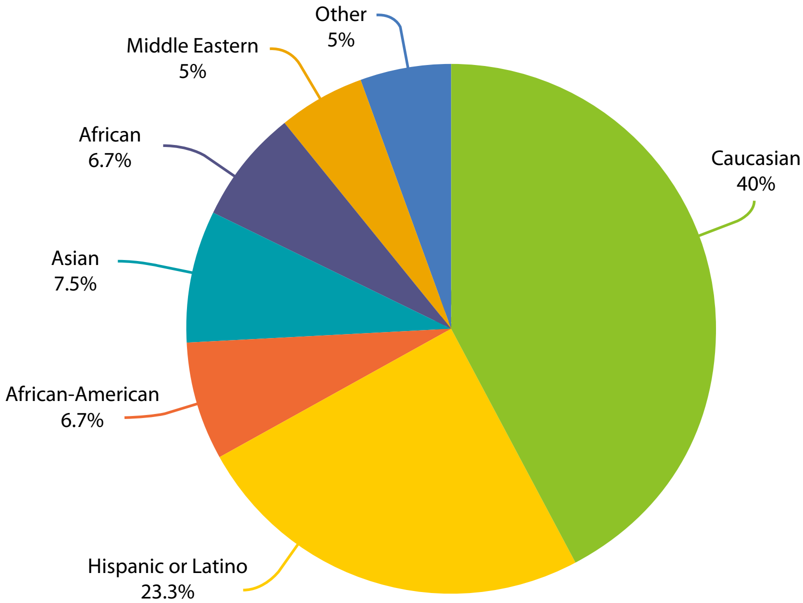

Fig. 3. Race and ethnicity of respondents.

Fig. 4. Why people got involved with community gardens.

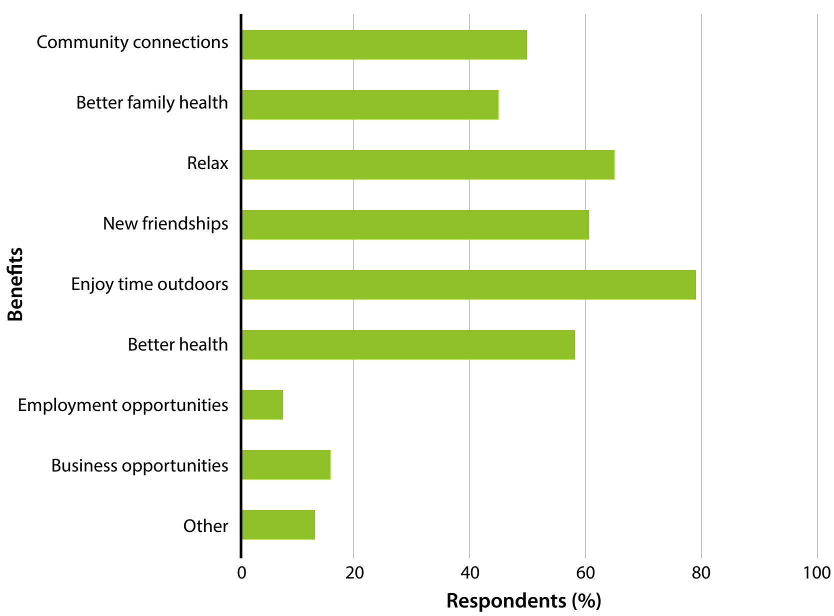

Fig. 5. Benefits of community gardens.

Findings: many benefits

The findings reveal that across a spatially and demographically diverse group of gardeners, there are many shared benefits and beliefs about the value of community gardens. Our findings validate the rich body of existing literature on urban agriculture that demonstrates the extent to which community gardens have the potential to serve at the nexus of social, economic and health empowerment in low-income communities. The data demonstrates that attitudes about health and well-being benefits are shared by almost everyone, yet as we discuss below attitudes about economic benefits are most pronounced in low-income communities.

Health, well-being and social capital

The survey results demonstrate the diverse motivations for community gardening, particularly as they relate to health and well-being. As shown in figure 4, in addition to the 84% of respondents who got involved with community gardening to grow their food, 60% of respondents were involved with community gardening to improve their health and 39% garden to make new friends.

With respect to broader perceived benefits of community gardening, figure 5 shows that 50% of the respondents believed that community connections are one of the benefits of belonging to a community garden. Furthermore, 61% had cultivated new friendships, 65% found community gardens relaxing and 79% enjoyed spending time outdoors. Furthermore, 90% believed their household diet had improved because of growing their own produce and 90% confirmed that their household had eaten more fresh fruits and vegetables since they started to grow their own produce.

With just a few exceptions, most respondents (90%) were first-time community gardeners. Many of them invested a considerable amount of time in their gardening activities; the survey found that 48% of respondents spent at least 5 hours each week at the garden. Respondents learned about the existence of their community garden from a variety of sources, including local organizations (20%), friends (41%) and family (12%), which speaks to the informal and formal channels through which knowledge about urban agriculture is disseminated.

The findings also illustrate the significant relationship between community gardens and the built environment. Many respondents, 40%, did not have space for their own garden. Furthermore, 88% believed that their neighborhood needed more community gardens; at least three of the gardens in the survey had waiting lists over 1 year long. This suggests an unmet demand for gardens and challenges with their spatial distribution. Furthermore, over one-third of the respondents, 35%, belonged to a garden that was over 5 miles away from their home, and 26% of the respondents travelled 1 to 4 miles to reach their garden. For many people, distances greater than 1 mile can be problematic

In addition to the 84% of respondents who got involved with community gardening to grow their own food, 60% of respondents were involved with community gardening to improve their health and 39% garden to make new friends.

without adequate transportation options. Most gardeners, 63%, used a car as their primary mode of transportation from their home to the garden; 23% walked, 6% biked and 5% took public transportation.

Economic benefits

This study was designed with an explicit focus on better understanding the economic benefits of community gardens. The findings suggest that the economic benefits have the potential to be most significant in lower-income communities. Similar to findings from other research (Blair et al. 1991; Patel 1991), 78% of respondents said that they saved money every month on their grocery bills. The majority, 68%, said that they saved between $0 to $39 every month, and 10% said that they saved between $40 and $60. In addition to these direct impacts, the responses point to less quantifiable, but equally compelling, potential economic benefits.

As shown in figure 6, when asked what they do with their produce, the overwhelming majority of respondents (96%) responded that they ate at least some of it at home and 26% drank some of it at home. Additionally, 55% gave produce to their extended family, 24% donated produce, 18% traded produce for other products and services and 64% gave produce to their friends. These networks of barter and donations have economic implications since the recipients of these items likely save money on their monthly food bills.

The survey found that 12.5% of respondents sold at least some of their produce to buyers. This statistic corroborates Armstrong's (2000) findings from her study of community gardens in upstate New York. Armstrong interviewed community garden managers to ascertain the reasons why people participate in community gardens, and she found that 10% of gardeners used the sale of their produce as an income supplement. This finding has several layers. Some community gardens have policies that prohibit or discourage the resale of produce grown on the site. One of the surveyed gardens is in a city in northern San Diego county that has municipal ordinances that are vague concerning gardeners' rights to sell their produce. After reviewing the city's municipal ordinances and community garden policies, we concluded gardeners' rights to sell were unclear, but the manager of the community garden shared with us her impression that gardening for retail use was prohibited.

Other gardens, however, encouraged their growers to use their plots as economic resources. For example, one surveyed garden is part of the International Rescue Committee's New Roots program, which provides community garden plots to new refugees, who use the sites for small business farming. The majority of gardeners surveyed at this site (84%), designed to serve a very-low-income population, reported that they used the community garden to supplement their income. Of the gardeners there, 70% spent over 10 hours a week at the garden and 70% reported that their participation in the community garden had helped them to increase their household income. All of these gardeners also responded that they would like to increase the amount of produce that they are able to sell.

Lessons, policy implications

Our findings have implications at several scales, from the individual gardener and their household to the larger civic infrastructure. For the individual gardener, the survey identified the benefits of community gardens across a demographically and geographically diverse population. On a larger scale, we found that community gardens are a spatially based nexus of social and health empowerment in all communities. Socially, they are hubs for community building and connection. They are rich sites for interpersonal relations and informal knowledge exchange. The survey responses do not capture it, but as we spent several hours at each site during our research, we were struck by the camaraderie among the gardeners and between the gardeners and garden managers. From a health and well-being perspective, our survey showed that these gardens enhanced physical and mental health. They contribute to personal and community well-being and serve as valuable sites for promoting health and enhanced social networks.

The physical location of community gardens is also highly valued, and in fact demand frequently outstrips supply. The development of community gardens is

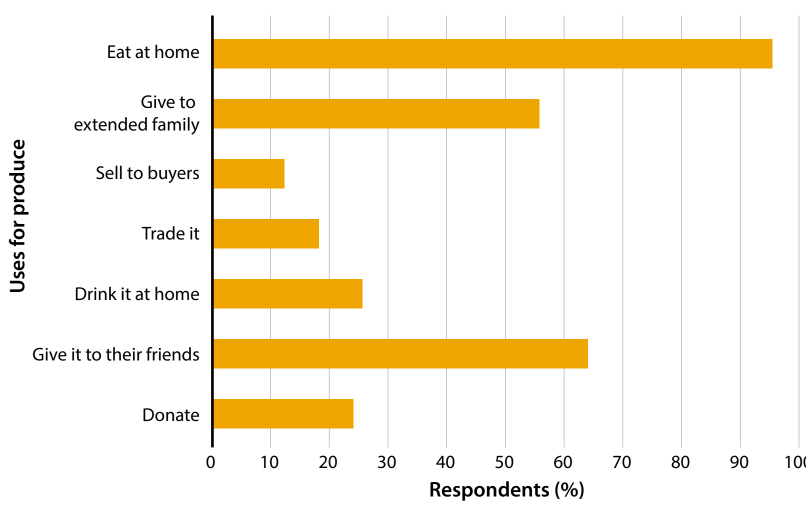

Fig. 6. Uses for produce grown at community gardens.

beneficial from a land use perspective. The size of the sites is not necessarily important. Distance is critical, though, and to avoid transportation barriers gardens must be situated in close proximity to alternative forms of transportation.

Economically, we found preliminary evidence that community gardens have the potential to positively contribute to household and community wealth in low-income communities through both formal and informal mechanisms. Many gardeners were able to measure the economic benefits in terms of money saved or money from produce sales; however, of particular interest to us, given that this project derived from a previous study on the informal economy, was the presence of informal produce exchange networks. We found a potentially robust network of barter and donations among community gardeners, particularly low-income ones, and their friends and families. With the presence of adequate support, training and local policies, these local gardeners may be able to successfully leverage untapped entrepreneurial capacity to directly sell their produce at farmers markets, produce stands or perhaps even local restaurants. Informal networks also may have the potential for further economic benefits by facilitating the bartering of unused produce for other goods and services or the donating of produce to friends and family to improve their health and reduce their food costs.

Following the work of Rogalsky (2010), who used ethnography and travel diaries to understand the spatial networks of low-income women, we propose that future research employ a similar approach to mapping out and quantifying informal produce exchange networks connected with community gardening activities.

Tijuana River Valley Community Garden, which has a long waiting list for plots, was one of eight sites studied. Of the 120 gardeners who responded to the survey, 55% said they gave produce to their extended family, and 18% traded produce for other products and services.

This would enhance our understanding of the economic impact, at all scales (both formal and informal), of community gardens.

At the policy level, fostering the growth of community gardens is enhanced when community groups work with state officials and municipalities. Current scholarship, also borne out in our research, has found that one of the biggest obstacles for small growers is access to land and capital. Therefore, we contend that by altering land use policy, cities can provide spaces for gardening on public lands, as well as ensuring the existence of consistent funding sources and simplifying bureaucratic requirements. California's new Urban Agriculture Incentive Zones Act (AB551), enacted in 2014, should help facilitate this because it was designed to increase land access for urban agriculture on vacant privately owned land.

Useful tools, such as the UC Division of Agriculture and Natural Resources *Guide to Implementing the Urban Agriculture Incentive Zones Act* (Zigas n.d.), should be widely disseminated. Furthermore, jurisdictions should be encouraged to permit the use of community gardens for small business farming. The International Rescue Committee's New Roots Program, for example, has experienced small-scale success and should be emulated. Efforts such as these would further enhance community garden contributions to community development.

Institutional shift

Universities are under increasing pressure to be socially accountable and to deliver knowledge and tools that prove useful in dealing with the 21st century's complex and costly problems. The UC Global Food Initiative supported this project in a way that encourages a rooted university transition — that is, a shift by our institutions of higher education and research to put more effort into problem-solving and solutions-oriented scholarship of engagement (in sync with basic science and discovery).

Our study underscores the merits of knowledge-action collaboratives and the civic infrastructure that they create. As a community-university partnership, we and SDCGN codesigned the survey to ensure that the resulting data would be beneficial to SDCGN membership as a whole as well as the individual community gardens and their gardeners. At the same time, the project incorporated a classroom-based component. We created a new research class in the Urban Studies and Planning Program at UC San Diego to work in parallel with the project. This class enabled undergraduate students to participate in all facets of the project from community outreach to survey design and administration and data analysis.

We intend to continue our efforts to build these knowledge-action collaboratives since they offer the potential to yield substantive benefits to all participants. They require a significant investment of time and a dedication to nurture trust and relationships, but if patience is exercised the merits are as follows. For faculty researchers who subscribe to the merits of public scholarship, these collaboratives build university-community trust, deepen civic infrastructure and lead to other opportunities for engaged scholarship. For community partners, collaboratives such as these can elevate the visibility of local concerns and serve as a catalyst for dialogue, action and policy formulation. Finally, the pedagogical merits of such knowledge-action collaboratives can be quite rich. They provide students with opportunities to apply classroom knowledge to real-world challenges, thereby deepening their understanding of complex issues while developing their skill sets and competencies. CA

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REVIEW ARTICLE

N_2O emissions from California farmlands: A review

Emissions estimates of nitrous oxide from the state's croplands are currently based on global average emission factors and derived from N inputs; local management practices should also be taken into account.

by Elizabeth Verhoeven, Engil Pereira, Charlotte Decock, Gina Garland, Taryn Kennedy, Emma Suddick, William Horwath and Johan Six

Abstract

Of the greenhouse gases emitted from cropland, nitrous oxide (N_2O) has the highest global warming potential. The state of California acknowledges that agriculture both contributes to and is affected by climate change, and in 2016 it adopted legislation to help growers reduce emissions of greenhouse gases, explicitly including N_2O. Nitrous oxide emissions can vary widely due to environmental and agronomic factors with most emission estimates coming from temperate grain systems. There is, however, a dearth of emission estimates from perennial and vegetable cropping systems commonly found in California's Mediterranean climate. Therefore, emission factors (EFs) specific to California conditions are needed to accurately assess statewide N_2O emissions and mitigation options. In this paper, we review 16 studies reporting annual and seasonal N_2O emissions. This data set represents all available studies on measured emissions at the whole field scale and on an event basis. Through this series of studies, we discuss how such farm management and environmental factors influence N_2O emissions from California agriculture and may serve as a basis for improved EF calculations.

The application of nitrogen (N) in the form of inorganic fertilizers, cover crops, manure, or compost is necessary to maintain economically viable yields without depleting soil N. However, increases in agricultural N application are not always balanced by plant N uptake or soil N storage, leading to an imbalance and potential loss of reactive N to the atmosphere or to other ecosystems where it significantly contributes to air and water pollution and global warming (Davidson et al. 2012; Galloway et al. 2003). The worldwide application of N has risen sharply in the past 70 years, and California is no exception to this trend (Rosenstock et al. 2013).

With a global warming potential 298 times greater than carbon dioxide (CO_2), nitrous oxide (N_2O) is the most potent of the three major agricultural greenhouse gases (CO_2, methane [CH_4] and N_2O). Of anthropogenic sources, N_2O emissions are also the largest contributor to ozone depletion (Ravishankara et al. 2009),

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Automated gas flux chambers monitor N_2O emissions in an almond orchard. Current estimates of emissions from cropland in California are based on the assumption that, in every crop system, 1% of the nitrogen applied as fertilizer is emitted as N_2O. Findings from the studies reported in this review provide more nuanced estimates, reflecting the large differences in emissions factors among crop systems.

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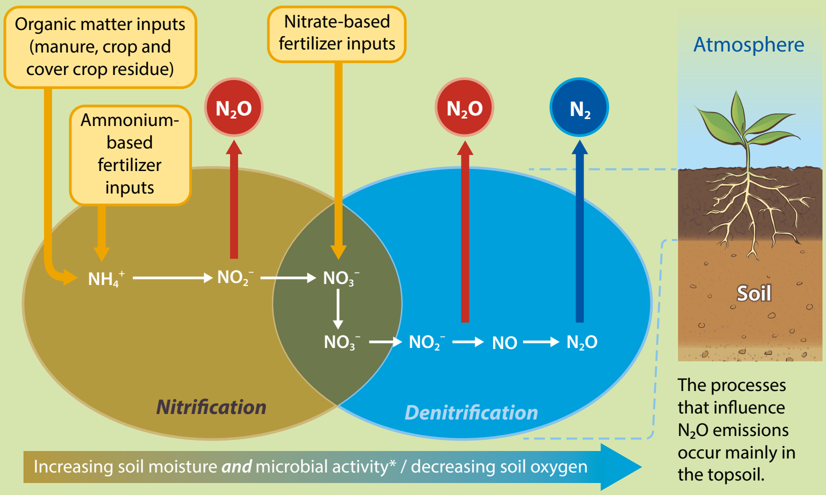
with agriculture accounting for more than 60% of global N_2O emissions (Mosier et al. 1998).

In California, N_2O emissions accounted for 2.8% (on a CO_2-equivalent basis) of statewide greenhouse gas emissions in 2014, of which agricultural soils made up 51% of emissions (CARB 2014). Current statewide emissions are calculated from global default emission factors (EFs) set by the Intergovernmental Panel on Climate Change (IPCC) based on a constant fraction of the amount of N applied. A default EF of 1.0% is typically applied, meaning that 1.0% of applied N is assumed to be lost as N_2O.

Global default EFs for specific management and N sources do exist, for example, ranging from 0.03% to 2.0% for flooded rice and manure, respectively. Yet high uncertainty surrounds these estimates, particularly for systems where little empirical data is available. Direct N_2O emissions generally do not represent an economically important loss to growers, but the high global warming potential of N_2O means these emissions have significant environmental impacts.

Indirect N_2O emissions may occur from leaching of dissolved N_2O in soil and surface water and subsequent off-gassing or leaching of nitrate (NO_3^-), which may later be reduced to N_2, producing N_2O in the process. NO_3 leaching may be extensive in irrigated systems that have periodic high N excess loads. Barum et al. (2016) calculated annual NO_3^--N losses of 71 to 214 lbs per acre per year (80 to 240 kg per hectare per year) in a California almond orchard. Clearly the management of such N losses is important for both economic, environmental, and human health reasons far beyond the potential for this N to be a source of N_2O. However, indirect emissions are beyond the scope of this review.

Box 1.
Factors influencing cropland N_2O emissions



The processes that influence N_2O emissions occur mainly in the topsoil.

N_2O emissions are determined by a combination of factors (below). The impact of a change in one factor depends on the values of the other factors.

Direct controls on N_2O production	Farm management controls
Soil moisture	Irrigation
Availability of NO_3, NH_4	Fertilizer input, crop N uptake, residue input
Availability of soil carbon	Tillage, residue inputs
Microbial activity	Soil amendments (i.e., compost, manure)
Soil pH	Fertilizer input, soil amendment
Soil temperature	Residue cover

* Aerobic microbial activity will reach maximum levels when water content allows for optimal diffusion of both substrate and O_2; at higher water contents respiration becomes diffusion limited (Schjønning et al. 2003; Skopp et al. 1990).

Management implications for N_2O mitigation

Increase nitrogen use efficiency. Irrigation and fertilization methods that allow for increased synchronization of N supply with plant demand increase plant N uptake and reduce N losses. Fall application of fertilizer likely decreases N use efficiency by increasing precipitation-induced N losses through nitrate leaching and N_2O emissions.

Increase water use efficiency. Buried drip and microjet irrigation systems can increase water use efficiency and reduce N_2O emissions.

Source of N does not matter. Both synthetic- and organic-derived N contributes to N_2O emissions. The application of organic matter as an N source provides valuable soil C, but increases the likelihood of climatic interactions (e.g., exposure to precipitation) and increases spatial and inter-annual variability in N_2O emissions. To the extent that is possible, incorporation of plant residues or N application before significant rainfall or irrigation should be avoided.

Importance of multiple variables in N_2O emissions. In all systems covered in this review, fertilization induced N_2O emissions, but no correlation between total N application rate and annual emissions was found. Thus, factors other than N application rate had a strong influence on emissions (e.g., soil type or irrigation method). In conclusion, default EFs based on N application rate may not be accurate for many California systems.

Year-round emissions. Fallow/winter season emissions are significant, representing between 29% and 64% of annual emissions. Both perennial and annual systems have the potential for high fallow/winter season emission pulses. Emissions occurring after the first seasonal fall rain dominate total winter/fallow season emissions; emissions shortly after fertilization dominate total growing season emissions.

How is N_2O produced?

In agricultural systems, N_2O is primarily produced through two microbial pathways: nitrification, which converts ammonium (NH_4^+) to NO_3^-, and denitrification, which converts NO_3^- to N_2 (Box 1). Both processes produce N_2O as a byproduct and can occur simultaneously in soil. However, nitrification is an aerobic process that requires oxygen, while denitrification is an anaerobic process that is inhibited at high oxygen concentrations. In soil, the oxygen content is largely controlled by soil moisture; when soil moisture is high, oxygen content is low and vice versa. Soil oxygen content is also controlled by microbial respiration and is related positively to the moisture content up to levels near saturation when a lack of oxygen inhibits many microbial processes. During periods of high microbial activity, soil oxygen is consumed, leading to an increase in N_2O production from nitrification (Zhu et al. 2013). Denitrifiers also consume N_2O when soil moisture is very high (Firestone and Davidson 1989). Therefore, soil moisture plays a large role in determining which process occurs and how much N_2O is eventually emitted from the soil. Soil bulk density, texture and structure also strongly influence soil moisture, oxygen and gas exchange, and therefore influence many microbial processes, including N_2O production and consumption.

Along with soil oxygen content, which is mostly determined by soil moisture and microbial activity, other soil environmental conditions (i.e., pH and temperature) and substrate availability (NH_4^+, NO_3^- and soil carbon [C]) control microbial N_2O production and consumption rates (see Box 1). The magnitude of each of these controls is in turn subject to their own set of biological and abiotic controls. Thus, much of the difficulty in predicting, measuring and managing N_2O emissions lies in understanding the interactions among these controlling factors.

Gas flux chambers deployed in two functional locations — the tree row and tractor row — in a prune orchard. It is important to measure emissions from both locations because of differences in soil moisture, the availability of nitrogen compounds, soil temperature and other factors.

California cropping systems and climate

The relatively arid, Mediterranean climate of California tends to favor nitrification, which occurs at lower soil moisture (Bateman and Baggs 2005). However, any irrigation event will increase soil moisture and microbial activity leading to the potential to increase N_2O pulses from both nitrification and denitrification (Scheer et al. 2008). The release of N and C from sudden soil wetting such as in irrigation events has been shown to fuel N_2O production from both nitrification and denitrification (Harrison-Kirk et al. 2013). In a review of N_2O emissions in Mediterranean systems, Aguilera et al. (2013) reported mean emissions four times higher in irrigated compared to rain-fed systems. Warm soil temperatures, which occur often in California, also tend to increase N_2O emissions (Smith et al. 1998). Denitrification derived N_2O emissions generally increase with increases in soil organic matter and C inputs, and rates may be partially C limited in low soil C systems, which could be the case for many California agroecosystems (Harrison-Kirk et al. 2013; Kennedy, Decock and Six 2013).

Unique to California is the growing importance of perennial orchard and vineyard cropping systems, which cover roughly half of the irrigated production acreage (CDFA 2016; NASS 2014) but are underrepresented in the global body of scientific literature on N_2O emissions. Perennial systems pose unique challenges to N_2O emission quantification because of the discrete management practices in the tree/vine row (cropped area) versus the tractor row (noncropped area).

Data collection

The data set we present here consists of 12 studies in which one or more of the authors of this article were involved and four additional studies that were found to meet our criteria for sampling frequency. Only studies with a minimum sampling frequency of two times per month were considered. All studies meeting this criterion utilized "event based" sampling, where sampling occurred daily for 3 to 7 days or until fluxes returned to background levels following fertilization, precipitation and selected additional management events dependent on the crop (i.e., tillage, irrigation, mowing, drainage, flooding). Three studies were found that did not meet these criteria for sampling frequency (Lee et al. 2009; Smukler et al. 2012; Townsend-Small et al. 2011). Together, this body of work comes from four research groups at UC Davis.

Within the 16 studies we identified 26 distinct treatment x year combinations (observations, n = 26)

TABLE 1. Management characteristics, measured annual emissions and calculated emission factors for the 16 studies reviewed

Crop	Study	County	Soil texture class (soil series)	Irrigation method	N application (method)*	Observation†	Annual N_2O emissions (pounds per acre)	Emission factor‡
Wine grape	Garland et al. (2014)	Colusa	Silty clay (Willows)	Surface drip	4.5 (Fg); 42 (cc)	Year 1	3.50 ± 0.50	7.5%
		Colusa	Silty clay (Willows)	Surface drip	5 (Fg)	Year 2	0.50 ± 0.09	10.4%
	Verhoeven and Six (2014)	Sacramento	Sandy clay loam (Dierssen)	Surface drip	8.6 (Fg); 107 (cc)	Year 1	1.79 ± 0.17	na¶
		Sacramento	Sandy clay loam (Dierssen)	Surface drip	9.0 (Fg); 121 (cc)	Year 2	1.43 ± 0.50	1.5%
	Garland et al. (2011)	Colusa	Silty clay (Willows)	Surface drip	4.5 (Fg)	No till	0.16±0.02§	na
		Colusa	Silty clay (Willows)	Surface drip	4.5 (Fg)	Conv. till	0.11±0.04§	na
Almond	Decock et al. (2017)	Colusa	Sandy loam (Arbuckle)	Microjet	240 (Fg)	Year 1	0.65 ± 0.12	0.4%
		Colusa	Sandy loam (Arbuckle)	Microjet	240 (Fg)	Year 2	0.58 ± 0.22	0.2%
	Alsina et al. (2013)	Colusa	Gravelly sandy loam (Arbuckle)	Microjet	210 (Fg)	Microjet	0.54 ± 0.22	0.3%
		Colusa	Gravelly sandy loam (Arbuckle)	Surface drip	201 (Fg)	Drip	1.44 ± 0.61	0.7%
	Schellenberg et al. (2013)	Kern	Sandy loam (Milham)	Microjet	200 (Fg)	UAN	0.71 ± 0.17	0.4%
		Kern	Sandy loam (Milham)	Microjet	200 (Fg)	CAN	0.47 ± 0.10	0.2%
	M. Burger (unpublished)	Colusa	Sandy loam (Arbuckle)	Microjet	200 (Fg)	Year 1	1.17 ± 0.52	0.6%
		Colusa	Sandy loam (Arbuckle)	Microjet	200 (Fg)	Year 2	0.63 ± 0.28	0.3%
Walnut	Pereira et al. (2016)	Yolo	Silt loam (Yolo)	Overhead sprinkler	71 (cc)	Year 1	1.09 ± 0.24	1.6%
		Yolo	Silt loam (Yolo)	Overhead sprinkler	71 (cc); 110 (feather meal)	Year 2	1.61± 0.15	0.9%
Prune	Verhoeven et al. (unpublished)	Yolo	Clay loam/silt loam (Brentwood/Yolo)	Microjet	80 (Fg)	Year 1	1.01 ± 0.23	1.1%
Rice	Pittelkow et al. (2013)	Colusa	Clay (Clearlake)	Ponded	125 (broadcast aq. NH_4^+)	Year 1	0.46 ± 0.08	0.4%
		Colusa	Clay (Clearlake)	Ponded	125 (broadcast aq. NH_4^+)	Year 2	0.37 ± 0.04	0.3%
	Adviento-Borbe et al. (2013)	Sutter	Clay (Clearlake)	Ponded	89 (broadcast urea)	Site 1	0.77 ± 0.14	0.9%
		Sutter	Clay (Marcum)	Ponded	89 (broadcast urea)	Site 2	1.68 ± 0.13	1.9%
Tomato	Kennedy et al. (2013)	Yolo	Clay loam (Brentwood)	Subsurface drip	5 (transplanting); 179 (Fg)	Drip (UN32)	0.85 ± 0.04	0.5%
		Yolo	Clay loam (Brentwood)	Furrow	146 (AN side dress); 65 (Fg)	Furrow (CAN)	2.73 ± 0.17	0.8%
	M. Burger (unpublished)	Yolo	Silt loam (Yolo)	Furrow	161 (banded)	Year 1	1.72 ± 0.44	1.1%

Continued next page

TABLE 1 (continued). Management characteristics, measured annual emissions and calculated emission factors for the 16 studies reviewed

Crop	Study	County	Soil texture class (soil series)	Irrigation method	N application (method)*	Observation†	Annual N_2O emissions (pounds per acre)	Emission factor‡
Dairy forage/ pasture	Lazcano et al. (2016)	San Joaquin	Coarse loam	Flood	613 (mixed manure + synthetic N)	Farm A	5.79 ± 0.11	1.0%
		San Joaquin	Coarse loam	Flood	749 (mixed manure + synthetic N)	Farm B	5.46 ± 0.57	0.8%
		Yolo	Clay loam	Flood	939 (mixed manure + synthetic N)	Farm C	12.43 ± 3.40	1.3%
	Angst et al. (2014)	Sonoma	Fine sandy loam (Bucher)	Rain-fed	366 (solid manure)	Year 1	16.96 ± 2.68	4.6%
Winter wheat	Zhu-Barker et al. (2015)	Solano	Silty clay (Capay)	Flood	100 (AA); 81 (urea top dress)	Year 1, field 1	1.17 ± 0.31§	0.6%§
		Solano	Silty clay (Capay), silty clay loam (Yolo)	Furrow	100 (AA); 88 (urea top dress)	Year 2, field 2	1.86 ± 0.29§	1.0%§

Treatment x year combinations are presented individually along with the standard error of the mean measured emissions, calculated from the reported number of replications. For studies where emissions were measured at multiple functional locations, spatially weighted emissions are reported. Emission factors were calculated by dividing annual emissions by annual N application rate.

* N application and method provides the available and relevant information on form of N applied and method of application. Fg = fertigation, cc = cover crop, AN = amonical nitrogen, AA = anhydrous ammonia.

† Distinguishing observation characteristic(s).

‡ Emission factors = percent of N applied emitted as N_2O (annual, unless noted). Emission factors were uncorrected for zero N treatments (i.e., background emissions).

§ Growing season data only.

¶ na = Annual emission factor data was not available. Cover crop residue N inputs from the previous year could not be determined (Verhoeven and Six 2014) or emissions were not measured for a full year (Garland et al. 2011).

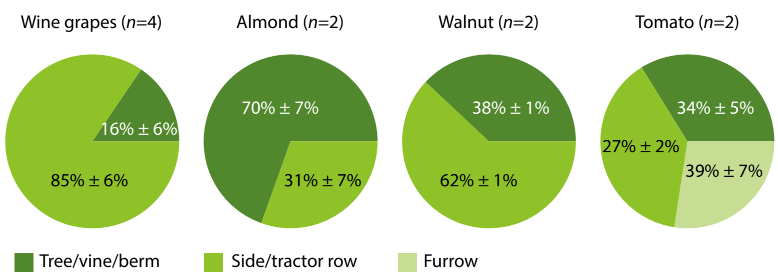


Fig. 1. Percent of annual emissions occurring from a given functional location. Values are means from studies reporting emissions at discrete functional locations.

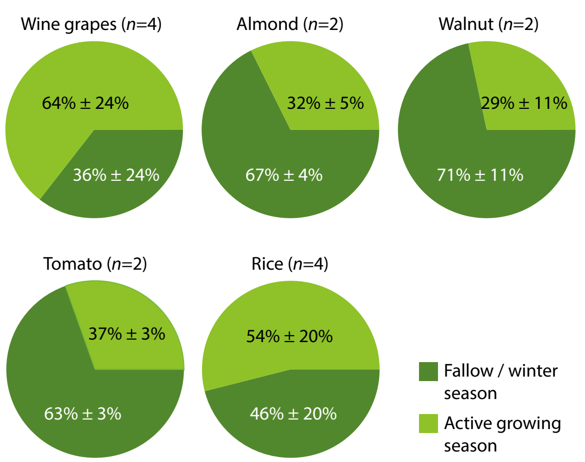


Fig. 2. Percent of annual emissions occurring during the winter/fallow season (September/October through March/April) or active growing season (March/April through September/October).

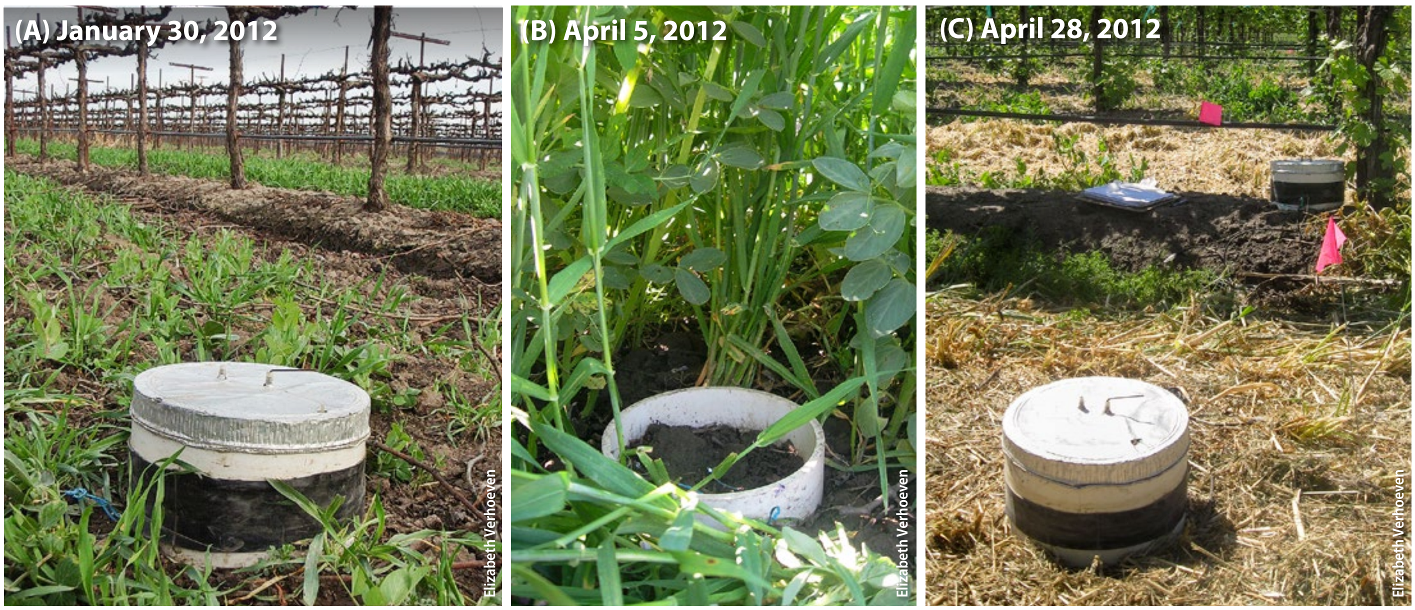
(table 1). Complete data and methodological details for 13 of the 16 studies are reported in individual papers (Adviento-Borbe et al. 2013; Alsina et al. 2013; Angst et al. 2014; Decock et al. 2017; Garland et al. 2011; Garland et al. 2014; Kennedy, Suddick, Six 2013; Lazcano et al. 2016; Pereira et al. 2016; Pittelkow et al. 2013; Schellenberg et al. 2012; Verhoeven and Six 2014; Zhu-Barker et al. 2015). Our intent was to report only data representing standard regional practices; thus, only values from treatments following established management and N application rates were used. Data for four additional observations are part of unpublished data sets (E. Verhoeven et al., unpublished; M. Burger, Department of Land, Air and Water Resources, UC Davis, unpublished).

In each study, in-situ N_2O measurements were taken using vented, static flux chambers as described by Parkin and Venterea (2010) and Hutchinson and Mosier (1981). Briefly, headspace air samples were collected at discrete intervals, injected into pre-evacuated Exetainer vials and later analyzed on a gas chromatograph. Mean annual emissions were linearly interpolated from daily flux values. When emissions were measured at multiple spatial locations in a given field, weighted averages based on spatial coverage were calculated and are reported in table 1. For full methodological details see Verhoeven and Six (2014). Comparisons between functional locations (fig. 1) or season (fig. 2) were done on studies where disaggregated data was available.

Basic field site characteristics, including irrigation and fertilization rates and methods, are reported in table 1. The growing season was defined as April-September or March-August (i.e., budding/planting) and the fallow/winter season as September-March or October-April (i.e., harvest/dormancy). When fertilizer was applied through irrigation systems, it was termed "fertigation". For all studies, we report system EFs uncorrected for background (zero N) emissions. Adviento-Borbe et al. (2013), Pittelkow et al. (2013) and Zhu-Barker et al. (2015) report fertilizer-induced emission factors ($EF_{fertilizer}$) in their original papers; therefore, our calculated emission factors differ from these.

Farm management effects on N_2O emissions

Agricultural management and cropping systems strongly affect N_2O production by altering C and N availability and environmental soil conditions (Box 1). Excluding dairy systems, mean annual N_2O emissions for the cropping systems reviewed ranged from 0.77 pounds N_2O-N per acre per year for almonds to 10.16



Photos show gas flux chambers and vegetation growth in the tractor row of a vineyard (A) early in cover crop growth, (B) at peak growth and (C) after mowing (with vine row in background). The images illustrate the dramatic differences in vegetation between functional locations and at different points in the year, and thus the need for field measurements of N_2O emissions across functional locations and throughout the year.

Author Gina Garland (left) records chamber temperatures and (right) takes chamber gas samples in a vineyard.

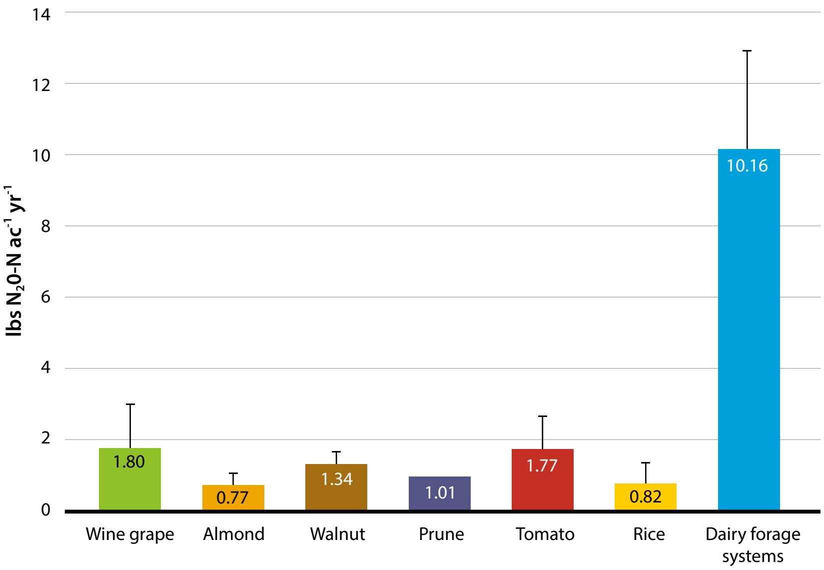


Fig. 3. Average annual N_2O emissions for each cropping system. Error bars represent the standard error of the mean. *n* = number of observations reporting annual emissions; wine grape (*n* = 4), almond (*n* = 8), walnut (*n* = 2), prune (*n* = 1), tomato (*n* = 3), rice (*n* = 4), dairy systems (*n* = 4). Dairy systems were defined by the production of forage or pasture with high manure N inputs; they include sites with pasture ryegrass, corn + forage mix, corn + winter wheat, corn + ryegrass.

pounds N_2O-N per acre per year for dairy forage systems (fig. 3). Aguilera et al. (2013) also found similar values for Mediterranean horticulture systems, 1.34 pounds N_2O-N per acre per year, but observed lower emissions, 2.68 pounds N_2O-N per acre per year, for liquid slurry systems than our dairy systems. N_2O emissions in the majority of systems reported here were only marginally higher than background agricultural emissions (uncropped agricultural soil) or emissions from natural systems at 0.83 pounds N_2O-N per acre per year and 0.37 to 0.82 pounds N_2O-N per acre per year, respectively (Kim et al. 2013; Stehfest and Bouwman 2006).

Spatial distribution

In perennial systems, management of the tractor row (noncropped area) is particularly variable across regions, farms and seasons. Tractor rows typically are not deliberately irrigated, but they may be wetted to varying degrees depending on the irrigation system (substantial wetting with overhead sprinkler or furrow irrigation versus little or no wetting with surface/subsurface drip or microjet sprinkler). Tractor rows also may be planted to a leguminous or grass cover crop, or allowed to self-seed with noncultivated vegetation, and they may be tilled or mowed with varying frequency. Since the management of these areas is not as time sensitive nor critical to crop production, the practices are inherently more variable and often no management records are kept for these activities. Among the studies with defined distinct functional locations, the tractor row accounted for 40%, 50%, 73%, and 70% to 82% of spatial coverage and corresponded to 31%, 62%, 57%, and 85% of total weighted emissions for almonds, walnuts, prunes, and wine grapes, respectively (fig. 1). Significantly different patterns of emissions between functional locations imply that both cropped and noncropped locations must be managed to effectively mitigate N_2O emissions. Among the perennial systems, tree or vine row emissions peaked at fertilization events while tractor row emissions were most influenced by climatic (i.e., first fall rain) events and were coupled with plant residue management.

Many annual systems are also characterized by distinct spatial heterogeneity between functional locations, typically in relation to how irrigation and fertilizer is applied. For example, working in a tomato system, Kennedy, Suddick and Six (2013) defined three distinct functional locations: berm, side and furrow. The authors observed higher variation in N_2O emissions between functional locations in a furrow-irrigated versus drip-irrigated system.

Irrigation

A total of six irrigation practices are represented in our data set: furrow, flood, overhead sprinkler, microjet sprinkler, surface drip and subsurface drip. In all of the microjet sprinkler and drip irrigation systems, fertilizer was applied through the drip system. For the remainder of the systems, fertilizer N was banded, dissolved in flood water, or spread as compost or residue (table 1). Irrigation with microjet or drip irrigation may improve water use efficiency by applying small amounts of water to match daily soil/crop evaporation. However, effects can be crop dependent (Bryla et al., 2003; Sharmasarkar et al. 2001).

In almonds, Alsina et al. (2013) observed a significant reduction in N_2O emissions in a microjet- versus drip-irrigated system. However, emissions across all almond studies were low compared to other crops. Kennedy, Suddick and Six (2013) reported significant reductions for buried drip irrigation versus furrow irrigation in tomatoes, namely due to increased fertilizer and water use efficiency with fertigation techniques via the drip. While we do not have sufficient coverage across crops and irrigation systems to draw broad conclusions, irrigation techniques that allow for dosing of N and water to match daily crop requirements appear to reduce N_2O emissions.

Fertilization

It has been well established that N_2O emissions increase with increasing fertilizer N application (Cole et al. 1997). However, a nonlinear relationship has often been observed, and emissions increase most rapidly when N rate exceeds crop demand (McSwiney and Robertson 2005; Van Groenigen et al. 2010). The challenge remains of better predicting the extent and timing of crop N uptake and finding a balance of reduced N input without sacrificing yield, thereby mitigating N pollution losses, including N_2O. However, reduced N input may not be necessary in micro-irrigation systems that dose N and water inputs and generally have higher yields. Fertilizer form and placement also influence emissions. Fertilizers that lead to increased soil pH and/or highly concentrate N application, such as drip versus microjet irrigation or knife injection versus banding of ammonium or urea, have been found to increase emissions. Zhu-Barker et al. (2015) found that injection of anhydrous ammonium increased seasonal N_2O emissions by 44% compared to application of banded ammonium sulfate. We found that fertilization with organic and synthetic N both resulted in N_2O emission pulses. During fertigation, emissions pulses were immediate but typically short lived, lasting between one and two days (fig. 4) and only measurable in the tree or vine row. In contrast, organic inputs from cover crops typically caused the highest fluxes at subsequent rain or irrigation events.

Tillage

Reduced- and no-till systems can alter N_2O emissions by modifying N and C availability, soil structure, microbial community structure and activity and, most profoundly, soil moisture. In dry climates, such as California, van Kessel et al. (2013) found that no-till and reduced tillage increased N_2O emissions during the first 10 years after switching from conventional tillage, but decreased emissions once the practice was in place for longer than 10 years. In our data set, only one study examined the role of tillage and found no effect of tillage on growing season emissions in a vineyard (Garland et al. 2011) (table 1). However, this was a short-term study where emissions were only measured during one growing season and after one year of no-tillage. A tillage effect may not have manifested in this short period; or it may have been most evident in the nonmeasured fallow season, when vineyard emissions can be quite high.

Cover crop and residue management

The addition of organic matter from cover crop and crop residues adds C and N to a system that can positively impact soil structure and fertility but also serve as substrates for microbial processes, including the production of N_2O. For example, Garland et al. (2014) observed N_2O emissions of 3.5 pounds N_2O-N per acre per year in a year when a cover crop was planted that supplied 42 pounds N per acre, while only 0.56 pounds N_2O-N per acre per year were emitted in the subsequent year when no cover crop was planted (table 1). At the walnut site, annual cover crop N inputs were estimated to be 50 and 92 pounds N per acre, for the tree row and tractor row, respectively. Yet, despite this difference in inputs, N_2O emissions in year one were similar for each location, 1.0 and 1.15 pounds N_2O-N per acre per year for the tree and tractor row, respectively. However, in year two, with the same cover crop N inputs, emissions were significantly higher in the tractor row, 1.05 and 2.15 pounds N_2O-N per acre for the tree and tractor row, respectively. The difference in functional location emissions between years may have resulted from an interaction between cover crop mowing and precipitation or irrigation timing, biennial distribution of feather meal N (110 pounds N per acre was applied in the second year only), or an interaction between the cover crop and feather meal that resulted in a stimulation of N turnover and emissions by either the cover crop or feather meal. Such results demonstrate the complexity of predicting emissions from residue N sources, in part because they may be more strongly affected by environmental variables than inorganic N sources.

We observed that peak N_2O emissions did not occur immediately after cover crop mowing, but typically after subsequent irrigation or precipitation events. For instance, in the prune orchard where a mix of grasses were kept mowed over the summer, emissions rose by a factor of 22, from 2 to 4 grams per acre per day to over 100 grams per acre per day following the first rain event in the fall (fig. 4); at the walnut site, a significant increase in emissions was observed when cover crop mowing was shortly followed by irrigation, rising from approximately 2 grams per acre per day to 20 grams per acre per day, while an analogous emission pulse was not observed when mowing and irrigation did not coincide. In tomato systems, Kennedy, Suddick and Six (2013) observed emissions to increase from baseline levels of 0 to 5 grams per acre per day to more than 100 grams per acre per day when crop residues were chopped and mulched at harvest, particularly in

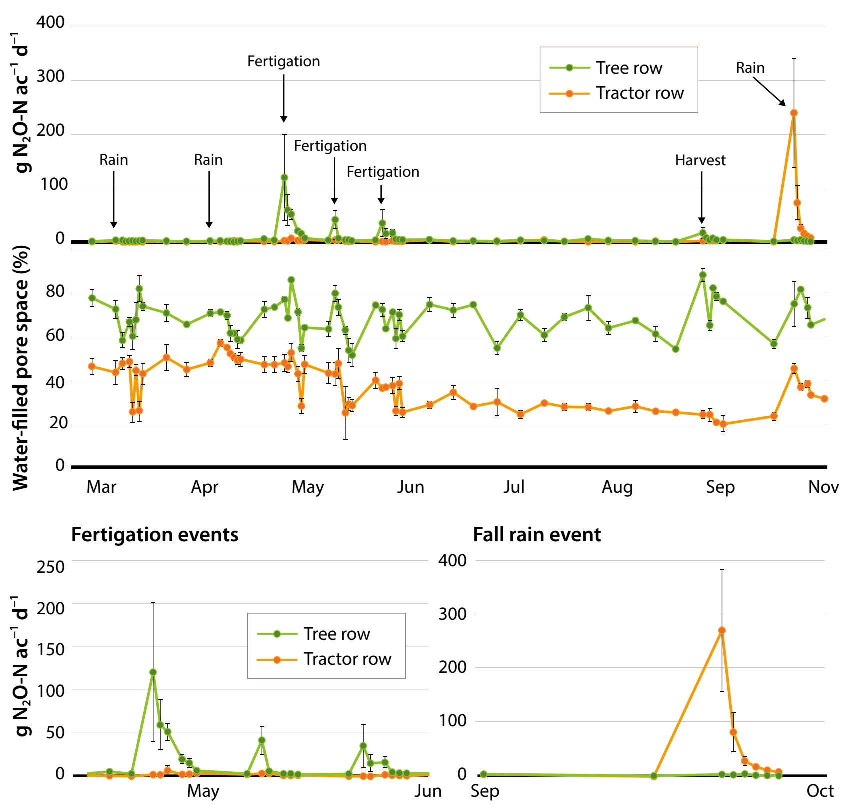


Fig. 4. Examples of temporal and spatial dynamics of N_2O emissions from a prune orchard, illustrating the effects of fertigation and precipitation events. Tree row = green dots, tractor row = orange dots.

Rafaela Conz, visiting scholar, taking chamber gas samples during gas flux measurements in a walnut orchard.

a drip-irrigated system. Equivalent or higher emissions were observed 6 weeks later during the first major fall rain event. In this case, emissions were highest in the furrow-irrigated system. Relatively large quantities of N-rich crop residue from annual vegetable systems may be particularly prone to such emissions; further research should investigate the timing of crop residue incorporation in relation to rainfall.

Annual and between-study variability was higher in wine grape systems than other cropping systems (fig. 3, table 1) and could be attributed to heterogeneous placement, timing and decomposition of cover crop residues, all of which can affect N_2O emissions. For example, Garland et al. (2014) observed seven-fold greater emissions in year one when a cover crop was grown compared to year two when the tractor rows were left fallow. Emissions derived from the cover crop were strongly influenced by precipitation in each wine grape study; for example, Verhoeven and Six (2014) reported that fall rain events in the tractor row accounted for approximately 10% of annual emissions.

Although transitory peak emissions associated with cover crop residue input may be high, cumulative emissions from these systems were low compared to the dairy systems considered in this study, but tended to be higher than tree cropping systems without explicit cover crops (i.e., almond and prune, fig. 3). Cumulative emissions were also lower than those found by Adviento-Borbe et al. (2007) for maize-soybean rotations (3.5 to 8.25 pounds per acre per year). Furthermore, emissions in all systems should be put in perspective to those of natural systems; native grasslands or forests also regularly emit N_2O in the normal course of organic matter decomposition, mineralization and N cycling and have mean emissions ranging from 0.37 to 0.83 pounds per acre for temperate systems (Kim et al. 2013; Stehfest and Bouwman 2006).

In sum, we do not want to discourage the use of cover crops, but rather to optimize their management. Increases in soil C from crop residue can provide myriad benefits (such as improved soil structure and increases in water retention and microbial abundance), particularly in C-poor California soils. Further research is needed on the effect of specific cover crop management practices on N_2O emissions (i.e., frequency of cuts, species, incorporation versus mulching). The timing of such practices in relation to irrigation and precipitation events is critical to N_2O emissions and the extent to which these can be offset while maintaining nutrient and water availability must be investigated.

Manure application

Large quantities of liquid and solid manure are produced in intensive dairy production and are typically applied locally in the production of forage crops. Because manure availability and N content cannot always be predicted, growers may also apply synthetic N. A recent study by Lazcano et al. (2016) reported N application rates and annual N_2O emissions to be nearly an order of magnitude higher than the other observations in our study (613 to 939 pounds N per acre and 5.46 to 12.42 pounds N_2O per acre, respectively). Despite the high productivity and relatively high nitrogen uptake efficiency of these systems, N application frequently exceeded crop demand and could be better optimized to reduce emissions. Improved manure storage and transport schemes could allow growers more flexibility in application timing and location, thereby reducing the need for synthetic N addition and enabling the application of manure at rates and times that better match crop N demand.

Climatic effects on N_2O emissions

Across systems, cumulative emissions were dominated by discrete events, namely by rain events in the fallow season and fertilization or fertigation events during the growing season. Fall rain events caused high emissions in both perennial systems (tractor row) and annual systems (all functional locations) and could be linked with a buildup of N and C from decomposing cover crop or crop residue. Rain-induced N_2O emission pulses are typical of many soils, such as California grasslands, as they become wetted during the onset of the rainy season (Herman et al. 2003). Across the 16 studies, increases in emissions up to ten-fold relative to background emissions were found following rain and fertigation events, with emission spikes reaching over 150-fold increases in some instances (fig. 4). Such dramatic increases were typically observed for only one or two days following an event, generally tapering off to background levels within a week.

The seasonal distribution of emissions was relatively consistent within a given crop (fig. 2), but with significant variation between crops. Fallow season emissions were 64%, 32% and 54% for the wine grape, almond and rice systems, respectively. Fallow season emissions, often including the first rain event, ranged from 7% to

97% of annual emissions for individual observations, demonstrating that, regardless of the system, they were significantly contributing to annual emissions, but again varied significantly with crop and year. Among dairy systems, Lazcano et al. (2016) generally found low emissions during the winter crop (forage mix, ryegrass or wheat) but observed that these emissions could be strongly affected by residue and fallow management of the preceding crop.

Emission factors

Emission factors represent the amount of N_2O-N emitted over a year relative to the amount of external N added to a system (synthetic N + organic N + crop residue N) and can provide a useful metric for comparing systems.

Many studies do not include crop residue N inputs because an accurate estimate of residue N and subsequent mineralization to available N is difficult to obtain. Rather, the influence of crop residue N is often accounted for through the comparison of crops or management practices.

Emission factors from measured surface fluxes are routinely calculated as either corrected or uncorrected for background fluxes (Garland et al. 2014; Rashti et al. 2015; Scheer et al. 2012). For background corrected fluxes, emissions from a zero added N plot are subtracted from fertilized emissions and the resulting net emissions are referred to as fertilizer-induced emissions ($EF_{fertilizer}$). Such an approach allows one to differentiate between the effects of fertilizer management versus other management.

Background emissions were measured in three of the studies included here and ranged from 0.21 to 0.76 pounds N_2O-N per acre, representing 18% to 68% of emissions in the fertilized plots (Adviento-Borbe et al. 2013; Pittelkow et al. 2013; Zhu-Barker et al. 2015). This variability in the relative contribution of background emissions shows that other management practices (such as irrigation and tillage), weather and residual N (from previous crops or N application) concentrations likely influenced gross emissions as well. In systems where N is applied locally by fertigation or at the tree base, emissions may be better estimated by improved spatial coverage and spatially weighted averages (Alsina et al. 2013; Decock et al. 2017; Garland 2011; Garland et al. 2014; Pereira et al. 2016; Schellenberg et al. 2012; Verhoeven and Six 2014).

Considering these factors and that a zero N treatment was not available for many of these on-farm trials, we calculated EFs uncorrected for background fluxes. It could be argued that EFs uncorrected for background fluxes, as we have reported, may be overestimates. Thus, the discrepancy in calculation schemes should be kept in mind. However, as stated above, we believe that in many of the systems measured, management practices beyond the quantity of fertilizer added were likely a stronger determinant of emissions.

Among all studies, EFs ranged from 0.2% to 10.4% (table 1), thus falling below and well above the IPCC default EFs of 1.0% (with a range of uncertainty from 0.3% to 3.0%). Default EFs have been derived from regressing N application versus N_2O emissions for many studies at a global level (IPCC 2007). When such a plot is constructed for our data set, a trend of increased emissions with increased N rate is only evident across crops but not within (fig. 5). Therefore, straightforward EFs may be misleading if emissions are more reflective of a system's N surplus than total N applied (Van Groenigen et al. 2010) and/or driven by other factors such as irrigation or crop residue management.

Emission factors were especially variable in the vineyard systems, ranging from 1.5% to 10.4%. This variability is attributable to high spatial and interannual variability, and highlights the difficulty in calculating EFs from cover crop or organic N inputs. For example, in the study by Garland et al. (2014), the cover crop was grown as part of a multi-year rotation; thus, if the "N-applied" were spread over a 2-year period, interannual variability would decrease. It is also difficult to account for the provision of belowground N through biological N-fixation, which can be substantial from leguminous cover crops. In a meta-analysis, Basche et al. (2014) found that cover crops increased N_2O emissions 60% of the time and emissions also increased with cover crop incorporation and leguminous species. Yet for all practices, the net effect neared zero when emissions were measured for at least a full year, indicating that on an annual and perhaps multi-annual scale the use of cover crops may be near neutral. Even though wine grapes have a high EF, the amount of N added to these systems is small compared to other crop systems, and therefore overall emissions in wine grapes are low compared to other crops. For these reasons, it must be

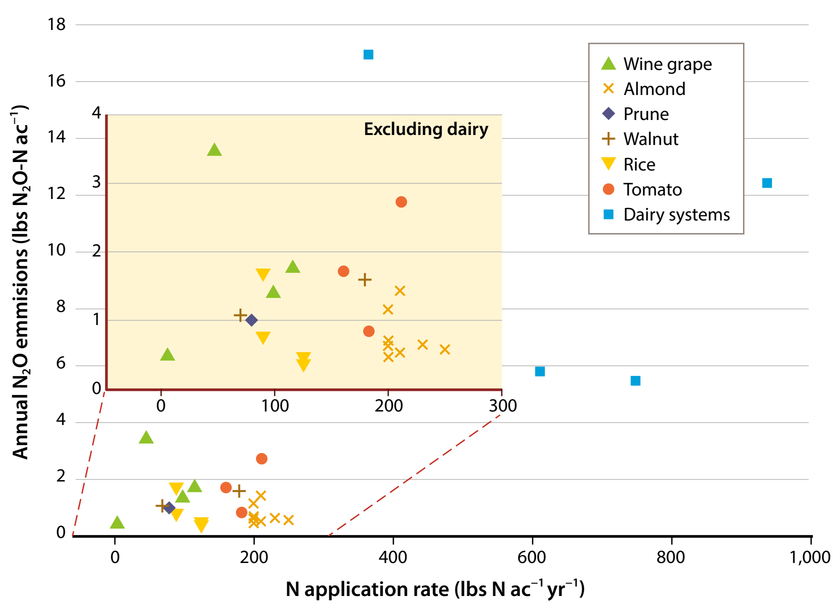


Fig. 5. Annual nitrogen application rate versus annual N_2O emissions by crop type. Dairy systems were defined by the production of forage or pasture with high manure N inputs; they include sites with pasture ryegrass, corn + forage mix, corn + winter wheat, corn + ryegrass.

stressed that the EFs we calculated are crop and system specific.

Low emissions and higher fertilization rates (200 to 240 pounds N_2O-N per acre) in the almond systems resulted in low EFs of 0.3% with a covariance of 51% (table 1).

In dairy systems, despite mean N_2O emissions nearly nine times higher than in other systems, the EF was 1.6% on average, nearly identical to the mean among all systems (1.5%). The high emissions but near-average EFs for dairy systems arise because nearly nine times the amount of N was also added in the dairy systems, indicating that N in these systems was either taken up with reasonable efficiency or lost through other pathways, such as NO_3^- leaching or NH_3 volatilization.

Emission factors in rice were also quite low, less than 1.0% for three of the four observations (Adviento-Borbe et al. 2013; Pittelkow et al. 2013).

These results clearly indicate the need for region- and crop-specific EFs for California agriculture. A starting point for improved EFs may be the EF inference scheme proposed by Lesschen et al. (2011). This scheme utilizes EFs that have been specified for a number of common practices and environmental variables such as source of N input, precipitation, soil type and land use. The scheme was developed for a European context; adaptation to California conditions would encompass EFs specific to practices here, such as those for irrigation strategy, cover crops and residue management.

Future research needs

While our data set includes emission data for some of California's top grossing crops (almonds, grapes, walnuts, tomatoes), notable gaps are in berry, hay and lettuce systems, which rank sixth, seventh and eighth, respectively, in statewide revenue. Almonds, grapes, walnuts and tomatoes are together produced on 1.9 million acres. Additionally, the geographical distribution of our data set was limited. Only two studies were conducted in one of the top ten California agricultural counties, Schellenberg et al. (2012) (Kern County) and Lazcano et al. (2016) (San Joaquin County). With the exception of rice, the crops studied were not evaluated in their largest areas of production. Developing accurate field emissions estimates is time-consuming and labor-intensive; hence, the majority of our studies have been conducted in field sites near UC Davis, where most of the authors are based. Emissions in other regions of California may differ substantially with variations in dominant soil types and climate. In general, N_2O emissions are often lower in dry climates compared to wetter ones (IPCC 2007). In particular, more work needs to be done in major agricultural areas with drier and warmer conditions (Fresno, Tulare and Kern counties) and also in wetter, coastal regions (Monterey County).

Among the studies reviewed here, many factors beyond crop type also varied, often significantly. Thereby our ability to identify the impact of any one factor such as irrigation management, soil type, fertilizer form and local weather conditions was limited. While difficult to coordinate, future work would benefit from a meta-structure that allowed for pair-wise comparisons of agronomic management effects within and between systems that are characterized by different crop rotations and environmental conditions.

N_2O emissions are only one metric of a system's sustainability and environmental impact. Current research is highlighting the balance between agronomic performance and environmental impact by reporting emissions on a yield-scaled basis. For example, work reported here in rice systems (Adviento-Borbe et al. 2013; Pittelkow et al. 2013) and almonds (Schellenberg et al. 2012) all reported yield-scaled EFs. Nitrogen in a system that is in excess of crop demand is also highly susceptible to leaching losses. The leaching of excess NO_3^- into groundwater and terrestrial and oceanic water bodies is a risk to human health and aquatic biodiversity and function (Galloway et al. 2008; Rosenstock et al. 2013). Similarly, indirect N_2O emissions can occur when N_2O becomes dissolved in water, leached out of the system and later emitted.

Eventually, we need to strive for a more holistic evaluation of agricultural systems, addressing ecological, economic and social aspects of sustainability. It is unlikely that one strategy will work across all regions and crops; however, judicious and synchronized application of water and N, timed with crop demand, is predicted to reduce emissions across climate zones and crops. Such practices will also help increase water and N use efficiency, thereby helping to conserve resources and reduce unnecessary losses. Nevertheless, such careful timing of water and N application is difficult to predict and can be costly to deploy. Policies should promote and aid the adoption of improved fertilizer application, irrigation practices and cover crop management. In conjunction, research should prioritize the refinement of region-specific EFs for irrigation strategy, cover crops and residue management.

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REVIEW ARTICLE

Review of research to inform California's climate scoping plan: Agriculture and working lands

California's diverse agricultural systems offer a range of opportunities for reducing climate-warming emissions.

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Abstract

Agriculture in California contributes 8% of the state's greenhouse gas (GHG) emissions. To inform the state's policy and program strategy to meet climate targets, we review recent research on practices that can reduce emissions, sequester carbon and provide other co-benefits to producers and the environment across agriculture and rangeland systems. Importantly, the research reviewed here was conducted in California and addresses practices in our specific agricultural, socioeconomic and biophysical environment. Farmland conversion and the dairy and intensive livestock sector are the largest contributors to GHG emissions and offer the greatest opportunities for avoided emissions. We also identify a range of other opportunities including soil and nutrient management, integrated and diversified farming systems, rangeland management, and biomass-based energy generation. Additional research to replicate and quantify the emissions reduction or carbon sequestration potential of these practices will strengthen the evidence base for California climate policy.

California has committed to cutting greenhouse gas (GHG) emissions by 40% of 1990 levels by 2030. As a sector, agriculture is responsible for 8% of state emissions. Approximately two-thirds of that is from livestock production (manure management and enteric fermentation); 20% from fertilizer use and soil management associated with crop production; and 13% from fuel use associated with agricultural activities (e.g., irrigation pumping, cooling or heating commodities) (CARB 2017a). California plays an essential role in the nutritional quality of our national food system, accounting for, by value, roughly two-thirds of U.S. fruit and nut production, half of U.S. vegetable production and 20% of U.S. dairy production.

Assembly Bill 32, California's primary climate policy law, adopted in 2006, has spurred research into practices and technologies that could assist in reducing emissions and sequestering carbon. Here we report on

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Converting farmland and rangeland to residential and urban uses results in a net increase of greenhouse gas emissions. Reducing the rate of conversion helps to avoid such emissions.

more than 50 California-based studies prompted by this landmark legislation. We note that the California Department of Food and Agriculture, California Air Resources Board, California Energy Commission and California Department of Water Resources have been critical to funding much of the science reviewed here. This article grew out of conversations with state agencies concerning the need for a review of the current evidence base to inform emissions-reduction modeling and revisions to the state Climate Change Scoping Plan (CARB 2017b), which specifies net emissions reduction targets for each major sector of the California economy (table 1). It is important to note that the Scoping Plan states that work will continue through 2017 to estimate the range of potential sequestration benefits from natural and working lands (including agriculture and rangelands).

With over 76,000 farm and ranch operations in California, covering about 30 million acres (USDA 2015), there are no one size fits all solutions. But as we outline below, there are numerous opportunities to both reduce GHG emissions and sequester carbon across diverse agricultural operations — small to large, organic and conventional, crop and livestock. Perhaps most importantly, many of these practices have co-benefits for water conservation, restoration and conservation of natural lands, or farm economics.

Farmland and rangeland preservation

Since 1984, farming and grazing lands have been converted to urban development at an average rate of 40,000 acres per year (DOC 2016). At this rate, and considering the higher rate of emissions from urban versus agricultural land, slowing agricultural land conversion represents one of the largest opportunities for agriculture to contribute to California's climate plan. Research from one county estimates that GHG emissions associated with urban landscapes are up to 70 times greater per acre than those from irrigated farmland when human emissions related to transportation, electricity, natural gas, and water are accounted for (Haden et al. 2013; Jackson et al. 2012). With continued population growth in the state, policies that promote more energy efficient patterns of urban development are critical to meeting climate targets and preserving irreplaceable farmland. Models show that coupling such urban development policies with farmland conservation could reduce transportation and building-related emissions from new residential development by 50% by 2050 under a low-emissions scenario (Wheeler et al. 2013).

With 80% of California's most productive rangeland privately owned, losses are projected at 750,000 acres by 2040 (Cameron et al. 2014). Conversion of rangeland to urban uses may increase GHG emissions up to 100-fold depending on how the rangeland is managed, and conversion to irrigated agriculture may lead to increases of up to 2.5-fold (Haden et al. 2013).

Land-use-related policies to reduce GHG emissions in California are still at an early stage. Several new incentive programs warrant future research to optimize their impact. These include the Sustainable Agricultural Lands Conservation Program (SALC), for purchase of conservation easements on farmland at risk of suburban sprawl development; the Affordable Housing and Sustainable Communities Program (AHSC), supporting development of affordable housing within existing urban areas; and the Transformative Climate Communities Program (TCC), slated to provide GHG-reducing planning grants to disadvantaged communities beginning in 2017. Together with legislation requiring a regional Sustainable Community Strategy, these can create a land use planning framework in California to preserve farmland, reduce GHG emissions, and achieve other co-benefits such as improved quality of life, public health and social equity.

Soil and nutrient management

Soils are complex biological systems that provide ecosystem services and can be managed to store carbon, reduce emissions and provide environmental and economic co-benefits. The diversity of California agriculture requires different management strategies to mitigate GHG emissions or sequester carbon.

Soil GHG emissions increase with soil moisture and nutrient availability. Significant reductions in GHG emissions can be achieved by shifting management practices to more efficient irrigation and fertigation

TABLE 1. GHG emissions targets per the 2017 Climate Change Scoping Plan update

	Estimated GHGs by sector ($MMTCO_2e$)		
	1990	2030 Proposed plan ranges	% Change from 1990
Agriculture	26	24–25	−4 to −8
Residential and commercial	44	38–40	−9 to −14
Electric power	108	42–62	−43 to −61
High GWP gases*	3	8–11	167 to 267
Industrial	98	77–87	−11 to −21
Recycling and waste	7	8–9	14 to 29
Transportation†	152	103–111	−27 to −32
Net carbon sink — landscapes‡	−7	TBD	TBD
Subtotal	**431**	**300–345**	**−20 to −30**
Cap-and-trade program	n/a	40–85	n/a
Total	**431**	**260**	**−40**

Source: CARB 2017b, Table II-3. Figures shown for 2030 for each sector represent expected changes in emissions under existing state policies. The cap-and-trade program is a market mechanism designed to efficiently drive the additional emissions reductions needed to reach the 2030 target. See www.arb.ca.gov/cc/cc.htm.

* These are gases such as refrigerants that, per unit, have a much more potent warming effect than carbon dioxide (GWP = global warming potential).

† Includes the freight, communications and utilities sectors.

‡ Refers to the potential for carbon sequestration by working lands (such as farms, ranches and managed forests) and natural lands. The potential magnitude of this benefit is still being evaluated.

systems such as micro-irrigation and subsurface drip. A comparison of subsurface drip versus furrow irrigation showed decreased GHG emissions in the former (Kallenbach et al. 2010; Kennedy et al. 2013). While cover crops often increase GHG emissions, integrating more efficient irrigation with cover crop practices decreased nitrous oxide emissions two- to three-fold in California processing tomatoes (Kallenbach et al. 2010; Kennedy et al. 2013).

In semi-arid regions such as California, the long-term implementation of no-till practices reduced emissions by 14% to 34%, but only after 10 years of continuous management. Under shorter time horizons, emissions increased by up to 38% (Six et al. 2004; van Kessel et al. 2013). Socioeconomic and biophysical limitations unique to California have led to low no-till adoption rates in California of roughly 2% (Mitchell et al. 2009).

Improved nitrogen management provides a high potential for reductions in emissions, including emissions associated with applied fertilizer as well as emissions related to the production and transport of inorganic nitrogen fertilizer (Steenwerth et al. 2015). N_2O emissions respond linearly to fertilizer application in lettuce, tomato, wine grape and wheat systems in California (Burger et al. 2012). However, once fertilizer rate exceeds crop demand, emissions increase at a logarithmic rate (McSwiney et al. 2005).

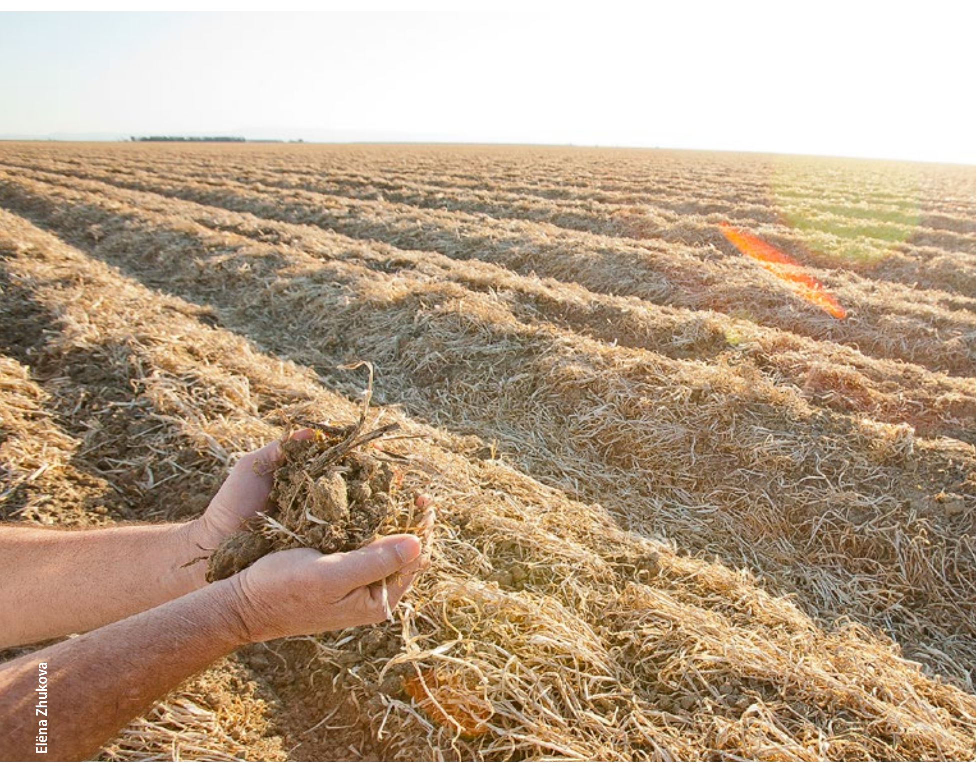
Fertilizer source has been broadly shown to influence N_2O emissions (Burger et al. 2011). Only a few California studies compare synthetic fertilizer sources. One shows that ammonium sulfate reduced N_2O emissions approximately 0.24 to 2.2 kg N per acre compared to aqua ammonium (Zhu-Barker et al. 2015a). Another study of comparing fertilizer sources found emissions reductions of up to 34% (Brown and Muhammad 2011; Schellenberg et al. 2012); however, the results were not statistically significant. Recently, California research has shown that the use of manure and green waste fertilizers can increase emissions when applied to the soil surface (Zhu-Barker et al. 2015b), particularly if their use is not timed to crop demand (Lazcano et al. 2016). Fertilizer source and timing, along with the use of nitrification inhibitors, are key areas for future research in the California context.

Management practices have the potential to increase total soil carbon, but the magnitude and persistence of sequestration is dependent on inputs and time. In grasslands, pilot studies of carbon sequestration associated with compost application are being conducted to validate early findings throughout the state (see "Rangeland management" section below). For cultivated systems, in two long-term projects at UC Davis, soil carbon increased 1.4 and 2.3 tons per acre in the top 12 inches of soil over 10 years (0.14 and 0.23 tons per acre per year) in cover cropped and organically managed soil, respectively (Poudel et al. 2002). In an ongoing experiment at the UC Agriculture and Natural Resources West Side Research and Extension Center, no-till combined with cover cropping and standard agronomic practice in a tomato-cotton rotation system has increased soil carbon 5.3 tons per acre over 15 years (0.3 tons per acre per year) compared to the standard tillage, no cover crop treatment (Mitchell et al. 2017).

In these two long-term studies, the soil carbon increase occurred between 5 and 10 years. However, when cover cropping and compost inputs were ceased at the first site (Poudel et al. 2002), it led to a rapid loss of soil carbon. This shows that soil carbon sequestration is highly dependent on annual carbon inputs and if management changes, soil carbon is prone to return to the atmosphere.

Given the reality of inconsistent management, rates of soil carbon sequestration that can be expected in row crop systems practice are perhaps 10% of the values seen in these long-term research trials, namely in the range of 0.014 to 0.03 tons per acre per year (unpublished data). If soil carbon sequestration and storage are priorities, management plans and incentive structures should account for the wide variability of California soils and the need for consistent management over time.

While any single soil and nutrient management practice may have limited impact on GHG emissions, many have well-documented co-benefits, including reductions in erosion, improved air quality (Madden et al. 2008), reduced farm machinery fossil fuel use (West et al. 2002), reduced nitrogen leaching (Poudel et al. 2002), enhanced water infiltration and reduced soil water evaporation (Mitchell 2012), and increased carbon stocks below the root zone to improve carbon sequestration (Suddick et al. 2013).



A no-till field with residue from a winter crop of triticale. Management practices can increase total soil carbon, but the magnitude and persistence of sequestration is dependent on inputs and time.

Integrated and diversified farming systems

Integrated or diversified farming systems are multi-purpose operations that may produce several commodities and utilize renewable resources. Examples include integrated crop and livestock systems; organic production; orchard and annual crop intercropping; use of perennial, salt-tolerant grasses irrigated with saline drainage water on otherwise marginal land; and pastures improved by seeding beneficial plants such as legumes. Through reliance on biological processes to build healthy soils and support above and below ground biodiversity, diversified systems offer potential GHG emission reductions (through, for instance, application of on-farm sources of organic matter residues from plants and animals rather than fossil fuel–based fertilizers, carbon storage in woody plants, and more efficiency in nutrient management due to crop rotations). Also, resilience to climate perturbations can occur by spreading economic risks across multiple farm products (Jackson et al. 2011) and by relying on on-farm resources and biodiversity, with less dependence on synthetic fertilizer and pesticides to improve soil and crop health (Gurr et al. 2003; Hodson and Lewis 2016; Suddick et al. 2010). Other environmental co-benefits can include more efficient use of water, improved water and soil quality, pest reduction or suppression, or enhancement of wildlife habitat and biodiversity.

These systems have been shown to reduce soil nitrate and nitrous oxide emissions, and increase carbon sequestration both in soils and above ground biomass (Bowles et al. 2015; Garland et al. 2011; Smukler et al. 2010, 2011; Williams et al. 2011). For example, frequent addition of various types of organic inputs increases labile and resistant soil carbon over a period of several years, so that soils exhibit more tightly coupled plant-soil nitrogen cycling. In turn, plant nitrogen demand is adequately met, but losses of nitrate are minimized (Bowles et al. 2015). In another case, an organic vegetable production system, the annual use of cover crops over 6 years led to greater increases in microbial biomass carbon pools, and compost additions increased measured soil organic carbon pool and microbial diversity in comparison to a cover crop grown every fourth year (Brennan and Acosta-Martinez 2017). Many of these studies examined California organic farms where multiple practices are often stacked, such as combining organic soil amendments, integrating cover crops into crop rotation for year-round plant cover and reducing tillage. In addition, farmscaping with perennials on field margins and maintenance of vegetated riparian corridors sequester carbon in the soil and woody biomass of trees and shrubs (Hodson et al. 2014; Smukler et al. 2010). Planting native woody species tolerant of drought for hedgerows, or resistant to water flux in riparian corridors, is a way to ensure adaptation and growth over many decades. Use of tailwater ponds and sediment traps also plays an important role in soil and water quality (Smukler et al. 2011).

Diversified, multipurpose systems provide other co-benefits depending on the set of practices involved. Practices that increase soil carbon also improve soil structure, nitrogen-supplying power and water-holding capacity (Burger et al. 2005). For example, a practice like cover cropping also can suppress weeds, influence crop nutrition and quality, especially in perennial systems like wine grapes, and provide habitat for beneficial predators (Guerra and Steenwerth 2011). Filter strips and riparian corridors can reduce soil erosion and thereby diminish contamination of surface water with valuable soil and nutrient resources, and pathogenic microbes (Tate et al. 2006). Hedgerows have been shown to increase pollinators and other beneficial insects in California (Morandin et al. 2011; Ponisio et al. 2015). Given the promise for multiple co-benefits, more types of California diversified systems deserve study, which would provide a better basis for metrics to evaluate their long-term contributions to climate and other goals.

Dairy and intensive livestock

Intensive livestock operations, particularly the state's large dairy sector, produce two-thirds of California's agricultural GHG emissions, and thus are a primary target for state climate regulations as well as incentives for emission reduction. At the same time, policies should account for the already high levels of resource efficiency in the California dairy sector. A key climate policy concept is to avoid "leakage," whereby strict climate policy to reduce emissions in one region causes increases in another. A recent comparison of the dairy sectors of the Netherlands, California and New Zealand documents that California dairies on average produce more milk per cow than dairies in the Netherlands, and more than 2.6 times as much as dairies in New Zealand, while operating under stricter environmental regulations (Rabobank 2014).

A vetch-pea cover crop in Mendocino County.

Chuck A. Ingels

Currently, the Intergovernmental Panel on Climate Change (IPCC) recommends using a fixed emission factor for dairy operations that is based on gross energy intake, which does not take diet composition into consideration (IPCC 2006). Calibration of GHG models

The dairy and beef cattle sectors together account for almost two-thirds of the state's agricultural GHG emissions. Changes to feed and manure management practices can reduce these emissions.

for California using dietary information will provide a more accurate basis for measuring progress than current IPCC values, and for assessing the potential benefits of different forage and feed practices on emissions. There are several methodologies developed in the last few years that can provide more accurate estimates of GHG emissions in California (Moraes et al. 2014; Santiago-Juarez et al. 2016). These methods incorporate the impact of diet, accounting for, as an example, the fact that fiber content is positively associated with methane emissions while lipid content is negatively correlated.

About half of California's livestock GHG emissions comes from enteric fermentation and half from manure in concentrated beef cattle and dairy operations. The largest opportunities for changes in livestock practices center on feed (composition and precision feeding) and manure management. California offers a uniquely diverse range of crop byproducts for use as dairy cow feeds, and research has improved our understanding of the impacts of different feeds on productivity, economics and GHG emissions (Moate et al. 2014; Moraes et al. 2015; Niu et al. 2016). For example, grape pomace, a byproduct of the wine industry, has been shown to reduce methane emissions when fed to dairy cattle in pelleted form without reducing milk production (Moate et al. 2014). A shift towards solid manure management practices (such as solid scrape) may result in reduced GHG emissions by reducing the anaerobic digestion that occurs when water is used to flush manure into storage lagoons. However, Owen and Silver (2017) indicated solid manure management can produce substantial GHG emissions; thus, minimizing manure storage time is important to mitigating emissions. One caution: there is a risk that focusing on one climate pollutant, such as methane, could lead to practices that have negative trade-offs, such as increased N_2O emissions (Owen and Silver 2017), and nutrient loading in soil and water (Niu et al. 2016).

A recent report submitted to the California Air Resources Board suggests it may be technically feasible for California to achieve a 50% reduction in methane emissions from dairy manure management by 2030 if supportive policies are created (Kaffka et al. 2016). This would require capturing or avoiding methane generated from manure storage on dairies from an estimated 60% of dairy cows in California, particularly the largest dairy operations where cost-benefit considerations are most favorable (CARB 2016). If successful, a gallon of California milk may be the least GHG intensive in the world. The report outlines several alternative manure management practices and technologies. These include:

- Switching from flush water lagoon systems without methane capture to solid-scrape or dry manure management;
- Covering manure lagoons to capture biogas, which can then be used for transportation fuels, on-farm electricity, or injected into natural gas pipelines;
- Installing anaerobic digesters to capture and utilize methane for similar uses, supported by CDFA's dairy digester program;
- Pasture-based dairy management, in which manure is left on the field and decomposes largely aerobically (producing significantly less methane than in anaerobic decomposition), though N in manure may be used less efficiently as a fertilizer in this case.

A diversity of practices is needed to reflect the range of dairy sizes and layouts in California. For example, lagoon storage systems, which can emit large amounts of methane, lend themselves to the use of covers or engineered anaerobic digestion systems for bio-methane collection. Potential trade-offs of these practices with respect to air quality, crop management, nutrient use efficiency and cost, however, require further analysis. Pasture systems are used in coastal areas where farms have less crop land available than in the Central Valley; pasture requires significantly more land and water for feed production compared to current dairy systems that rely on corn silage, grass silage and alfalfa (CARB 2016).

Rangeland management

Comprising more than two-thirds of California's agricultural acreage (USDA 2015), these working lands provide ecosystem services in addition to supporting production of livestock. Grasslands have higher levels of total soil carbon compared to cultivated lands (Steenwerth et al. 2005), and similar amounts to California forests.

There are numerous options for increasing carbon storage in rangelands. Modeling analyses project that restoration of native oaks could increase carbon storage in wood biomass and litter (Kroeger et al. 2009). In a study of riparian revegetation in Marin, Sonoma and Napa counties, modeled soil carbon sequestration rates averaged 0.8 tons C per acre per year, while modeled results of restored woody riparian areas demonstrated ecosystem carbon storage potential (soil plus woody biomass) of 16.4 tons C per acre per year over a 45-year period (Lewis et al. 2015). Cultivation and re-seeding to restore native perennial grasses also shows promise. Native grasses may sequester carbon in slightly deeper soil levels due to perennial root systems (Potthoff et al. 2009; Steenwerth et al. 2002). Rangelands with native grasses and oaks have lower soil carbon losses (Koteen et al. 2011) and higher nitrogen cycling rates (Parker et al. 2009).

Approaches to verifying carbon sequestration on rangelands requires a long-term approach. Soil carbon can take decades to build to a measurable level: rangelands rarely receive intensive management and these systems are much more exposed than irrigated agriculture to annual variations in moisture. On average, California's grasslands lose carbon, but the net C gain or loss depends on precipitation, with net losses of carbon in years when the timing of precipitation causes a short growing season, and gains when the timing of rains lead to a longer growing season (Ma et al. 2007).

The use of composted materials in rangelands may reduce N_2O emissions in comparison to those materials entering waste streams and being subject to the standard manure and green waste management practices (Ryals et al. 2013; DeLonge et al. 2013). One study on California's coastal and valley grasslands showed that use of compost above standard application rates could boost net ecosystem carbon by 25% to 70%, sequestering carbon at a rate of 0.2063 tons C to 0.2104 tons C per acre over the 3-year study or a rate of 0.0688 tons C to 0.0701 tons C per acre per year, largely by decreasing the amount of C that is being lost from these grasslands (Ryals et al. 2013). Researchers using the DAYCENT model to look at different compost amendments and project over longer time frames found that the net climate mitigation potential ranges from 0.5261 to 0.6394 tons CO_2 equivalent per acre per year in the first 10 years (Ryals et al. 2015), and declines by approximately half of that by year 30. Applying organic materials to rangelands in Southern California demonstrated co-benefits: stabilizing soil nitrogen stocks, improved plant community resilience and productivity, and increased soil organic matter after 1 year of application (Zink and Allen 1998). However, due to the very limited number of studies and the need to demonstrate sustained carbon sequestration, long-term studies (greater than 10 years) that span California rangelands are needed to validate these results and provide long-term policy recommendations. Climatic variation

Restoration of native oaks and woody riparian areas on rangelands offers opportunities for increasing carbon storage in these systems.

Lance Cheung, USDA

Currently, biomass energy production in California from agricultural residues — such as pistachio shells (foreground) and wood chips (background) — is largely based on the combustion of material from orchards and vineyards. Because biomass-based energy is more expensive than other renewable sources, policy changes or incentives are needed to expand this sector.

across the state may enhance or diminish observable carbon sequestration benefits. Further, it will be important to ensure that rangeland compost application practices do not lead to undesired plant species shifts and do not create negative trade-offs for water quality through nutrient run-off or leaching; it will also be important to track emissions associated with fossil fuel use for transportation and distribution of compost across rangeland sites.

Additional practices that have shown benefit elsewhere and should be examined in California include planting of legumes, fertilization, irrigation and grazing management. In particular, grazing management may significantly impact rangeland carbon sequestration. While heavy grazing that leads to erosion can degrade carbon storage, there is conflicting evidence in California and elsewhere on specific grazing practices that can benefit soil carbon (DeLonge et al. 2014). Most studies in California that have assessed the effects of grazing on soil carbon compared only grazed versus ungrazed (e.g., Silver et al. 2010), without assessing the effects of grazing duration, intensity, frequency and rest periods.

The USDA Natural Resources Conservation Service provides cost-share programs for range managers to split the cost of implementing improved management techniques. Currently, only 30% to 40% of California ranchers participate in these programs (Lubell et al. 2013). The research above points to the magnitude of opportunity from alternative rangeland practices and the need to identify socioeconomic opportunities and barriers to greater participation in range management incentive programs.

Biomass-based energy production

The most recent assessment of biomass in California details the availability of resources, including agricultural biomass, among others, that could support generation of three to four times the current biomass-based renewable energy being produced, depending on policies and regulations affecting biomass use (California Biomass Collaborative 2015). Biomass use for energy, however, has declined in recent years, as it is generally more expensive than alternative fuels. In addition, interconnection issues between biomass facilities, such as anaerobic digesters, and utilities complicate and increase the cost of new facilities. Research and policy actions to reduce barriers and incentivize co-benefits from the use of biomass for power and fuel will be required to expand this sector sustainably.

Current biomass energy production from agricultural residues in California is largely based on combustion of nut shells and woody biomass from orchards and vineyards. While one grower has installed a successful on-farm small-scale gasification systems for nut shells and wood chips, larger scale facilities that convert woody biomass to electricity are typically more than 40 years old, and the power produced is more expensive than other forms of alternative energy. Many plants are now idle or closed, leaving tree and vine producers with few or more expensive options for disposal of biomass.

Other underutilized agricultural biomass includes rice straw and livestock manures suitable for anaerobic digestion technology (Kaffka et al. 2012 and 2016). Manure alone is not a high biogas-yielding feedstock. Supplementing manure with fermentable feedstocks such as crop or food processing residues (Amon et al. 2011) can improve the energy and economic return from anaerobic digesters (Kaffka et al. 2016), but this practice currently faces regulatory and practical obstacles, like managing an additional source of organic materials and additional nutrients and salts. Nonetheless, there is limited, but real potential for some crop-based biofuels and bioenergy in California based on locally optimal feedstocks and biorefineries (Jenkins et al. 2009; Kaffka et al. 2014).

Priorities for future research

Here we identify cross-cutting priorities that will enable scaling and, equally important, the integration of multiple practices to achieve more substantial progress toward both climate change mitigation and adaption in agriculture. Among the priorities we identify are:

- Replication and longer-term studies to quantify the GHG mitigation or carbon sequestration associated with specific practices.
- Quantification of synergies from stacking multiple practices over time and scale (e.g., field to region)

to address efficacies for carbon sequestration, emissions reductions and nitrogen use.

- Characterization and, where possible, quantification of co-benefits (water, economic, air quality) from soil management practices, livestock grazing and manure management, and biomass-based fuels.
- Using social and political science research to identify socioeconomic factors that either create barriers or promote adoption of practices (e.g., social networks, gender, social norms, and values).
- Validation of metrics for soil health parameters, including calibration of models for California conditions that may be used to estimate metrics, such as:
- Potential use of remote sensing to measure adoption of specific practices outlined above.
- Validation and/or calibration of models for estimating GHG emissions, including the crop and soil process model, DAYCENT (Del Grosso et al. 2005), and the USDA's whole farm and ranch carbon and GHG accounting system, which uses the DAYCENT model (COMET-Farm; http://cometfarm.nrel.colostate.edu/).
- Research into the design of incentives (such as payments, tax credits, low interest loans, etc.) to leverage private investment and promote adoption of emissions-reduction practices in agriculture.
- Development of metrics and sampling or survey tools to assess adoption of emissions-reduction practices.
- Development of farmer demonstration and evaluation networks for scaling up the adoption of improved performance systems.

As this report outlines, the practices and technologies that can assist California to meet its climate change goals are as diverse as the types of agricultural practices across the state. Support for research within California agro-climactic contexts has been critical to identifying these climate strategies. Similarly, state incentive programs are critical to promoting adoption of these practices at scale through co-investment with the agriculture sector to achieve the goal of sustaining a vibrant food system for our state and nationally. CA

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REVIEW ARTICLE

Biocontrol program targets Asian citrus psyllid in California's urban areas

Two parasitoids of the Asian citrus psyllid, from Pakistan, have been released in Southern California with promising results.

by Ivan Milosavljević, Kelsey Schall, Christina Hoddle, David Morgan and Mark Hoddle

Abstract

In California, Asian citrus psyllid vectors the bacterium *Candidatus* Liberibacter asiaticus, which causes the lethal citrus disease huanglongbing. The top priority for California's citrus industry has been to diminish the rate of bacterium spread by reducing Asian citrus psyllid populations in urban areas, where this pest primarily resides. Attempts at eradicating and containing the psyllid with insecticides were unsuccessful. An alternative approach has been a classical biological control program using two parasitoids from Pakistan, *Tamarixia radiata* and *Diaphorencyrtus aligarhensis*, which attack the psyllid nymphs. *T. radiata* has established widely and, in combination with generalist predators, natural enemies are providing substantial control of psyllids in urban areas.

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Asian citrus psyllid (ACP), *Diaphorina citri* Kuwayama (Hemiptera: Liviidae), has emerged as the most important exotic insect pest of citrus in California. Damage is two-fold. First, psyllids cause direct injury to citrus through feeding on phloem juice in immature foliage, deforming the leaves (Halbert and Manjunath 2004); and second, and more importantly, they vector the bacterium *Candidatus* Liberibacter asiaticus (*C*Las), which causes the lethal and untreatable citrus disease, huanglongbing (HLB), also called citrus greening disease.

Characteristic symptoms associated with *C*Las infection are reduced vigor, foliar discoloration and dieback, misshapen fruit with bitter juice and malformed seeds, premature fruit drop, overall yield reductions and, ultimately, tree death (Gottwald 2010). Though symptoms may not appear for several years, *C*Las-infected plants are bacteria reservoirs from which ACP acquires and spreads the HLB-causing pathogen. *C*Las spread is exacerbated prior to detection if ACP populations are high and not managed. While there are some differences in susceptibility across citrus varieties, virtually all commercially available varieties are vulnerable to *C*Las infection.

HLB is the most important vector-borne disease threat to the citrus industry in the United States. ACP and *C*Las were first found in the United States in Florida in 1998 and 2005, respectively (Grafton-Cardwell et al. 2013). Since then, the ACP-*C*Las pathosystem has been detected in six U.S. states, and ACP establishment has been confirmed in 10 U.S. states.

The emergence of HLB in Florida citrus orchards has had significant economic impacts. Approximately 75% of all citrus trees grown in Florida are infected with *C*Las. Consequently, production costs have increased by 33% because of increased ACP-*C*Las management, and productive acreage has declined by 44% (from a high of 815,100 acres in

Asian citrus psyllids spread huanglongbing, a lethal citrus disease that poses a serious threat to the U.S. citrus industry. Psyllid populations are now established in urban areas of Southern California, where a classical biological control program with parasitoids from Pakistan is attempting to reduce psyllid numbers and migration into commercial citrus production areas.

Mike Lewis, UC Riverside

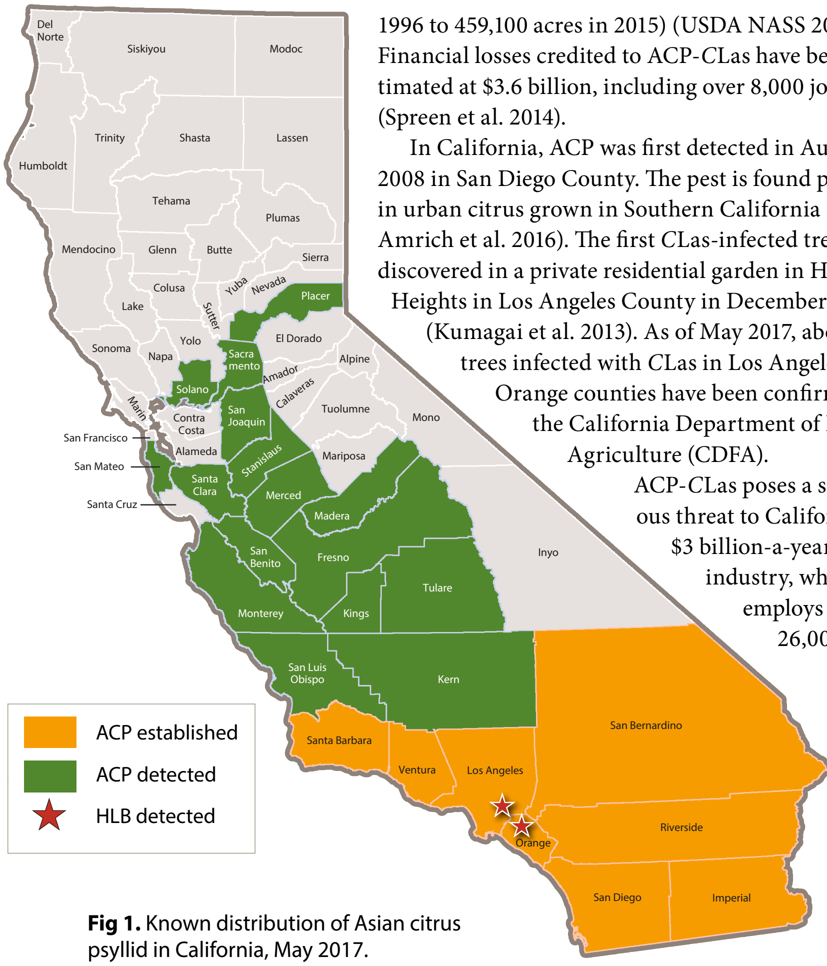


Fig 1. Known distribution of Asian citrus psyllid in California, May 2017.

1996 to 459,100 acres in 2015) (USDA NASS 2016a). Financial losses credited to ACP-*C*Las have been estimated at $3.6 billion, including over 8,000 jobs lost (Spreen et al. 2014).

In California, ACP was first detected in August 2008 in San Diego County. The pest is found primarily in urban citrus grown in Southern California (Kistner, Amrich et al. 2016). The first *C*Las-infected tree was discovered in a private residential garden in Hacienda Heights in Los Angeles County in December 2012 (Kumagai et al. 2013). As of May 2017, about 60 trees infected with *C*Las in Los Angeles and Orange counties have been confirmed by the California Department of Food and Agriculture (CDFA).

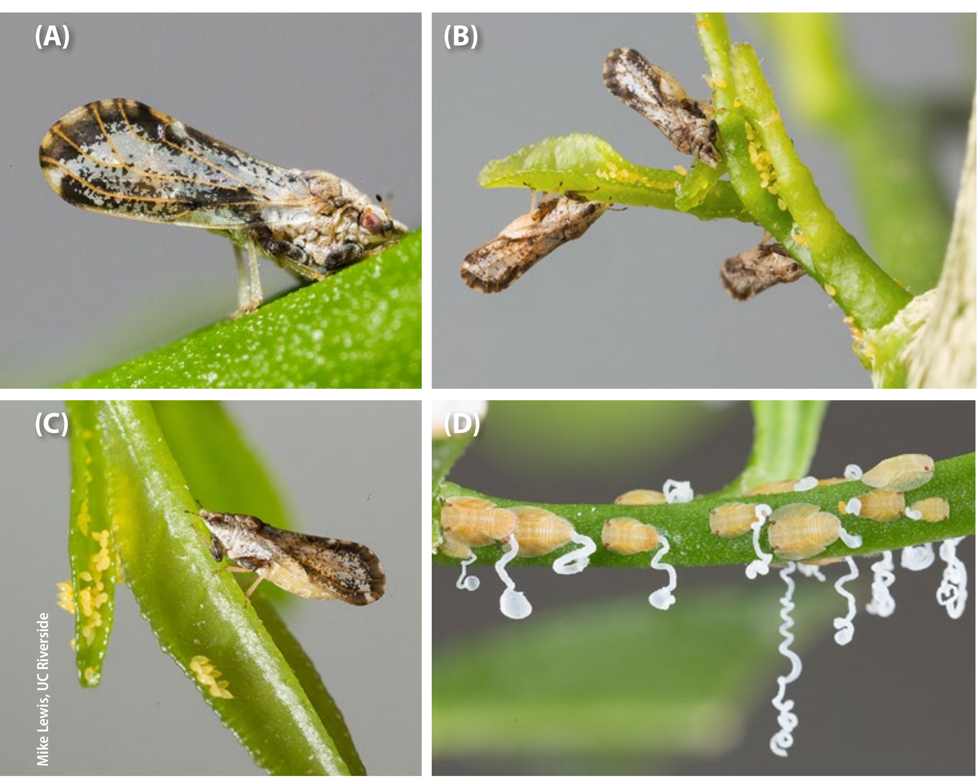
ACP-*C*Las poses a serious threat to California's $3 billion-a-year citrus industry, which employs over 26,000 people (Richards et al. 2014). California is the number one producer of fresh-market citrus in the United States, supplying more than 85% of the oranges, mandarins and tangerines and over 90% of the lemons (USDA NASS 2016b). There is zero industry tolerance for misshapen and bitter fruit in California's fresh-market citrus crop. California growers are already faced with escalating ACP-HLB management costs, and economic forecasts indicate that expenses associated with ACP-*C*Las may rise to $220 million a year in the next 5 years (Bennet 2016).

*C*Las spreads rapidly through ACP populations and citrus groves (Hall et al. 2013). Citrus orchards may become economically unfeasible 2 to 5 years following infection of the first tree (Bassanezi and Bassanezi 2008). The most important contributing factors to rapid spread of *C*Las by ACP are (A) the high dispersal potential of adult psyllids, which is facilitated by their good flight capabilities and small size, enabling them to be blown long distances by wind and go undetected on shipped plants and (B) rapid psyllid population growth, which results from short generation times and the high fecundity of females (Lewis-Rosenblum et al. 2015). Additionally, uninfected psyllids are more attracted to *C*Las-infected trees than to uninfected trees, which may further facilitate rapid pathogen spread (Mann et al. 2012). Thus, suppressing ACP populations is important for reducing *C*Las movement, which in turn maximizes orchard longevity and productivity.

Growing concerns about ACP

As of 2017, ACP populations have been found in 24 counties throughout California (CDFA 2017a), including the major commercial citrus production area in the San Joaquin Valley, which accounts for ~ 77% of California's citrus industry (fig. 1) (USDA NASS 2016b). Fortunately, the commercial production areas have not yet suffered from the widespread establishment of the ACP-*C*Las complex. The distribution of *C*Las has remained largely restricted to Hacienda Heights, San Gabriel and Cerritos in Los Angeles County and Anaheim in Orange County (fig. 1).

A heat risk map for HLB in Southern California has been developed by the U.S. Department of Agriculture (USDA), and this probabilistic map is used to direct ACP natural enemy releases (see below for details on ACP parasitoids imported from Pakistan) in urban areas in accordance with perceived likelihood of the occurrence of *C*Las-infected trees (fig. 2A). As ACP continues to spread, there is an increased risk of ACP-*C*Las establishing in major citrus growing areas of California.



Asian citrus psyllid life stages: (A) adult psyllid feeding on young tissue, (B, C) gravid adult females and eggs on citrus flush and (D) nymphs producing white honeydew secretions that are harvested by Argentine ants.

In an attempt to eradicate ACP populations in residential areas, the CDFA ran pesticide application and monitoring programs during the initial stages of the ACP invasion into Southern California (Hoddle 2012). Pesticide applications consisted of fast-acting cyfluthrin foliar sprays followed with slower-acting and persistent systemic imidacloprid soil drenches. While the CDFA spray program was moderately successful in killing ACP on infested backyard citrus, it was prohibitively expensive, at ~ $200 million (approximately $100 per property), and it was estimated that less than 10% of residential citrus at risk of ACP infestation was treated. Consequently, the ACP urban spray program was largely terminated in 2012 after 3 years (Hoddle and Pandey 2014).

Following the first detection in San Diego County, ACP rapidly spread throughout Southern California. Established populations also have now been recorded in the Central Coast (2009), Central Valley (2012) and the greater San Francisco Bay Area (2014) (fig. 1). In response to this spread, a CDFA-appointed ACP quarantine first implemented in September 2008 in San Diego was initially restricted to 20 square miles (52 square kilometers) (Victoria Hornbaker, CDFA, personal communication); it has now increased and spans 24 counties encompassing over 62,000 square miles (160,000 square kilometers) (CDFA 2017a). The quarantine aims to reduce ACP-*C*Las spread by regulating the movement of citrus and closely related species (CDFA 2017b).

Backyard citrus represents a large portion of total citrus acreage in California. In Los Angeles County alone, it has been estimated that over 1.2 million residences may have at least one backyard citrus plant (Hoddle 2012). Residential areas are important reservoirs for ACP and *C*Las in California, and there is a high risk of infected vectors moving from these areas into commercial groves (Gottwald 2010).

In Florida, abandoned citrus groves have been identified as significant reservoirs for ACP and *C*Las, with infected psyllids dispersing to commercial groves in spring and summer (Lewis-Rosenblum et al. 2015). Most commercial citrus production areas in California are naturally arid, so abandoned groves tend not to persist; however, abandoned citrus in moister coastal areas could become reservoirs. Neglected citrus groves may become more common across the state if *C*Las becomes more widely established and increased management costs make production unprofitable.

Native rutaceous plants (i.e., citrus relatives) are widely distributed in California wilderness areas, especially in strategically significant locations near commercial production areas in the San Joaquin and Coachella valleys and Imperial and San Diego counties (Calflora 2017). It is unknown if these wilderness areas harbor ACP-*C*Las populations or if they could act as potential spillover hot spots for ACP-*C*Las spread, as migrating ACP could introduce *C*Las into commercial citrus production areas (Grafton-Cardwell et al. 2013).

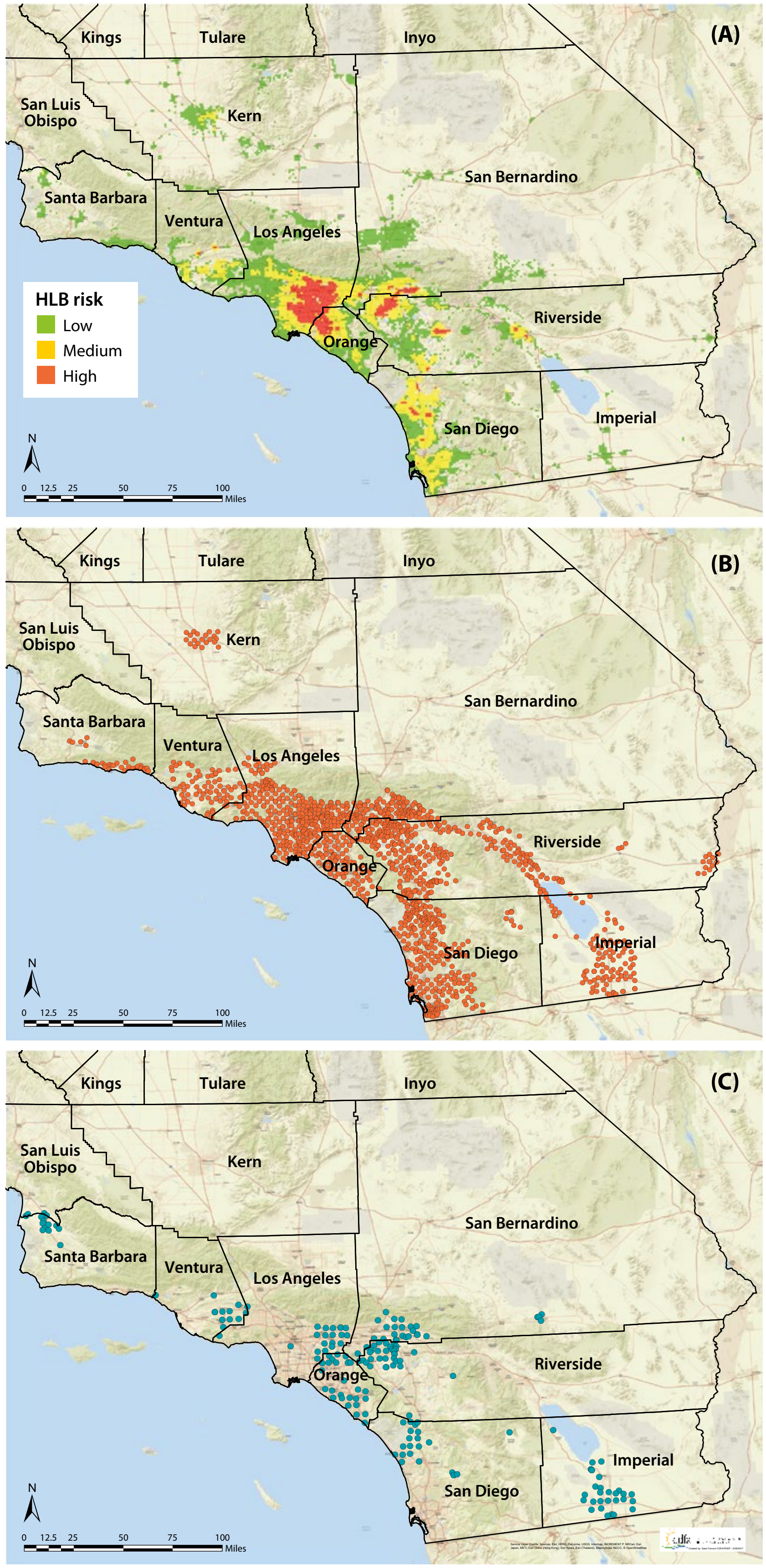


Fig. 2. (A) Huanglongbing risk grids generated by USDA researchers in 2016. Southern California release locations through 2016 of the psyllid parasitoids (B) *Tamarixia radiata* and (C) *Diaphorencyrtus aligarhensis*.

In the absence of insecticide management, biological control of ACP may be the only feasible population suppression tool in areas (i.e., urban environments, wilderness areas, and organic or abandoned citrus orchards) not under active management.

Natural enemy prospecting program

Initial surveys of ACP populations in urban-grown citrus, and the subsequent rearing and dissection of recovered nymphs, revealed a lack of specialist natural enemies (e.g., parasitoids), which may be the reason ACP populations spread rapidly in Southern California (Hoddle 2004, 2012). This apparent lack of specialist natural enemies, coupled with the cessation of CDFA's urban spray programs for ACP control, prompted a search for effective biological control agents to suppress ACP population growth.

Beginning in September 2010, researchers at UC Riverside in collaboration with CDFA and USDA scientists initiated development of a classical biological control program targeting ACP populations in urban Southern California. *Diaphorina citri* has a native range that includes the Indian subcontinent (Beattie et al. 2009). Natural enemy prospecting was conducted in the Punjab province of Pakistan, because climate matching indicated that this area has a ~ 70% climate match with the major citrus production areas in California's Central Valley (Hoddle and Pandey 2014). Biocontrol theory suggests that climate matching is important for improving the likelihood that a natural enemy will establish in the intended introduced range; preadaptation to the prevailing climate eases at least one establishment barrier (Van Driesche et al. 2008).

Hussain and Nath (1927) stated in their treatise on *D. citri* that the diversity of parasitoid species associated with ACP nymphs in Punjab was high, with possibly nine species being recorded attacking immature stages. Their work, however, resulted in the description of just one parasitoid species, *Tamarixia radiata* (Waterston) (Hymenoptera: Eulophidae). The identities of the other species were not known when California's ACP biocontrol program commenced.

Foreign exploration efforts by UC Riverside scientists in Punjab were conducted in collaboration with researchers in the Department of Entomology at the University of Agriculture, Faisalabad. This excellent cooperative arrangement was essential for the successful collection of ACP natural enemies from citrus production areas around Sargodha, Toba Tek Singh, Faisalabad and Gujranwala.

Safeguards to minimize risks

Potential natural enemy species from Punjab, Pakistan, were imported under a USDA APHIS permit into quarantine at UC Riverside from April 2011 to April 2013. These collections resulted in the rearing of 3,675 parasitoids from which 13 ACP-associated parasitoid species were identified (Hoddle et al. 2014). Two species were particularly highly represented: 55% of collected parasitoids were identified as *T. radiata* and 28% were *Diaphorencyrtus aligarhensis* (Shafee, Alam and Argarwal) (Hymenoptera: Encyrtidae) (Hoddle 2012).

The 11 other parasitoid species included three leaf miner parasitoids, two egg parasitoids, one scale parasitoid and five obligate hyperparasitoids of *T. radiata* and *D. aligarhensis*; these additional 11 parasitoid species do not attack ACP (Bistline-East and Hoddle 2014,

Huanglongbing symptoms, photographed in Florida: (A) irregular blotchy yellowing or mottling of leaves and (B) reduced plant vigor and foliar dieback in *C*Las-infected citrus trees in advanced stages of decline. Researchers estimate that the Florida citrus industry has lost $3.6 billion, including over 8,000 jobs, as a result of HLB (Spreen et al. 2014).

UC researchers collaborated with researchers at the University of Agriculture, Faisalabad, in Punjab, Pakistan, to collect natural enemies of ACP. *Left,* fieldwork in some areas involved assistance from citrus farmers. *Right,* at the university citrus research orchard, Christina Hoddle (left) processed ACP-infested citrus cuttings before taking them to a lab to rear the parasitoids; here, she is working with students Shouket Zaman Khan (back center) and Saif ur Rehman (right front).

2016; Hoddle et al. 2014). Hussain and Nath's (1927) estimate of nine natural enemy species associated with ACP nymphs in Punjab was concluded to be incorrect; they had perhaps inadvertently assumed that parasitoids attacking other cryptic citrus pests (e.g., cicadellid eggs) on ACP-infested foliage were natural enemies of ACP (Hoddle et al. 2014).

Host range and host specificity studies concluded that the two primary ACP parasitoids, *T. radiata* and *D. aligarhensis*, likely posed no undue risk to nontarget psyllid species in California (Bistline-East and Hoddle 2014; Hoddle and Pandey 2014). These findings resulted in USDA APHIS issuing permits authorizing the release of *T. radiata* and *D. aligarhensis* for classical biological control of ACP in California.

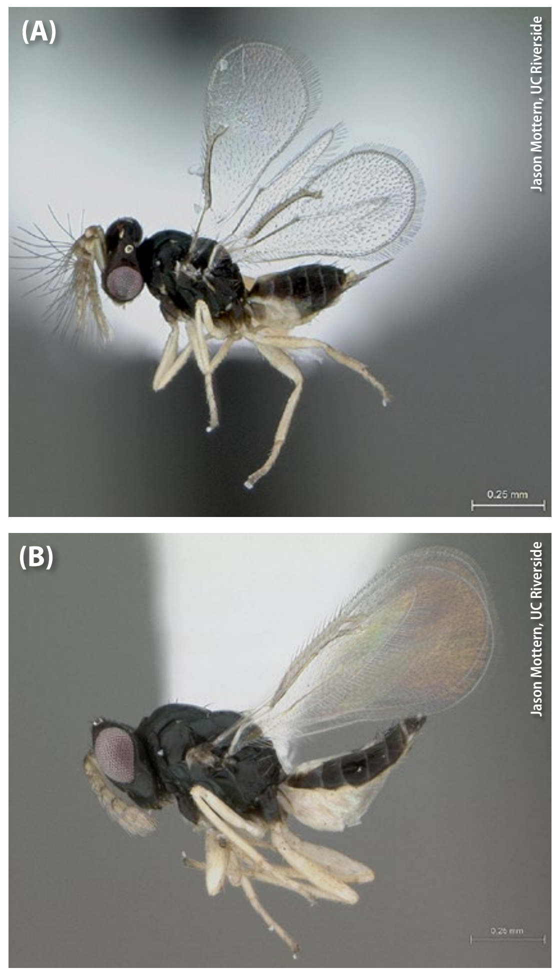
California's ACP biocontrol program

T. radiata is a host-specific ectoparasitoid of fourth and fifth instar ACP nymphs. It was the first natural enemy species released in California, in December 2011. Female *T. radiata* kill ACP nymphs through a combination of parasitism and host feeding, which provides nutrients for parasitoid egg development. It has been estimated that a single female can kill up to 500 nymphs in her lifetime (Chien et al. 1995).

Over the last 5 years, more than 5 million *T. radiata* have been mass-reared and released in Southern California in a collaborative effort by the CDFA, UC Riverside, USDA and the California citrus industry. *Tamarixia radiata* releases are made using a 1-square-mile (2.6-square-kilometer) grid that spans more than 45,000 square miles (116,500 square kilometers) across nine counties in Southern California (fig. 2B). Releases have resulted in widespread establishment of *T. radiata*. Approximately 95% of surveyed release and nonrelease sites (n = 100) distributed in six counties had *T. radiata* activity, and detections indicated that the parasitoid had migrated into nonrelease locations (n = 28), with some finds at least 8 miles (~ 13 kilometers) from the nearest release site (Hoddle et al. 2016). Molecular testing of field-recovered *T. radiata* indicated that they had genetic signatures unique to the Pakistan populations released in Southern California (Dr. Paul Rugman-Jones, UC Riverside, personal communication).

Postrelease monitoring in California indicates that the average parasitism of ACP nymphs by *T. radiata* is ~ 20% (range is 13% to 63%), but it can vary greatly across study sites over time (Kistner, Amrich et al. 2016). Moreover, the combination of *T. radiata* and increased attacks by native predators, such as syrphid fly larvae, which have started using ACP nymphs for food, are having a substantial impact, reducing urban ACP populations by more than 90% at some locations at certain times of year. As of this writing (spring 2017), *T. radiata* releases are largely restricted to urban-grown citrus; releases are not made in commercial citrus production areas that are under area-wide management, where insecticide applications are coordinated over large areas and spray residues cause substantial mortality of *T. radiata* (Hall and Nguyen 2010).

In Florida, *T. radiata* imported from Taiwan and Vietnam have established widely (Hoy and Nguyen 2001). But their impact on ACP is not high, especially in comparison to coccinellid predator species, which appear to be significantly regulating ACP populations (Michaud 2004). The reasons for the putative poor performance of *T. radiata*

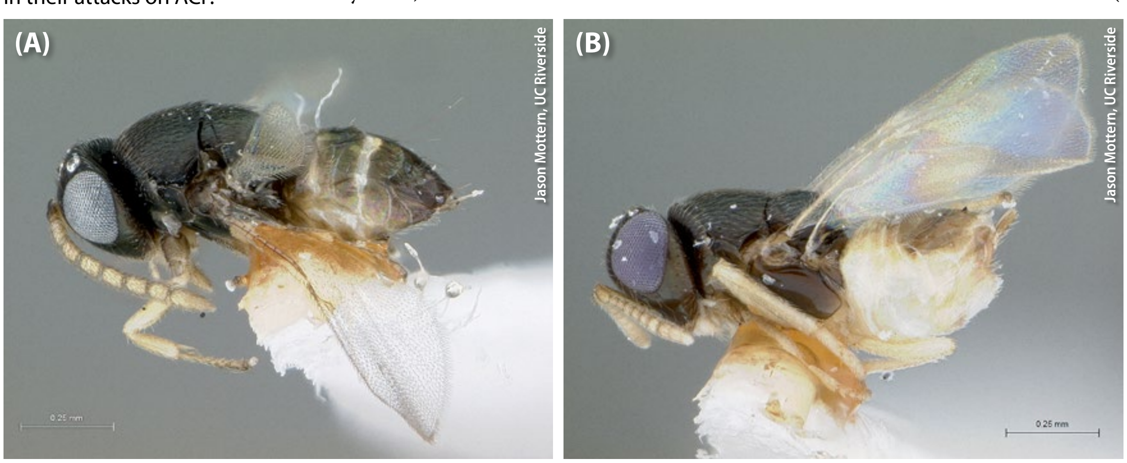


Adult *Tamarixia radiata* (A) male and (B) female. The latter kill Asian citrus psyllid nymphs through a combination of parasitism and host feeding.

Tamarixia radiata developmental biology: (A) female laying an egg underneath a psyllid nymph, (B) parasitoid egg (arrow) attached to its host, (C, D) *T. radiata* nymph feeding externally on its host, (E) developing *T. radiata* pupae removed from ACP mummies and (F) an adult *T. radiata* that has emerged from the anterior region (circular exit hole) of the ACP mummy. *T. radiata* has established widely in Southern California since releases began in late 2011.

in Florida are varied and may include the parasitoid's high sensitivity to pesticide residues in commercial citrus groves, low levels of genetic variation in released parasitoids that may have reduced their fitness and subsequent efficacy, and interference by ants tending honeydew-producing ACP nymphs (Navarrete et al. 2013). Studies in Florida have shown coccinellid predation of ACP nymphs already parasitized by *T. radiata* can result in over 95% mortality of developing *T. radiata*. This is an additional factor potentially contributing to low parasitism rates observed in Florida (Qureshi and Stansly 2009).

The second natural enemy species that has been released in California is *D. aligarhensis*, a host-specific solitary endoparasitoid of second through fourth instar ACP nymphs (Bistline-East et al. 2015). Like *T. radiata*, *D. aligarhensis* kills its hosts through a combination of parasitism and host feeding, and a single *D. aligarhensis* female can kill up to 280 nymphs in her lifetime (Rohrig et al. 2011). Releases of *D. aligarhensis* began in California in December 2014 (Vankosky and Hoddle 2016). By February 2017, over 300,000 *D. aligarhensis* had been released in urban Southern California by CDFA and UC Riverside (fig. 2C).



Adult *Diaphorencyrtus aligarhensis* (A) male and (B) female. Because *D. aligarhensis* parasitizes different ACP life stages than *T. radiata*, researchers are exploring the idea that the two species, which coexist in their native range, could complement each other in their attacks on ACP.

The concept underlying efforts to establish two ACP parasitoid species in California is that *D. aligarhensis* may complement *T. radiata* because the two parasitoids have preferences for different ACP life stages and both species coexist in their native range and contribute to ACP control in citrus (Khan et al. 2014). While it is uncertain at this stage as to whether

The developmental biology of *Diaphorencyrtus aligarhensis*: (A) gravid female lays an egg inside the psyllid nymph; (B) in contrast to *T. radiata*, an adult *D. aligarhensis* emerges from the posterior of the ACP mummy. Studies of *D. aligarhensis* releases have not been completed yet, but early results indicate the species is able to reproduce in California urban citrus.

or not *T. radiata* and *D. aligarhensis* will be complementary in their attacks on ACP, several other biocontrol programs targeting invasive pests of citrus in California have been successful because of established natural enemy complexes. The most notable are cottony cushion scale, *Icerya purchasi* (Maskell) (Hemiptera: Monophlebidae), suppression by the coccinellid *Rodolia cardinalis* Mulsant in hot desert areas, and the parasitic fly *Cryptochaetum iceryae* (Williston) (Diptera: Cryptochaetidae) in cooler coastal zones (Quezada and DeBach 1973).

Releases of *D. aligarhensis* failed to establish populations in Florida. As seen previously with *T. radiata,* several factors may have led to this failure: (1) intensive insecticide use in citrus growing areas where *D. aligarhensis* was released (Rohrig et al. 2012), (2) the inferior competitiveness of *D. aligarhensis* compared to the widely established populations of *T. radiata* (Rohrig et al. 2012) and (3) the relatively low *D. aligarhensis* release numbers and frequency, which may not have been adequate to overcome establishment barriers.

Release and impact studies are still in progress, so it is too early to conclude that *D. aligarhensis* has established in California. However, evidence of *D. aligarhensis* parasitism of ACP has been found at over 85% of sites where this species was released. This finding tentatively suggests that *D. aligarhensis* can find ACP nymphs and is able to reproduce in California urban citrus, and that it may be able to coexist with *T. radiata* in this environment. Collectively, the two parasitoid species may intensify biocontrol of ACP in areas where they operate sympatrically.

Impacts of generalist natural enemies and invasive ants

California's biological control program targeting ACP has focused primarily on monitoring parasitoid establishment and their rates of spread and measuring levels of parasitoid-related mortality. However, a suite of naturally occurring generalist predators have been identified as important contributors to ACP mortality in urban areas. Studies conducted in Southern California have identified larvae of syrphid flies (Diptera: Syrphidae) and lacewings (Neuroptera: Chrysopidae) as members of this important predator guild (Kistner, Melhem et al. 2016). Field studies indicate that syrphid and lacewing larvae may account for ~ 86% of ACP predation events, and mortality rates for experimental cohorts of ACP nymphs may reach 93% (Kistner, Melhem et al. 2016).

Exchanges between natural enemies and ants that disrupt natural enemy activity are highly relevant interactions affecting biocontrol success. Ants are widely recognized as natural enemy antagonists because of the food-for-protection mutualisms they form with honeydew-producing hemipterans (HPHs), like ACP. Many species of HPH are invasive, economically damaging pests (e.g., aphids, mealybugs, scales, whiteflies and psyllids) (Helms 2013).

In addition to directly protecting HPHs from natural enemies, ants disperse tended pests to new foraging areas and provide sanitation services to HPHs, which

An Argentine ant captures a foraging adult *T. radiata*. Argentine ants tend colonies of ACP nymphs for the collection of honeydew. Worker ants protect the nymphs from natural enemies, which can significantly reduce biological control of ACP. Research suggests that liquid poison baiting is an effective tool in reducing ant infestations in citrus and other managed agricultural systems.

reduce the incidence of disease and honeydew drowning. Furthermore, tended HPHs may respond to ant presence by increasing their rate of phloem ingestion, resulting in more rapid development and higher reproductive output (Yoo and Holway 2011). Because ants may exacerbate existing pest problems, ant control is a critical component of integrated pest management (IPM) programs targeting HPH pests, particularly programs that rely on biological control agents for population suppression.

It is anticipated that biological control of ACP in California will increase the efficacy and sustainability of other control strategies, including insecticide-reliant programs, because lower populations of ACP may need less management, and less frequent insecticide applications will slow the development of pesticide resistance.

Given the considerable biocontrol efforts targeting ACP, there is a lack of research investigating the impact of ant–ACP mutualisms on natural enemy efficacy. Although studies from Florida found that ACP parasitism by *T. radiata* was substantially higher in groves where ACP-tending ant species were controlled (Navarrete et al. 2013), this interaction remains largely unstudied with ant species in California.

In Southern California, the most ubiquitous ant found in citrus is the invasive Argentine ant, *Linepithema humile* (Mayr) (Hymenoptera: Formicidae). This notoriously pestiferous and ecologically disruptive species has thrived in California for over a century. *L. humile* infestations are most extensive within managed environments, such as the citrus agroecosystem, because of irrigation and abundant food resources. In groves with heavy HPH infestations, a citrus tree may receive more than a million *L. humile* visits in a day (K. Schall and M. Hoddle, unpublished data). In a survey of urban citrus gardens in Southern California, *L. humile* was present in ~ 90% of surveyed trees, with ~ 55% of ACP colonies tended by workers. At these sites, ACP parasitism by *T. radiata* was significantly higher in citrus lacking *L. humile* (> 90%) than in citrus where *L. humile* was tending ACP colonies (< 12%) (Tena et al. 2013).

The results of replicated field trials in urban citrus groves in Riverside, California, further clarified the implications of the *L. humile*–ACP relationship for ACP biocontrol. ACP parasitism by *T. radiata* was 70% to 800% higher and generalist predators were ~ 1 to 4 times more abundant in ACP colonies where *L. humile* was excluded or controlled, using a sticky barrier or liquid poison bait, compared to unmanaged populations of ants that had access to ACP nymphs (Schall and Hoddle 2017).

The high frequency of antagonistic interactions observed between *L. humile* and natural enemies of ACP is likely responsible for the disparities observed between treatments. For example, conflict with ants on citrus flush often resulted in prematurely terminated oviposition attempts by *T. radiata*, allowing ACP nymphs to escape parasitism. In some instances, ants were observed to capture and kill foraging *T. radiata*.

Together, these results suggest that *L. humile* can significantly suppress ACP biocontrol. Implementation of a liquid baiting regime for *L. humile* management is a highly effective method for improving biocontrol and reducing infestations of ant-tended HPH pests in managed agricultural systems (Cooper et al. 2008), including citrus (fig. 3) (Schall and Hoddle 2017).

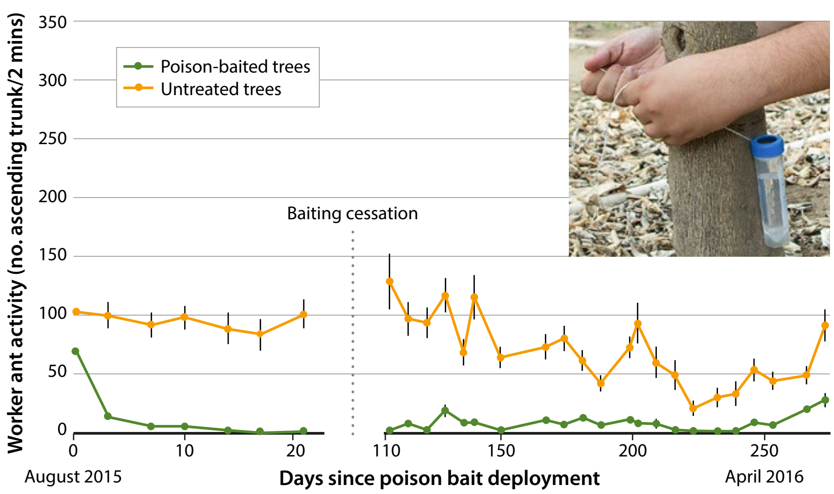


Fig. 3. Visual two-minute assessments of Argentine ant activity on 33 liquid poison–baited (0.0001% thiamethoxam in a 25% sucrose solution) and untreated navel orange trees in an unsprayed citrus grove over a 9-month period. Activity on baited trees decreased by ~ 75% within a few days of treatment and remained near 0 for the entire baiting period. Following bait removal in November, activity on previously baited trees was low and did not show signs of recovery until late April.

Future developments

It is anticipated that biological control of ACP in California will increase the efficacy and sustainability of other control strategies, including insecticide-reliant programs, because lower populations of ACP may need less management, and less frequent insecticide applications will slow the development of pesticide resistance. Reduced ACP populations resulting from natural enemy activity may also suppress rates of *C*Las spread and reduce economic losses resulting from HLB development in orchards.

However, ACP population suppression by natural enemies alone is unlikely to provide complete suppression of *C*Las spread in California. To reduce rates of *C*Las spread further, especially in commercial citrus production areas, IPM programs targeting ACP need to be developed that successfully incorporate a suite of complementary population control tools including natural enemies, ant suppression, insecticides and possibly the development of new citrus varieties tolerant of or resistant to ACP-CLas. Because ACP is significant within a complex of citrus pests, incipient management programs will need to be accommodating of well-developed control practices for other key citrus pests (e.g., California red scale) to minimize disruption of those existing programs.

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RESEARCH ARTICLE

The economics of managing Verticillium wilt, an imported disease in California lettuce

Successfully controlling Verticillium wilt requires future investment, but there is no incentive for short-term growers who rent land to absorb those costs; nor is there incentive for spinach seed companies to test or clean spinach seeds.

by Christine L. Carroll, Colin A. Carter, Rachael E. Goodhue, C.-Y. Cynthia Lin Lawell and Krishna V. Subbarao

Abstract

Verticillium dahliae is a soilborne fungus that is introduced to the soil via infested spinach seeds and that causes lettuce to be afflicted with Verticillium wilt. This disease has spread rapidly through the Salinas Valley, the prime lettuce production region of California. Verticillium wilt can be prevented or controlled by the grower by fumigating, planting broccoli, or not planting spinach. Because these control options require long-term investment for future gain, renters might not take the steps needed to control Verticillium wilt. Verticillium wilt can also be prevented or controlled by a spinach seed company through testing and cleaning the spinach seeds. However, seed companies are unwilling to test or clean spinach seeds, as they are not affected by this disease. We discuss our research on the externalities that arise with renters, and between seed companies and growers, due to Verticillium wilt. These externalities have important implications for the management of Verticillium wilt in particular, and for the management of diseases in agriculture in general.

Invasive plant pathogens, including fungi, cause an estimated $21 billion in crop losses each year in the United States (Rossman 2009). California, a major agricultural producer and global trader, sustains significant economic damage from such pathogens. Fungi damage a wide variety of California crops, resulting in yield- and quality-related losses, reduced exportability, and increased fungicide expenditures (Palm 2001).

The value of California's lettuce crop, which represents the majority of the United States' lettuce production, was $2.0 billion in 2016 (National Agricultural Statistics Service 2017). Measured by value, lettuce ranks in the top 10 agricultural commodities produced in California (National Agricultural Statistics Service 2015). Much of California's lettuce crop is grown in Monterey County, where lettuce production value is 27% of the county's agricultural production value (Monterey County Agricultural Commissioner 2015). Approximately 10,000 to 15,000 acres are planted to

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Lettuce ranks in the top 10 agricultural commodities produced in California and much of it is grown in Monterey County. *Verticillium dahliae*, a soilborne fungus that causes Verticillium wilt, first appeared in lettuce in 1995 in Watsonville. The main source of the disease is infested spinach seeds. Lettuce and spinach are often planted in sequence.

Marita Cantwell

lettuce in Monterey County each season (spring, summer and fall). Spinach, broccoli and strawberries are also important crops in the region.

This paper discusses the economics of managing *Verticillium dahliae*, a soilborne fungus that is introduced to the soil via infested spinach seeds and that causes lettuce to be afflicted with Verticillium wilt, which first appeared in lettuce in 1995 in Watsonville, California. Since then, the disease has spread rapidly through the Salinas Valley, the prime lettuce production region of California.

Verticillium wilt

No effective treatment exists once plants are infected by *V. dahliae* (Fradin and Thommas 2006; Xiao and Subbarao 1998). The fungus can survive in the soil for 14 years as microsclerotia, which are resting structures that are produced as the pathogen colonizes a plant. This system allows the fungus to remain in the soil even without a host plant. When a susceptible host is planted, microsclerotia attack through the root, enter the water conducting tissue, and interfere with the water uptake and transport through the plant. If the density of microsclerotia in the soil passes a threshold, a disease known as Verticillium wilt occurs.

Verticillium wilt first killed a lettuce crop in California's Parajo Valley in 1995. Prior to 1995, lettuce was believed to be immune. By 2010, more than 150 fields were known to be infected with Verticillium wilt (Atallah et al. 2011), amounting to more than 4,000 acres. As not all the fields that were infected by 2010 were known at the time Atallah et al. (2011) was published, the number of fields affected by 2010 is actually even higher, numbering over 175 fields (Subbarao 2011). Although growers have resisted reporting the extent of the disease since 2010, it is likely that the number of affected acres has increased since then.

V. dahliae is introduced to the soil in three possible ways. First, it can be spread locally from field to field by workers or equipment. Local spread is a relatively minor contributor, however, and growers have taken steps to mitigate this issue themselves, for example by cleaning equipment before moving between fields.

A second way in which Verticillium wilt is introduced to the soil is via infested lettuce seeds. However, studies of commercial lettuce seed lots from around the world show that fewer than 18% tested positive for *V. dahliae* and, of those, the maximum incidence of infection was less than 5% (Atallah et al. 2011). These relatively low levels do not cause Verticillium wilt in lettuce at an epidemic level. Models of the disease suggest that it would be necessary for lettuce seed to have an incidence of infection of at least 5% and be planted for three to five seasons in order for the disease to appear, with at least five subsequent seasons required for the high disease levels currently seen (Atallah et al. 2011).

The third way in which Verticillium wilt is introduced to the soil is via infested spinach seeds. Spinach seeds have been shown to be the main source of the disease (du Toit et al. 2005; Short et al. 2015); 89% of spinach seed samples are infected, with an incidence of infected seeds per sample of mean 18.51% and range 0.3% to 84.8% (du Toit et al. 2005). The precise impact of planting infected spinach seeds on Verticillium wilt of lettuce was recently assessed and proven to be the cause of the disease on lettuce (Short et al. 2015). The pathogen isolated from infected lettuce plants is genetically identical to the pathogen carried on spinach seeds (Atallah et al. 2010).

Infected spinach seeds carry an average of 200 to 300 microsclerotia per seed (Maruthachalam et al. 2013). As spinach crops are seeded at up to 9 million seeds per hectare for baby leaf spinach, even a small proportion of infected seeds can introduce many microsclerotia (du Toit and Hernandez-Perez 2005).

One method for controlling Verticillium wilt has been to fumigate with methyl bromide. As methyl bromide is an ozone-depleting substance, the Montreal Protocol has eliminated its use for fumigation of vegetable crops such as lettuce; however, certain crops such as strawberries received critical-use exemptions (CUEs) through 2016 (California Department of Pesticide Regulation 2010; U.S. Environmental Protection Agency 2017), and the residual effects from strawberry fumigation provide protection for one or two seasons of lettuce before microsclerotia densities rise (Atallah et al. 2011). The long-term availability of this solution is limited and uncertain. The California Strawberry Commission has still been attempting to obtain CUEs for 2017, but so far has not been successful and methyl bromide cannot be used currently. Other fumigants, including chloropicrin and 1,2-dichloropropene, have replaced methyl bromide with mixed results in preventing Verticillium wilt.

Lettuce infected with verticillium wilt. No effective treatment exists once plants are infected. Verticillium wilt can be controlled with soil fumigation, planting crops other than spinach, and the testing and cleaning spinach seeds.

A second method for controlling Verticillium wilt is to plant broccoli. Broccoli is not susceptible to Verticillium wilt and it also reduces the levels of microsclerotia in the soil (Shetty et al. 2000; Subbarao and Hubbard 1996; Subbarao et al. 1999). Some growers have experimented with this solution, but relatively low returns from broccoli in the region prevent this option from becoming a widespread solution.

Planting all infected acreage to broccoli may also flood the market, further driving down broccoli prices. With a season length of 2 to 3 months, between 4 and 6 crops of broccoli could be planted within a year, and multiple crops of broccoli would be necessary to reduce Verticillium wilt. Using the very conservative estimate of 4,000 acres infected by Verticillium wilt, this could result in harvested acres of broccoli ranging from 16,000 to 24,000 acres per year (or 32,000 to 48,000 acres if infected acres are equal to 8,000). Given that approximately 50,000 acres of broccoli are harvested in Monterey County annually, planting all infected acreage to broccoli could nearly double county broccoli production. Furthermore, if more acres than expected are infested (on average, about 35,000 acres are planted to lettuce each season, for three seasons per year, and resulting in approximately 100,000 harvested acres per year), the level of broccoli production required to use planting broccoli as a control method would be even greater.

Verticillium wilt can be prevented or controlled by the grower by fumigating, planting broccoli, or not planting spinach.

A third method for controlling Verticillium wilt is to not plant spinach, since spinach seeds are the vector of pathogen introduction (du Toit et al. 2005). Growers who use this control method must forgo any profits they would have received if they planted spinach, relative to the profits from any low-return crop they might plant instead.

In addition to the control measures that the grower can take, Verticillium wilt can also be prevented or controlled by a spinach seed company through testing and cleaning the spinach seeds. Testing or cleaning seeds is an important option for preventing *V. dahliae*. from being introduced into a field, but can be uncertain and potentially costly. Although *V. dahliae* cannot be completely eliminated by seed cleaning, incidence levels in spinach seed can be significantly reduced (du Toit and Hernandez-Perez 2005). Very recent developments in testing procedures suggest that testing spinach seed for *V. dahliae* might soon be feasible on a commercial basis. Moreover, a very recent innovation speeds up testing spinach seeds. Previously, testing for *V. dahliae* in spinach seeds took approximately 2 weeks and could not accurately distinguish between pathogenic and nonpathogenic species (Duressa et al. 2012). This new method takes only one day to complete, is highly sensitive (as it can detect one infected seed out of 100), and can distinguish among species (Duressa et al. 2012).

Verticillium wilt can therefore be prevented or controlled by the grower by fumigating with methyl bromide, planting broccoli, or not planting spinach. Control options such as fumigating with methyl bromide and planting broccoli require long-term investment for future gain. Verticillium wilt can also be prevented or controlled by the spinach seed company by testing and cleaning the spinach seeds. However, as we explain below, all these control options are plagued with externalities.

Externalities

An externality arises whenever the actions of one individual or firm have a direct, unintentional, and uncompensated effect on the well-being of another individual or the profits of another firm (Keohane and Olmstead 2016). When individuals or firms make their decisions, they generally do not account for any externalities they may impose on others. When individuals or firms do not account for those externalities, their decisions may not be optimal from a societal point of view. In this paper, we discuss two externalities that arise due to Verticillium wilt and review our research on these externalities.

Intertemporal externality

When faced with managing a disease that requires future investment, short- and long-term decision-makers may have different incentives and choose to manage the disease differently. Because the options for controlling Verticillium wilt require long-term investments for future gain, an intertemporal externality arises with short-term growers, who are likely to rent the land for only a short period of time. Renters, therefore, might not make the long-term investments needed to control Verticillium wilt. As a consequence, future renters and the landowner may suffer from decisions of previous renters not to invest in control options. Thus, decisions made by current renters impose an intertemporal externality on future renters and the landowner. The intertemporal externality is depicted in figure 1.

Anecdotal evidence suggests that land values can drop as much as 25% when it is discovered that acreage is contaminated with *V. dahliae*. Landowners have also reported renters asking for reduced rent because of *V. dahliae* contamination.

In Carroll et al. (2017b), we analyze the factors that affect crop choice and fumigation decisions made by growers and consider how the decisions of long-term growers (whom we call "owners") differ from those of short-term growers (whom we call "renters"). We examine whether existing renter contracts internalize the intertemporal externality that a renter's decisions today impose on future renters and the landowner, and analyze the implications of renting versus owning land on welfare.

To analyze these issues, we develop and estimate a dynamic structural econometric model of growers' dynamic crop choice and fumigation decisions and compare the decision-making of long-term growers (owners), who have an infinite horizon, with that of short-term growers (renters), who have a finite horizon. A structural econometric model is one that combines economic theory with a statistical model; a model is dynamic if it models decision-making over time. A structural econometric model generates parameter estimates with direct economic interpretations. We use the parameter estimates to simulate counterfactual scenarios regarding renting and owning.

We use a dynamic model for several reasons. First, control options such as methyl bromide fumigation and planting broccoli are investments, in the sense that they require expending money or foregoing profit in the current period in exchange for possible future benefit. Second, these investments take place under uncertainty. The investments are irreversible, there is uncertainty over the reward from investment, and growers have leeway over the timing of investments. Thus, there is an option value to waiting which requires a dynamic model (Dixit and Pindyck 1994). A third reason to use a dynamic model is that long-term growers and short-term growers have different planning horizons, implying that short-term growers may be less willing to make the long-term investments needed to control Verticillium wilt. A dynamic model with different time horizons for long-term and short-term growers best enables us to compare these two types of growers.

When it is costly for the renter to prevent Verticillium wilt, and costly for the landowner to observe the renter's actions, a contract may not suffice to internalize the intertemporal externality. Furthermore, if contracts that include stipulations to control Verticillium wilt are not the norm in the area, highly restrictive contracts may be less desirable and receive lower rents.

Although we do not have data on contracts, it is a testable empirical question whether existing renter contracts internalize the intertemporal externality imposed by renters on future renters and the landowner. We compare the results from short-term growers with those from long-term growers, and also compare results from short-term growers early in the time period (1993 to 2000) with those later in the time period (2001 to 2011). Verticillium wilt was not identified on lettuce until 1995 and the likely sources of the disease were not known until years later. If contracting internalized this externality, we would expect to see more evidence in the later period.

We apply our dynamic structural econometric model to Pesticide Use Reporting (PUR) data from the California Department of Pesticide Regulation. Our data set is composed of all fields in Monterey County on which any regulated pesticide was applied in the years 1993 to 2011, inclusive. Additional data on prices, yields and acreage come from the Monterey Agricultural Commissioner's Office.

According to our results in Carroll et al. (2017b), we find that although methyl bromide fumigation and planting broccoli can both be effective control options, growers with a short time horizon have no incentive to commit to such actions. In contrast, long-term decision-making by owners yields higher average present discounted value of per-period welfare and more use of the control options, likely due to differences in incentives faced by owners versus renters, differences in the degree to which the intertemporal externality is internalized by owners versus renters, the severity of Verticillium wilt, the effectiveness of control options and rental contracts, and a longer planning horizon.

Although contracts can be a potential method for internalizing an externality between different parties, our empirical results show that existing rental contracts do not fully internalize the intertemporal externality imposed by renters on future renters and the landowner. This outcome may be because of the relatively recent development of the disease and knowledge of its causes, more restrictive contracts not being the norm, the possibility of land unknowingly being contaminated before rental, or difficulty in enforcing or monitoring aspects of the contract such as whether boots and equipment are washed between fields.

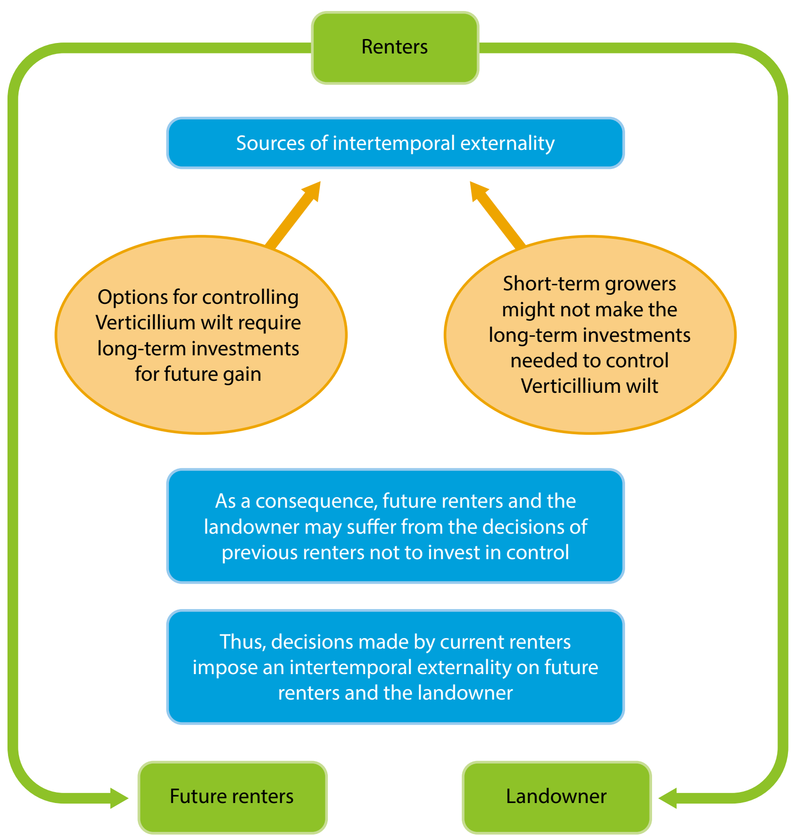

Fig. 1. Intertemporal externality. As indicated by the green arrows, the intertemporal externality is an externality that renters impose on the future renters and the landowner.

Supply chain externality

In addition to the intertemporal externality, a second externality that arises due to Verticillium wilt is a supply chain externality between companies selling spinach seed and growers who may grow lettuce. Growers wish to protect their fields from Verticillium wilt, but they cannot easily prevent introduction of the disease by spinach seeds when spinach is planted without incurring testing costs and cleaning fees. Currently, seed companies are unwilling to test or clean spinach seeds, especially as spinach producers are not affected by this disease. Thus, decisions made by seed companies regarding whether and how much to test or clean spinach seeds impose a supply chain externality on growers. In particular, decisions by seed companies not to test or clean spinach seeds impose a negative supply chain externality on growers.

There are several reasons why the supply chain externality exists between spinach seed companies and growers. First, testing and cleaning spinach seeds is uncertain and potentially costly, and although testing or cleaning seeds may prevent *V. dahliae* from being introduced into a field, spinach seed companies may not have an incentive to test or clean spinach seeds, as they do not internalize the costs that infected spinach seeds impose on growers.

A second reason the supply chain externality exists is that, owing to asymmetric information, the price signal for tested and cleaned spinach seed versus contaminated seed is weak. Growers buying spinach seeds with the intention of planting lettuce in the following season may be willing to pay a very high price for clean seed after accounting for their potential loss in harvest revenue for lettuce and penalties for breaking contracts with lettuce shippers if their lettuce is afflicted with Verticillium wilt. However, if a seed company has infected seed that it cannot otherwise sell, the seed company may be willing to pay a high price to clean the seed without passing on the cost if the seed company wishes to maintain market share (Dale Krowlikowski, Head of Operations and Research, Germains Technology Group, personal communication, 2015). Thus, owing to asymmetric information, there is no direct price signal between seed companies and growers, and, as a consequence, seed companies impose an externality on growers that they do not internalize.

A third reason the supply chain externality exists between spinach seed companies and growers is that Verticillium wilt in lettuce is an example of a market failure in which transaction costs between seed companies and lettuce growers prevent them from reaching a potentially more efficient equilibrium solution. Transaction costs increase with the number of agents. There are a large number of growers attempting to bargain with a relatively small number of seed companies. Due to the small number of seed companies, some growers are hesitant to resort to legal means, such as working toward a seed testing or cleaning requirement from the county agricultural commissioner, lest seed companies decide to leave the market. There are precedents for such requirements; for example, the office of the Monterey County Agricultural Commissioner currently enforces a host-free period to prevent the establishment of lettuce mosaic virus and also enforces a lettuce seed "indexing" or testing requirement to prevent the introduction of the disease.

Thus, owing to the lack of incentives for spinach seed companies to test or clean spinach seeds, asymmetric information, and transaction costs, spinach seed companies are unwilling to test or clean spinach seeds. Thus, decisions made by seed companies not to test or clean spinach seeds impose a negative supply chain externality on growers. The supply chain externality is depicted in figure 2.

In Carroll et al. (2017a), we analyze the supply chain externality between growers and seed companies. We calculate the benefits to growers from testing and cleaning spinach seed by simulating growers' optimal decisions and welfare under different levels of seed testing and cleaning. We then estimate the spinach seed company's cost to test and clean spinach seeds in order to reduce the level of microsclerotia, and compare the spinach seed company's cost to the grower's benefits. Because seed cleaning cost data are not available, we use several functional forms and parameters to estimate potential cost functions. We then use the benefits

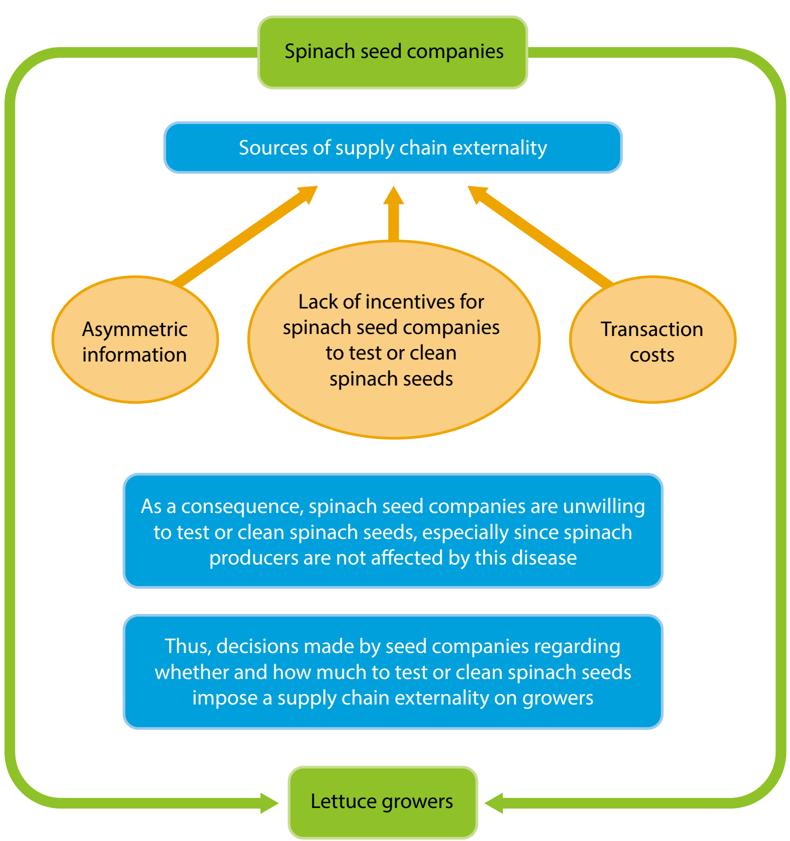

Fig. 2. Supply chain externality. As indicated by the green arrows, the supply chain externality is an externality that spinach seed companies impose on lettuce growers.

and costs to determine the welfare maximizing level of seed testing and cleaning.

According to our results in Carroll et al. (2017a) using data over the entire time period, we find that in more than half of the cases, the socially optimal amount of spinach seed testing and cleaning is more than what arises when the externality is not internalized (the status quo). Significant welfare gains arise only when the seed company tests and cleans the spinach seeds so thoroughly that planting spinach does not have any significant negative effect on grower payoffs after controlling for spinach price. In other cases, even though it maximizes welfare, the socially optimal amount of spinach seed testing and cleaning does not yield any welfare gains.

Thus, we find in Carroll et al. (2017a) that a cooperative solution would increase welfare, and in most cases, a cooperative solution would require that the spinach seed company engage in more spinach seed testing and cleaning than in the status quo. Our work regarding the supply chain externality between seed companies and growers sheds light on how treatment of spinach seeds could potentially reduce externalities between seed companies and growers.

Conclusion

When managing crop disease, it is important to consider any externalities that may plague the available control options. In this paper, we discuss our research on the externalities that arise with short-term growers (Carroll et al. 2017b) and between seed companies and growers (Carroll et al. 2017a) due to Verticillium wilt, which has important implications for the management of Verticillium wilt in particular, and also for the management of diseases in agriculture in general. The results of our research are of interest to policymakers, the agricultural industry, and academics alike. CA

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RESEARCH ARTICLE

Land access and costs may drive strawberry growers' increased use of fumigation

The phaseout of methyl bromide and increasing regulation of other fumigants did not decrease overall fumigant use in California strawberries. Here are some likely reasons why.

by Julie Guthman

Abstract

2016 marked the year of the final phaseout of methyl bromide for use in strawberry production. During the long phaseout period, one replacement fumigant met so much public opposition it was taken off the market, while restrictions on use of other fumigants increased. As part of a larger study on the challenges facing the strawberry industry, I tracked fumigant use through California's pesticide use reporting system from 2004 to 2013. During the last few years before the phaseout, I interviewed 74 growers in the four main strawberry production regions about how they were now managing soilborne pests. As a general trend, growers had increased their use of chloropicrin and switched from broadcast fumigation to bed fumigation, and many were experimenting with organics. At the same time, significant percentages of growers were reluctant to change fumigation regimes or adopt nonchemical options of pathogen control. Some were unable to adopt less chemical-intensive methods because of land access conditions and land costs. Given these land-related obstacles, policymakers ought to consider strategies that will incentivize transitions to nonchemical alternatives and mitigate the financial risks.

Last year, 2016, marked the final phaseout of methyl bromide for use in strawberry production. By year's end, many of the pessimistic predictions about the California strawberry industry's future had not come to pass. Consumer costs had not increased to cover expected higher production costs (e.g., Carpenter et al. 2000; Norman 2005), nor had production substantially moved to Mexico, which, per Montreal Protocol rules, initially was granted a longer phaseout period than the United States (Carter et al. 2005; Goodhue et al. 2005).

Indeed, both the overall production of strawberries and the rates of productivity continued to increase in California throughout the phaseout period, and prices for berries declined rather than rose (Mayfield and Norman 2012). Even in the last years of the phaseout, acres planted in strawberries held relatively steady — 37,732 acres were planted in 2012 and 36,039 were planted in 2016, with little variation in between those years (California Strawberry Commission 2016).

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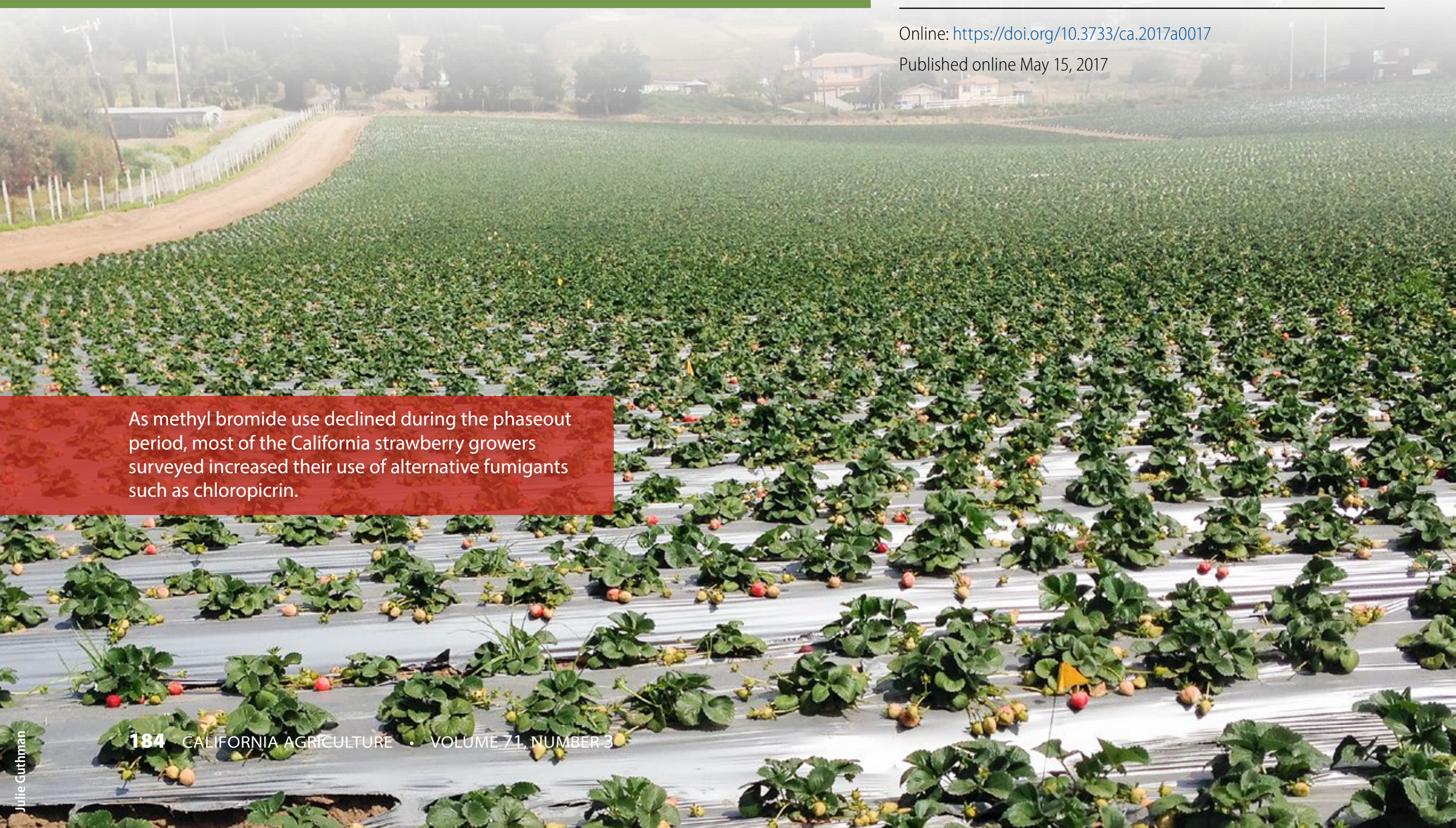

As methyl bromide use declined during the phaseout period, most of the California strawberry growers surveyed increased their use of alternative fumigants such as chloropicrin.

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During the final years of the phaseout, I completed a study of the strawberry industry, one of the goals of which was to learn how growers were managing soilborne pests and to see what, if any, changes they had made in recent years in light of regulatory pressures to curtail fumigant use. Through interviews, I learned of factors that were either encouraging or impeding transitions to nonchemical methods of soil disinfestation. Results of this study shed light on why most growers have not transitioned to nonchemical pest control strategies despite the long phaseout period for methyl bromide.

Fumigation options, regulations

For about 50 years, California's strawberry industry has relied on chemical fumigants to disinfest soil of pathogens, as well as to control weeds and nematodes. The most favored fumigant has been methyl bromide, a broad-spectrum fumigant, supplemented with chloropicrin. With its unpleasant smell and tendency to cause eyes to tear, chloropicrin served as a warning agent. Additionally, it created a synergistic effect with methyl bromide.

In 1991, the Montreal Protocol on Substances that Deplete the Ozone Layer mandated the phaseout of methyl bromide. As a signatory to the convention, the United States agreed to stop producing and importing methyl bromide by 2005. However, as that deadline drew near, U.S. negotiators, under pressure from the strawberry industry, successfully lobbied for provisions that would grant critical use exemptions (CUEs) for producers who claimed that no viable alternative was available. CUEs thereby allowed for the continued use of methyl bromide in strawberry production well beyond the international deadline of 2005 (Gareau 2008; Mayfield and Norman 2012). Nonetheless, in accordance with the Protocol, approved amounts of methyl bromide for use by strawberry growers declined precipitously during the years of this study in anticipation of the total ban at the end of last year. Nursery stock producers received a separate "quarantine" exemption to prevent the introduction of certain pests into new areas.

Over the course of the phaseout, many in the industry hoped for a replacement chemical. The most promising replacement, methyl iodide, met considerable public opposition, however, and was withdrawn from the market soon after California approved the chemical for use (Guthman 2016). Meanwhile, chloropicrin began to see tighter use restrictions following its 2010 designation as a toxic air contaminant by the U.S. Environmental Protection Agency (EPA) and re-review by California's Department of Pesticide Regulation (DPR). In 2015, DPR mandated enhanced mitigation measures for chloropicrin applications that were modified in 2016. These included wider buffer zones between applications and nearby buildings, incentives in the form of reduced buffer zone requirements with the use of totally impermeable film (TIF) to cover fumigations, and increased monitoring requirements. These measures are detailed in Goodhue et al. (2016). 1,3-dichloropropene (Telone), used by some strawberry growers, is already limited by township caps. During the phaseout period for methyl bromide, DPR began undertaking further risk assessment to determine whether the caps are sufficient to protect public health (DPR 2014).

Other substitute chemicals, used less frequently in strawberry fumigation, have also seen more scrutiny. In 2010, DPR released new permit conditions for metam sodium, metam potassium and dazomet, primarily increasing buffer zones and worker protections. This is likely not the end of the restrictions. In 2013, DPR published an action plan that argued for curtailing and eventually phasing out all fumigants to protect the health of farmworkers, bystanders and nearby communities (DPR 2013). Although the plan's primary purpose was to generate innovation and dissemination of alternative methods of soil management, it signaled encouragement to reduce fumigant use.

Pesticide use decision-making

A wealth of studies have examined the factors, variables and considerations that shape grower decisions about pesticide use. A significant set of these focus on how differing perceptions of pest virulence, treatment efficacy, and the health and environmental risks of chemicals play a role in pesticide use decisions (Hashemi and Damalas 2010; Heong et al. 2002; Khan and Damalas 2015; Parveen et al. 2003; Penrose et al. 1996). Some studies note that the perceived potential for economic loss from pesticide reduction often overrides other concerns (Damalas and Koutroubas 2014; Kishi 2002; Tucker and Napier 2001).

A buffer zone around a home in Monterey County. To reduce human exposure to fumigants, California regulations require growers to maintain unfumigated buffer zones between fumigant applications and nearby buildings. One consequence, according to the strawberry growers surveyed, has been a shift, where feasible, to more remote locations.


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Another set of studies focus on the personal and farm characteristics that are associated with grower interest in pesticide reduction. Several studies have found, for example, that growers who adopt sustainable agriculture techniques tend to be younger and/or more educated (Comer et al. 1999; Damalas and Koutroubas 2014; Lasley et al. 1990; Lighthall 1995). Others have emphasized the importance of growers' access to economic resources, and technical support and information (Chaves and Riley 2001; Khan and Damalas 2015; McNamara et al. 1991; Mumford 1981; Robinson et al. 2007; Thiers 1997; Thomas et al. 1990).

Some studies have considered obstacles to pesticide reduction, such as labor costs and availability (Pfeffer 1992) and the pressure exerted by buyers and extension agents to use pesticides (Barraza et al. 2011; Bellamy 2011; Galt 2014; Harrison 2011). A few have suggested that a constellation of factors influence pesticide use decisions, that they cannot be distilled to one or two factors (Beus and Dunlap 1994; Carolan 2005; Duram 2000; Williamson et al. 2003).

Research has also examined rationales for transitioning to organic production. Many of these studies emphasize growers' beliefs and values (Cranfield et al. 2010; Darnhofer et al. 2005; Devitt 2006; Fairweather 1999; Kings and Ilbery 2010). Others give greater emphasis to the role of comparative production costs and marketing opportunities (or obstacles) in growers' decisions to convert acreage to organics (Bartulović and Kozorog 2014; Campbell 1996; Duram 1997; Fairweather 1999; Guthman 2014; Padel 2001; Smit et al. 2009).

The vast majority of the pesticide use research presumes that growers are in a position to reduce their use of pesticides voluntarily. Studies that examine regulation-driven changes in pesticide use are hard to come by. Also, the role of land (e.g., availability, cost, conditions of access) in pesticide decisions has received little attention, other than a few studies that examine the constraints that tenant farmers encounter for pesticide reduction due to landlord skepticism (Carolan 2005; Constance et al. 1996) or research showing how land values have affected organic conversions (Guthman 2014; Risgaard et al. 2007). My study addressed the nonvoluntary reduction of pesticide use by assessing grower decision-making in a regulation-forcing context and by prompting growers about land considerations.

Fumigant use data, interviews

As part of a large research project covering a range of issues related to the challenges facing the strawberry industry, I tracked fumigant use in nine counties through California's pesticide reporting program from 2004 to 2013. The nine counties contained the primary areas of fumigant applications for strawberries, including the nursery stock production areas in the far north of the state.

From 2013 to 2015, I also interviewed strawberry growers in the four counties that contain the main centers of strawberry fruit production: Watsonville (Santa Cruz County), Salinas (Monterey County), Santa Maria (Santa Barbara County) and Oxnard (Ventura County). The interviews covered topics beyond the topics of fumigant use and alternatives reported here. They were semistructured, based on themes determined in advance but designed to allow the interviewer to explore issues raised by the interviewee, including unexpected themes (David and Sutton 2004). For the purposes of reporting on fumigation use and alternatives, interviews consistently included questions on farm data, fumigation regimes, experience with organics and experimentation with nonchemical alternatives. Sample questions on these themes can be found in the sidebar below.

To identify, characterize and locate growers in the four counties in which I intended to conduct interviews, I obtained pesticide use data from each of those counties from 2011, data that the state mandates counties collect and make public. Even though the California Strawberry Commission's website in 2011 claimed there were about 400 strawberry growers in the state of California, during that year there were 443 pesticide use permits for strawberry fumigation in

Sample interview questions

1. Farm data

- How many acres do you grow? Where?
- What do you grow besides strawberries? In rotation with strawberries or on separate plots?
- How many acres in strawberries?
- How many years have you been farming? Farming strawberries?
- Do you lease or own your land? Or both?
- How many acres in organic or transitioning? Which parcels?

2. Practices

- What is the primary way you currently deal with pathogens?
- What is your fumigation regime (what chemicals, what methods)?
- Why that chemical, those methods?
- Do you use different regimes for different parcels? Why?
- How has your fumigation program changed over the past 10 years?
- What mitigation measures do you use?
- Have you experimented with alternatives? Which ones? What were the results? Will you continue?

3. Influences

- How do you decide which fumigants to use, when and in what quantities?
- Who do you look to for advice?
- What, if any, restrictions/advice does your buyer give?
- How do your lease arrangements/land ownership influence your fumigation decisions?
- How about mitigation measures?
- How does past history of pathogens on parcels influence fumigation decisions?
- Have you tried organics? Why or why not?
- On which parcels have you tried organic production? Why those?
- What other factors have influenced your decision-making (*possible prompts*: methyl bromide phaseout; increasing regulation/restrictions in general; pesticide activism/shifting political environment; toxicity; cost)?

those four counties alone, representing 411 business entities (which I refer to here as "Doing Business As" entities, or DBAs). During the interviews, I learned that many growers held multiple permits under different entities and across counties, which explained the inflated numbers.

Given the data available (not all counties provided contact information and not all contact information was correct), the difficulty of reaching many potential research subjects and the reticence of many to be interviewed about pesticide use, I opted for a convenience sample. I interviewed every grower who was reachable, willing to schedule an interview and then showed up for it (n = 74). The sample turned out to be broadly representative of the sector, although large growers made up a higher percentage of the sample since they tend to stay in business longer and have more reliable contact information. This oversampling of large growers was especially the case for Santa Barbara County, which did not provide contact information, forcing me to rely on publicly available contact information.

Growers with both organic and conventional systems and transitioning-to-organic growers appeared oversampled as well, but this was a function of a noticeable increase in organic growers since 2011, detailed below. I included only a few organic growers farming in diversified systems, instead choosing to focus on those for whom strawberries were the primary crop. Indeed, many growers with diversified systems were not included in the pesticide use data at all, which therefore understated the population of organic growers. Table 1 describes the sample across three dimensions compared with the number of DBAs in those four counties; the notes contain important caveats on the population data.

To arrange interviews, I or one of two research associates contacted growers with cold calls. The interviews took place at growers' homes and offices and occasionally by phone at the time of contact. With interviewee permission, most interviews were audio-recorded; otherwise interviewers took hand notes. In accordance with a human subjects protocol approved by the UC Santa Cruz Institutional Review Board, interviewees were promised protection of confidential information and anonymity in reporting results.

Following the interviews, research assistants transcribed the interviews and sorted the data into a standardized Word template along predetermined themes (e.g., fumigation practices, fumigation perspectives, fumigation information). These Word documents were uploaded into Nvivo (QSR International), a qualitative research software, which auto-coded each of the questions. I was then able to sort by theme and develop more refined codes that categorized grower responses within a broader theme. Doing the more refined operation myself minimized the potential for inconsistent coding. These refined categories were the basis of the responses reported in the study results. Not all growers answered or expanded on every question, which is why the total responses for a question could be less than the sample size.

Research collaborator Sandy Brown interviews a strawberry grower in Santa Barbara County. Nearly one-third of growers surveyed continued using methyl bromide during the phaseout period, despite its high cost. This was due in part, these growers reported, to lease agreements with vegetable or flower growers who would rotate their crops with strawberries, thereby getting much of the benefit of a recently fumigated field without having to fumigate the fields themselves.

More fumigant used during phaseout

As a general trend, growers did not significantly reduce their use of fumigants in the new regulatory context, but instead shifted to using chemicals that were still allowed, albeit with stricter mitigation measures. Figure 1 shows the pounds of fumigants applied to strawberry crops in the nine counties from 2004 to 2013. The decline of methyl bromide use during that period was far outweighed by the increase in use of alternative fumigants, chloropicrin in particular. One of the reasons that fumigant use increased, even as acres in production held steady, is that chloropicrin alone is not as effective as it is in combination with methyl bromide (Lloyd and Gordon 2016; Triky-Dotan et al. 2016).

In keeping with this trend data, the interviews indicated that the vast majority of growers with

TABLE 1. Description of sample, in relation to 2011 business entities (DBAs)*

County of operation	Strawberry acreage†	Organic/conventional‡
Monterey (n = 22/148, 15%)	Under 20 acres (n = 6/115, 4%)	All conventional (n = 36/349, 10%)
Santa Barbara (n = 9/74, 12%)	20 to 50 acres (n = 9/88, 10%)	Mixed organic and conventional/ transitioning (n = 31/38, 82%)
Santa Cruz (n = 19/94, 20%)	51 to 100 acres (n = 8/63, 13%)	All organic (n = 6/24, 25%)
Ventura (n = 24/95, 25%)	Over 100 acres (n = 47/145, 32%)	Unknown (n = 1)
	Unknown (n = 4)	
Total **n = 74/411, 18%**		

* Use of DBAs somewhat overstated number of growers, because a grower may have multiple DBAs and operate in multiple counties.

† The number of DBAs in each acreage category were rough estimates, since acres in production are inconsistently reported in the pesticide use reporting system.

‡ Numbers of all organic, mixed organic and conventional, and transitioning DBAs were underreported, since organic status was not necessarily reported through the pesticide use reporting system.

conventional operations moved to using chloropicrin as the primary fumigant (table 2). In describing their rationales for moving away from methyl bromide, some said that there was no longer enough available, while others mentioned that it had become too expensive. These responses are two sides of the same coin: chloropicrin became much cheaper than methyl bromide because methyl bromide was in such short supply. Early adopters of chloropicrin alone moved to it to gain competitive advantage and to deflect public scrutiny. Only one grower, who runs a very small conventional operation, ceased fumigating.

An important question is how and why 23 of the 62 growers who responded to the question in interviews continued to use methyl bromide despite the cost and imminent phaseout. Some of them, those who used it on a spot basis, suggested they were eligible for CUEs due to particularly troublesome areas in their fields. Others used methyl bromide as their primary fumigant for as long as they could simply for its efficacy — and were willing to pay over twice the per-acre cost. Several of these growers admitted (and several other growers alleged) that being long-time, good customers of Tri-Cal, the fumigation company to which CUEs were allocated, enabled them to access the chemical.

The other reason that growers continued to fumigate with methyl bromide was because they rotated land with a vegetable or flower grower who demanded it. Such lease agreements, typical of the Salinas and Pajaro Valley regions in Monterey and Santa Cruz counties, are in many ways a win-win situation for vegetable and strawberry growers. Strawberry growers have access to ground for 14 or 15 months, allowing them to fumigate in the late summer, plant in late fall and start harvesting in late winter or early spring and continue harvesting through the fall, making for a lengthy harvest season and, hence, a profitable year. For their part, leafy greens growers can squeeze in two rotations of vegetables in the remaining 8 months. In doing so, they obtain the benefit of fumigation without having to report it. It is effectively an off-label use of fumigants for vegetable growers (Brian Leahy, DPR director, personal communication).

The increase in chemical use was surprising given that mitigation measures for several chemical fumigants are structured to encourage fumigation methods that reduce chemical use (Goodhue et al. 2016). For instance, growers may have smaller buffer zones if they fumigate in beds (through irrigation lines), which uses less fumigant than broadcasting (where the fumigant is injected into the soil of a leveled field by a fumigation rig and the planting beds are then constructed and covered with plastic to prevent the chemical from volatizing); growers who broadcast-fumigate are limited to fumigating in one 40-acre block at a time, but if they use totally impermeable film (TIF), which is required in some counties, they may have smaller buffer zones.

Most growers interviewed continued to use broadcast fumigation (table 3). Growers who used bed fumigation said that cost was a primary factor; many of them farmed in hilly areas, where broadcasting (also called flat fumigation) is more difficult. Growers who broadcast-fumigated cited efficacy as a key rationale. Their concerns have been corroborated by recent research, which attributes new pathogen outbreaks to bed fumigation. Apparently, pathogens remain in the rows between the beds and are able to recolonize (Goodhue et al. 2016; Koike and Gordon 2015). Besides efficacy, the primary reason growers broadcast-fumigated was that they rotated the land with leafy greens growers and, like many who use methyl bromide, were under a lease agreement in which the vegetable growers insisted they broadcast-fumigate — even when strawberry growers held the master lease. In other words, lease arrangements that were otherwise beneficial

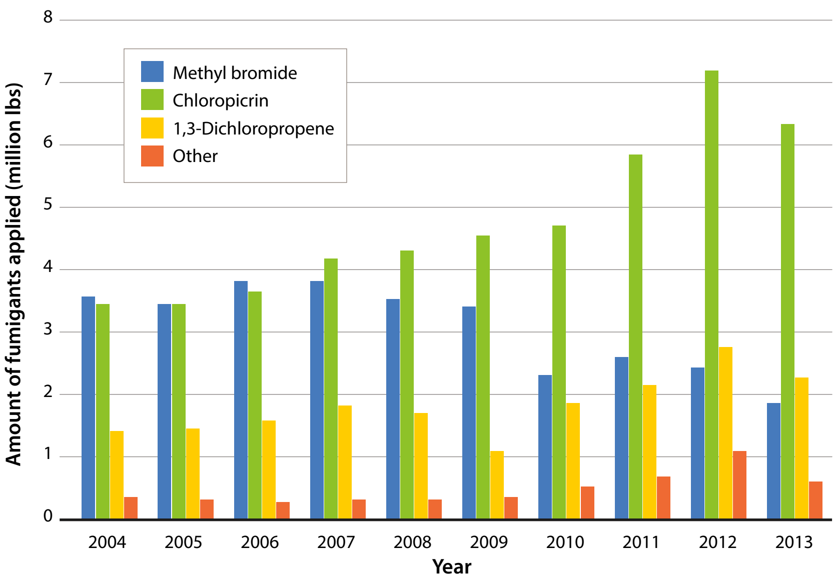

Fig. 1. Pounds of fumigants applied for nine counties in the study, 2004 to 2013. *Source:* California pesticide use reporting program (www.cdpr.ca.gov/docs/pur/purmain.htm).

TABLE 2. Conventional growers' fumigant choices, interviews 2013–2015

Choice	No. of responses
Methyl bromide as primary fumigant	11
Chloropicrin as primary fumigant with methyl bromide on spot basis	12
Chloropicrin in combination with 1,3-D	24
Chloropicrin alone	14
No fumigant	1
Total responses	**62**

TABLE 3. Conventional growers' fumigation methods, interviews 2013–2015

Method	No. of responses
Broadcast fumigation	25
Bed fumigation	23
Broadcast and bed fumigation, field dependent	5
Total responses	**52**

to strawberry growers were partially responsible for thwarting any reductions in their fumigant use.

Land issues came up in the interviews in another way. Growers who were in a position to lease new parcels chose parcels remote enough to not require buffer zones. This movement into more rural areas follows on research that showed that differing field conditions create highly uneven buffer zone sizes, giving growers without nearby buildings a distinct advantage (Goodhue et al. 2016). Indeed, the stricter buffer zone mitigations appear to be one of the reasons that strawberry production has shifted north from the Oxnard area to the relatively rural Santa Maria area that straddles Santa Barbara and San Luis Obispo counties. Growing strawberries in remote areas may curtail the public's exposure to pesticides, but it does not reduce fumigant use overall.

Increase in organic production

Another overarching trend that emerged with increased fumigation restrictions is the increase in organic strawberry production. Acres in organic production increased considerably after 2005, when the phaseout of methyl bromide was set to begin (fig. 2). The dip in 2009 was likely recession related, because overall organic production in California fell as demand for organic produce slowed following the financial crisis of 2007–2008 (Guthman 2014). Acres in organic strawberry production have picked up since, and organic strawberry sales show even more robust growth, from about $25.1 million in 2005 to $93.6 million in 2012 (Klonsky and Healy 2013; Klonsky and Richter 2011). More recent figures are not available, but interview data suggested this trend was unabated.

Interview data did not entirely support the supposition that the transitions to organic were driven by increased regulation. Of the 34 mixed, transitioning or recently transitioned growers interviewed, 29 discussed their rationales for transitioning at least some of their fields to organic production (table 4). Of these, only eight stated that pesticide restriction was one of the factors guiding their decision; among the eight were growers who grew organic crops in the buffer zones of fumigated fields.

A few strictly conventional growers mentioned they would eventually transition to organic production if the restrictions continued. However, the majority of transitions already made were not motivated by either safety concerns or the potential loss of a favored technology, at least directly. In most cases, growers moved into organic production for market considerations. For some, that meant the higher prices and profits for organic berries — costs for organic production are fairly comparable on a per-acre basis to costs for conventional production, but, because of higher prices, profits for organic strawberries can be over $12,000 per acre higher (Bolda et al. 2010; Bolda et al. 2014). For others, this meant buyers (grower shippers, retailers and

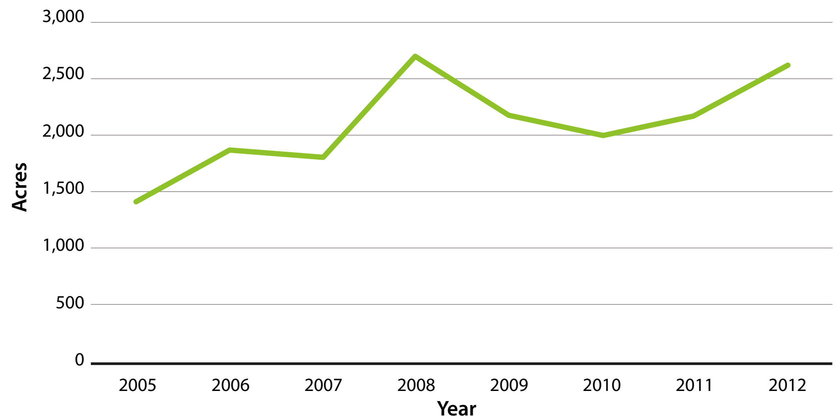

Fig. 2. Acres of organic strawberries in California. Acreage increased about 80% from 2006 to 2012, but still represented only 7% of all strawberry land in the state. *Source:* Klonsky and Healy (2013); Klonsky and Richter (2011).

farmers' market customers) had shown interest in their supplying organic strawberries.

The transitions to organic farming did not necessarily reduce overall amounts of fumigants used. Even though many of the transitioning growers planned on increasing their organic acreage, others were experimenting with organics while increasing the use of fumigants on their nonorganic fields. Moreover, few growers transitioned conventional land into organic production. Five of the transitioning growers began organic production on land that had not been in crop production, such as pasture (a more popular option in relatively rural Santa Maria), and another five found land that was already certified organic.

Seven growers who had gone through the normal process of transitioning land into organic production saw that process as a real obstacle to developing their organic programs. Transitioning involves avoiding the application of disallowed substances for 3 years, while not receiving the price premium for organic crops.

Land value is obstacle to change

In recent years, with support from the California Strawberry Commission, the U.S. Department of Agriculture (USDA) and DPR, researchers have developed and tested several nonchemical approaches to the elimination of soil pathogens. These include solarization, steam sterilization, biofumigation with mustard seed meal, and anaerobic soil disinfestation (ASD), all

TABLE 4. Reasons for transition to organic production, interviews 2013–2015

Reason	No. of responses
Restrictions on pesticides	8
Market interest or better prices	21
Personal or family health and safety	4
Other	4
Total responses*	**29**

* Responses add up to more than total responses since some growers gave multiple reasons.

of which have shown some promise (Daugovish et al. 2016; DPR 2013; Hodson and Lewis 2016; Koike and Gordon 2015).

Many growers in the sample, including nine who remained conventional growers solely, had tried or were considering trying nonchemical alternatives to fumigation. Of 16 interviewees who had experimented with ASD, half found it promising, but few if any had tried it for the whole farm. In contrast, the few growers we interviewed who used more diversified farming methods to control pathogens were much more satisfied with the results. Along with growers, field trial researchers have found effective pest suppression with rotations of plants with biofumigation properties, such as brassicas, along with cover crops and composting, especially in 3- to 4-year cycles (Hodson and Lewis 2016; Lloyd 2015; Muramoto et al. 2014). The problem, however, with any nonchemical alternative that requires growers to rotate strawberries with a lower value or no-value crop, especially over several years, is that lease costs are generally based on an expectation that strawberries will be grown on an annual basis, not be a minor crop in an integrated diversified system.

Policymakers need to consider strategies that will mitigate the financial risks for growers wishing to attempt nonchemical alternatives or transition conventional land to organic production.

Many growers interviewed complained of rising land costs, with growers in the Oxnard area often alluding to bidding wars over land suitable for strawberry production. With high and possibly rising land values, many of these nonchemical alternatives are viable only if growers are able to obtain premium prices in the market — in other words, they may be practical only if consumers are willing to pay much more for strawberries. In this way, the cost of land remains an obstacle to farming without fumigants.

Policy changes

To summarize, this study found that the strategies growers used to compensate for the imminent loss of methyl bromide did not result in reductions in overall fumigant use. In other words, growers worked around the regulations. Even most growers who were experimenting with organic production did not attribute that decision primarily to fumigation restrictions, but rather to market opportunities. Arguably, these findings about the effects of fumigation regulations are unique within a literature that has focused largely on voluntary efforts to reduce pesticides and not assessed the effects of regulations. The study results suggest changes should be considered by policymakers.

The main strategies growers pursued during the final years of the phaseout period for methyl bromide — switching to chloropicrin, moving production into more rural areas, and transitioning into organics — are closely tied to their access to land. Sublease arrangements with vegetable growers thwarted their ability to turn to less intensive fumigation regimes. The availability of land without buffer zone requirements encouraged movement to new locations, and the chance to attain already certified or easily certified organic land encouraged growers who otherwise might not have considered organic production to enter the market. None of these strategies is exactly in keeping with regulatory intent: two do not reduce overall chemical use, while the other does not bring more conventionally farmed land into organic production. Meanwhile, the cost of land remains a formidable obstacle to farming without fumigants.

Thus far, policy efforts to encourage farming without fumigants have focused on funding support for research, development and extension of less toxic and/or nonchemical alternatives to fumigation. These are important and should be bolstered. Yet this research suggests that support for alternatives may not be enough, especially when land costs pressure growers to maintain, if not intensify, current production practices. To the extent that land costs, availability and lease restrictions impede fumigant reductions, policymakers need to consider strategies that will mitigate the financial risks for growers wishing to attempt nonchemical alternatives or transition conventional land to organic production. These could include transition subsidies, government-funded crop insurance directed at pesticide reduction or even agricultural easements to modulate urban pressures on agricultural land.

New policies such as these may not be the easiest to implement politically, but they could go further than existing efforts in reducing fumigant use. As this research also makes clear, regulatory work-arounds are not uncommon, especially those that involve land. So if indeed fumigant use reduction is a serious goal, regulators involved in pesticide use permitting and organic transitions need to consider mechanisms to eliminate those opportunities. CA

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