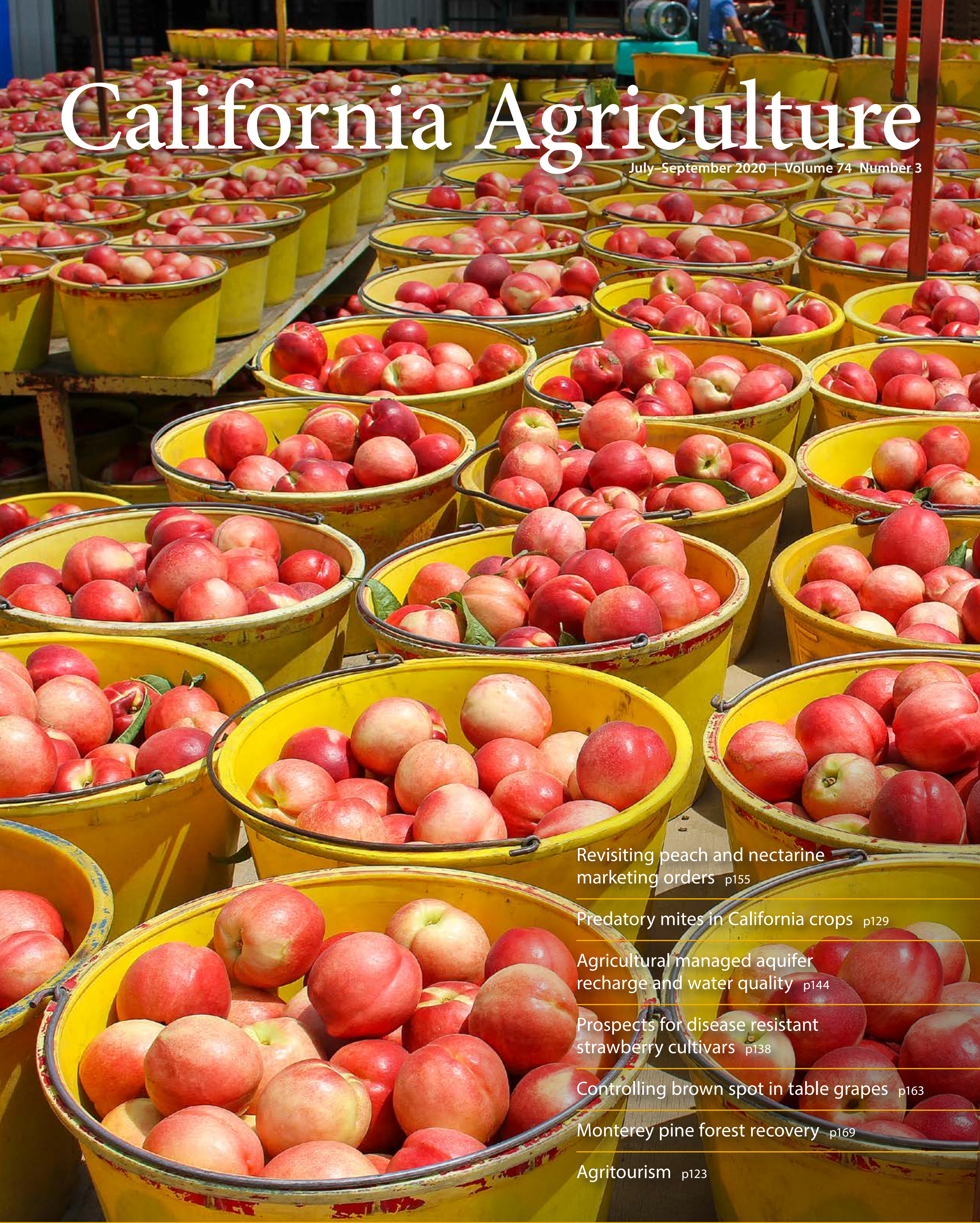

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COVER: At R&D Farms in Reedley, Calif., nectarines and peaches are picked in buckets to protect fruit during handling just before transfer to the packing line for cleaning, sanitation, sorting, sizing and packing. *Photo by Carlos H. Crisosto.*

CONVERSATION

Q-and-A: COVID-19's effects on food systems, youth development programs and nutrition

An interview with UC Cooperative Extension experts about the effect of the coronavirus pandemic on food systems, youth development and nutrition.

Online: https://doi.org/10.3733/ca.2020a0024

Through the COVID-19 pandemic, UC Agriculture and Natural Resources (UC ANR) has continued to work to safeguard abundant and healthy food for all Californians, promote healthy people and communities, build skills needed in the workforce and help to develop an inclusive and equitable society. For insights into how the pandemic is affecting life in California and UC ANR's programs in these areas, *California Agriculture* spoke with UC ANR experts in the fields of food systems, positive youth development and nutrition. The edited conversations appear below.

Gail Feenstra, Deputy Director of the Sustainable Agriculture Research and Education Program (a UC ANR statewide program) and Food and Society Coordinator for the Agricultural Sustainability Institute at UC Davis

California Agriculture: Your expertise lies partly in local and regional food systems, giving you an overview of issues from the farm to distribution channels and all the way to communities and consumers. In broad terms, how would you say the coronavirus has affected the food system so far?

Gail Feenstra

Gail Feenstra: We've seen some major pivoting of activity. For businesses across the supply chain, things were really chaotic in the early days. Things have gotten a little calmer now, but there's some good and bad news. The good news is we're not seeing the grocery store shortages and hoarding like we were in the early days. On the negative front, there are plenty of farmers still struggling to figure out what their markets are going to look like. Some of them have pivoted to new markets and others have not been successful in finding markets. Institutional markets have suffered — schools, corporate cafeterias and obviously restaurants. On the other hand, certain other markets have ramped up. Everybody wants a community-supported agriculture or subscription box, which is a box of locally grown produce that people pay for in advance.

California Agriculture: How about the rest of the food chain? How has the pandemic affected distributors?

Gail Feenstra: Some suppliers are scrambling. For some, it's probably less of an issue than for the producers. People still need to eat, so if they're not going to restaurants, they've got to get their food from a grocery store. If you look at the U.S. population, before COVID, people got close to 50% of their food outside the home. And that changed pretty drastically. People are cooking more, gardening more. They are also supporting takeout to some extent.

Another issue I'd like to bring up, a part of the supply chain often forgotten, is farmworkers. They are at the highest risk. They're putting their lives on the line every day. According to a recent study coordinated by the California Institute for Rural Studies, agricultural workers in Monterey County were three times more likely to become infected by COVID-19 than persons employed in nonagricultural industries. And farmworkers are not getting enough of what they need to stay healthy. Often they're people of color, and do not have access to adequate health care, nutritious food and housing. Also, if farms go under, they lose their jobs.

California Agriculture: Another issue you're involved in is sustainable agriculture. I'm wondering what effect the virus is having on efforts toward environmental, economic and social sustainability. Can sustainability efforts proceed amid the coronavirus, or is a lot of that just stopped for now?

Gail Feenstra: Well, some of the social issues, in terms of credit and access to resources for small and mid-scale farmers and workers and processors — that part is not going as well as it could. One of the things that this coronavirus did was unmask some of the things in the food system that were already problematic.

It is showing how we are deficient in some areas — for example, infrastructure in regional food systems, especially infrastructure that would benefit mid-scale farmers and ranchers. It's just not available — for example, facilities for processing beef or lamb or pork, so that ranchers don't have to drive for a day to get to a processing facility. There just isn't enough that caters to regional or smaller-scale ranchers. The system is not built for that.

California Agriculture: Is there anything I should have asked but haven't?

Gail Feenstra: One important issue is building our understanding of farmers and other people in the food system who are Black, indigenous and people of color. We need to be focusing on them because they are the ones that are really in need of resources. And it's not just about white people helping them. It's more about facilitating those groups building their own leadership structures and power base so that they can begin to participate more fully in the food system along with everybody else. For example, I'm thinking of the Hmong and Vietnamese farmers in the southern part of the state. There are a lot of Hispanic growers too. And then there are the native tribes. And I think, as Cooperative Extension, we need to be attuned to these groups more and figure out how we can work with them to build a resilient food system that also works for them.

Fe Moncloa, 4-H Youth Development Advisor in Santa Clara County

California Agriculture: Could you explain what your work in positive youth development consists of in normal times, when there's no pandemic going on?

Fe Moncloa: For me, positive youth development in Santa Clara County mostly means supporting the staff who provide oversight and management of the 4-H club program and supporting staff who work in partnership with schools and with community nonprofit organizations.

California Agriculture: What does actual program delivery to the kids look like?

Fe Moncloa: I'll focus on one part that most people are not familiar with. At a school in our area, I work with teenagers who are new immigrants to the United States and either just arrived or have lived in the United States for a year or two, tops. They are predominantly Spanish speakers and they're learning English. I teach computer science concepts to teenagers who have never, ever learned anything around computational thinking. After they learn it, I ask them to teach it to younger children. They do incredibly well. My staff member in that same school trains seventh and eighth graders in a curriculum called Youth Experiencing Science. It's a well-known curriculum that was developed in California years and years ago, and we continue to use it. It was written specially so that teenagers could teach it to younger children. My staff invests about 20 hours in training these teenagers to teach the curriculum to kids from kindergarten through third grade.

California Agriculture: How has the pandemic changed things — both for you and for the work you're trying to do in your area?

Fe Moncloa: When shelter-in-place started, I was personally in disarray, so I figured that my volunteers and families were also in disarray. So I waited a couple of weeks and then convened a meeting with all the project leaders. We gave them some tips on how to engage children via online learning and had a brainstorming session. Then we created Google documents to keep track of who was doing what regarding the 50 or so projects that were happening in the club program before shelter-in-place. We ended up continuing 18 of them — basically, the ones that were possible to deliver remotely.

A lot of our volunteers found themselves working from home, or running their own businesses from home, and taking care of their children at the same time. In addition to that, we were asking them to teach a project. That's the reality of volunteerism right now. In my first meeting with volunteers, I told them there was no pressure — that if they had a sliver of time to support young people, my staff and I were here to support them. Out of the 18 projects that happened, I would say that half of them are led by teenagers. One thing that has been crucial in the club program is staying connected. Because that's what kids are craving right now.


Paul Sakuma/AP Images for National 4-H Council

Fe Moncloa

California Agriculture: Obviously the coronavirus is a problem in a lot of ways. But does it in any sense represent an opportunity for youth development? Is it something you can make a virtue from?

Fe Moncloa: Well, one opportunity I see is that young people are learning new skills, like video-making — it's something they may have done in the past, but just for fun. Now they're getting really good at it. They're learning about lighting and sound. In the typical 4-H way, we ask them to make a video, and after they make it, we say "Well, you might want to consider this and this, and change this and that." So they're learning as they're doing it, which is our model. The other thing I have seen is teenagers learning how to engage younger children in fun, interactive ways via Zoom.

Karina Díaz Rios

Karina Díaz Rios, UC Cooperative Extension Nutrition Specialist at UC Merced

California Agriculture: How is the coronavirus pandemic affecting food security for people in California?

Karina Díaz Rios: This may sound counterintuitive because of the type and size of the agricultural activity in California, but access to nutritious food was an issue in many communities in California even before the pandemic hit. According to the latest reports from the Economic Research Service of the U.S. Department of Agriculture, about 10% of California households are food insecure, which means that they have inconsistent or limited access to enough food for an active, healthy life.

If you compare these numbers with the national food insecurity rate, which is about 12%, you would think that California is not in particularly bad shape. However, there's another story to tell. In particular segments of the population in the state, food insecurity is really a big issue, with some communities being affected at a rate as high as 40%, in the case of low-income Californians, or around 25% in some counties in the San Joaquin Valley.

The public health catastrophe we're dealing with right now has exacerbated these disparities. Distressing estimates indicate California has seen the largest increase in food insecurity during the pandemic, with Los Angeles County being at the very top across the nation. This means communities already affected by food insecurity are now even more prone to suffer the consequences of not having access to a quality diet — consequences such as malnutrition and a concomitant worsening of health.

California Agriculture: So the pandemic is affecting people's ability to get enough food to eat. Is it also affecting their ability to eat healthy food?

Karina Díaz Rios: Food-insecure people tend to spend more of their food money at convenience stores, where prices are often higher than the larger grocery stores and the variety and quality are usually lower. This means that the overall quality of the diet of food-insecure households is about 5% to 10% lower than households that are food secure. That doesn't sound like much, but the average diet quality of folks in the United States is already suboptimal — around 60 out of 100. If 100 is the highest-quality diet, 60 is not much more than halfway there. So a reduction of 5% to 10% is really consequential.

The issue is not that food-insecure people make bad choices. In buying certain kinds of food instead of others, people are making the right choices based on their circumstances. Shopping in convenience stores might be the logical action when time or other resources, like transportation or income, are limited — and when planning meals maybe isn't realistic because of lack of practice or other competing priorities. It's difficult to plan when your income is unstable.

California Agriculture: How does all this affect the work that you do?

Karina Díaz Rios: This is an area where there are challenges, but also opportunities. The Cooperative Extension army of nutrition educators is very well suited to help overcome some of the obstacles that the pandemic has posed for accessing resources, whether in-kind resources like food assistance or educational resources. They know their communities. They can identify the needs in their communities and help address them more easily than people who are not in such good touch with the community. Another extremely good thing about our Cooperative Extension system in California is that people are very creative. We have people who can come up with solutions in a heartbeat and implement them.

California Agriculture: Lots of children around the state won't be returning to school in the fall, at least at first. What effect does remote education, as opposed to in-school education, have on the food security issues that you cover?

Karina Díaz Rios: A large number of low-income students who qualify for food assistance and school meal programs are not going to get those meals if they don't go to school. There are efforts in several school districts to make sure that low-income children are actually receiving these meals. These efforts are particularly key right now, but it takes a great deal of planning and resources to make it happen. But also, these school meals only represent, at best, two-thirds of the daily caloric needs for children who get breakfast and lunch from school. So they can still be on a caloric deficit if they don't have enough food at home, which again, is more likely to be the case because of the pandemic.

California Agriculture: Do you foresee that the coronavirus is going to cause any long-lasting changes in the realm of nutrition? Or, after a vaccine is developed, do you imagine that things will more or less go back to the way they were?

Karina Díaz Rios: I am concerned that the people most affected by higher food insecurity due to the pandemic are going to be children. A lack of nutrients, even for a limited time, can affect children's ability to grow and thrive. So I just hope that these days are not going to have a lasting impact on these children — but it's a possibility.

— Lucien Crowder

Research highlights

Recent articles from the Agricultural Experiment Station campuses and UC ANR's county offices, institutes and research and extension centers.

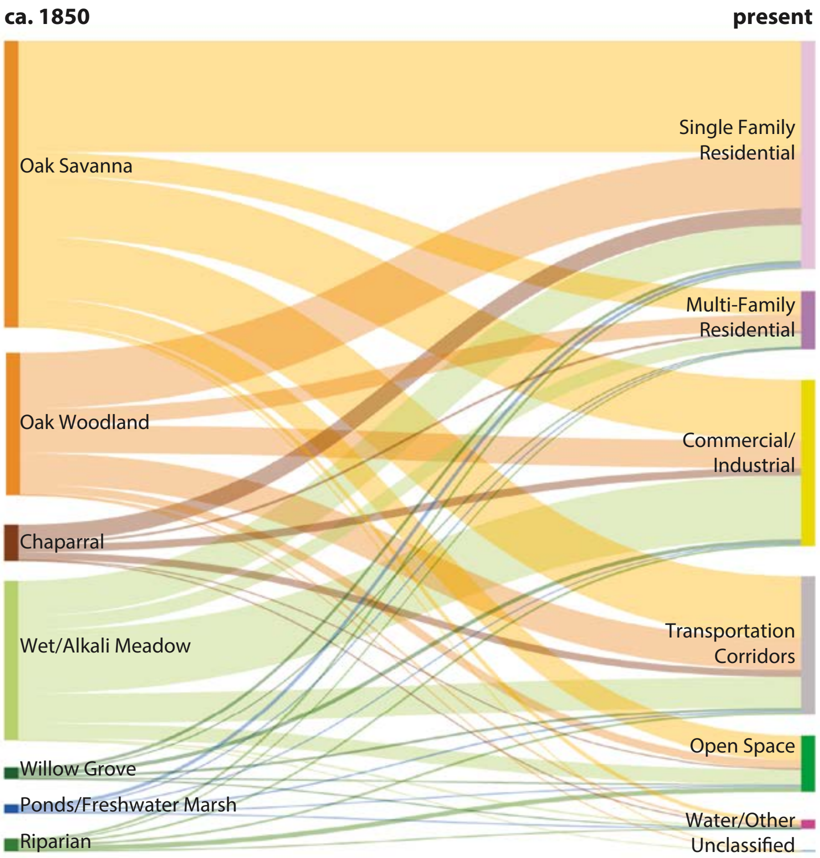
Online: https://doi.org/10.3733/ca.2020a0013

Study challenges hypothesis that urbanization increases carbon storage in Mediterranean climate zones

When landscapes are urbanized, they can lose much of their carbon storage potential. But because urbanization often entails irrigation and tree planting, some hypothesize that urbanization can lead to increased carbon storage. Little long-term research, however, has compared carbon storage in contemporary urban areas to carbon storage in the same locations before they were urbanized.

Researchers from UC Berkeley's Department of Geography and its Department of Environmental Science, Policy and Management endeavored to quantify and map aboveground carbon storage in California's Santa Clara Valley (also known as Silicon Valley), comparing the valley's aboveground carbon storage today to storage before the widespread Euro-American modification of the 19th century. Drawing on numerous historical archival sources, the researchers developed maps of the valley's land cover circa 1850, finding that about two-thirds of land was once covered by oak savanna and oak woodland habitats. The researchers, performing calculations that involved a host of factors such as density of tree stands and diameter of trees before urbanization, estimated that the study area's carbon storage before 1850 ranged between 784,000 megagrams and 2.2 million megagrams. Contemporary carbon storage in the study area is 895,000 megagrams. These results suggest that in Silicon Valley, urbanization has resulted in changes in aboveground carbon storage ranging from a nonsignificant 14% increase in carbon storage to a significant 60% decrease over the past 160 years or so.

The researchers write that their work challenges the hypothesis that aboveground carbon storage increases when Mediterranean-climate ecosystems undergo urbanization, irrigation and tree planting. Furthermore, they report that their research demonstrates the value of using historical sources from before 1900 to reconstruct the way that carbon storage and other ecosystem services have changed over long time scales.



Land cover/land use transformation in Santa Clara Valley, ca. 1850 to present day (ca. 2013). The thickness of each line corresponds to the total area that has undergone each transformation.

Beller EE, Kelly M, Larsen LG. 2020. From savanna to suburb: Effects of 160 years of landscape change on carbon storage in Silicon Valley, California. Landscape Urban Plan 195:103712. https://doi.org/10.1016/j.landurbplan.2019.103712

In Sugarloaf Creek Basin, soil water availability little changed by managed wildfire

In many forested areas in California's Sierra Nevada mountains, humans have suppressed fire since the beginning of the 20th century. Fire suppression has entailed several negative consequences, including reduced heterogeneity in the landscape and, due to high fuel loads, increasingly intense wildfires.

Managed wildfire — a policy of allowing wildfires in certain areas under certain weather conditions to burn unimpeded — is an increasingly common land management tool in California's forests. Managed wildfire, because it can reduce tree density and tree water use, can lead to increased groundwater storage, higher streamflow and greater availability of soil moisture. But little research has been conducted on the hydrologic effects of managed wildfire in watersheds such as those in the Sierra Nevada.

Researchers from the U.S. Geological Survey, the UC Berkeley Department of Environmental Science, Policy and Management and the UC Berkeley Department of Civil and Environmental Engineering studied the Sugarloaf Creek Basin, a watershed in Sequoia-Kings Canyon National Park. In this basin, fire appears to have occurred about every nine years between 1700 and 1900, with fire suppression beginning shortly before 1900. In 1968, the National Park Service adopted a policy of allowing wildfires ignited by lightning to burn; by 2016, 10 fires of 40 hectares or more had occurred within the basin. The researchers mapped the perimeters of all fires that had burned in the basin between 1952 and 2016 and — using plot measurements, remote sensing of vegetation and soil moisture measurements — characterized the response of vegetation and soil moisture to almost five decades of managed wildfire.

UC Berkeley researchers hike through a meadow in Sugarloaf Creek Basin. Under the right circumstances, allowing more fires on the landscape might help wet meadows such as this one expand in size, leading to more groundwater storage.

The researchers determined that fire in the basin over the study period had been limited to drier, mixed-conifer sites; that patches of overstory tree mortality caused by fire were limited in scope; and that fire had done little to remove trees in the middle and lower stratas. Fire had created few dense meadows; rather, fire more often had led to establishment of sparse meadow and shrub areas, whose soil moisture profiles are similar to those in nearby areas of mixed-conifer vegetation. Overall, compared to a nearby watershed that was both wetter and had burned more frequently, managed wildfire in the Sugarloaf Creek Basin had led to relatively little change in dominant vegetation and soil moisture response. The authors suggest that, during future wildfires, soil moisture increases within the basin might be encouraged by allowing greater tree mortality in areas adjacent to wetlands. Even then, they note, the hydrologic benefits of managed wildfire in a fairly dry watershed such as the Sugarloaf Creek Basin might be limited.

Stevens JT, Boisramé GFS, Rakhmatulina E, et al. 2020. Forest vegetation change and its impacts on soil water following 47 years of managed wildfire. Ecosystems. https://doi.org/10.1007/s10021-020-00489-5

Fluorescent compound helps intelligent weeders in celery fields

Because field-grown vegetables at the seedling stage are highly vulnerable to weed competition, weeds must be removed early in the crop cycle to prevent yield losses. But weed control proves challenging for many growers because farm labor is often in short supply and effective vegetable herbicides sometimes aren't available. These challenges have sparked interest in intelligent weeders — autonomous machines that remove weeds while leaving crops unharmed. But intelligent weeders often struggle to differentiate weeds from vegetable crops. This challenge might be overcome through crop signaling, a technique that allows target crops to be identified rapidly and accurately.

Researchers including Wen-Hao Su and David C. Slaughter of the UC Davis Department of Biological and Agricultural Engineering, and Steven A. Fennimore of the UC Davis Department of Plant Sciences, conducted research into the ability of rhodamine B (Rh-B), a fluorescent compound with unique optical properties, to help smart machines reliably detect locations in fields of vegetable crops. The researchers applied Rh-B, in various doses and for various durations, to celery roots before transplantation to the field. The researchers assessed Rh-B transport in plants; the compound's photostability; and the compound's potential impact on seedling growth on the farm.

The researchers found that Rh-B, when absorbed through celery roots, moved throughout the plant in 24 hours. Higher doses of Rh-B led to more absorption, but also injured plants. The researchers determined that treating celery roots with a solution containing 60 parts per million of Rh-B was safe for plants and led to good photostability in seedlings for about five weeks after transplanting. Such a dose allowed a machine vision system to rapidly identify celery plants at the early growth stage and therefore to differentiate between crops and weeds.

Su W-H, Slaughter DC, Fennimore SA. 2020. Non-destructive evaluation of photostability of crop signaling compounds and dose effects on celery vigor for precision plant identification using computer vision. Comput Electron Agr 168:105155. https://doi.org/10.1016/j.compag.2019.105155

Camera traps used for estimating population demographics of deer

Populations of black-tailed deer have declined in the western United States over the last several decades. Researchers from UC Berkeley and UC Davis conducted research to test whether camera traps can be used to quantify population characteristics of black-tailed deer. The researchers, using images of naturally occurring physical characteristics of deer — including antler patterns for males and ear notches for females — developed a model that allowed them to estimate deer abundance, sex ratios, size of individuals' home ranges and more.

The researchers placed 13 cameras at water sources on a private ranch in California. They placed bait in front of each camera once a month. Between May 2012 and January 2013, they recorded 9,000 visits by 50 individual deer. They estimated deer populations in the area at 7.7 animals per square kilometer in the summer and 8.6 in the fall; a sex ratio of 12.5 males to 100 females; and a ratio of 47 fawns to 100 adult females. According to the researchers, their work demonstrates that commonly deployed camera traps can help to quantify population characteristics and monitor populations — and can aid in decision making about harvesting and habitat management.

Macaulay LT, Sollmann R, Barrett RH. 2019. Estimating deer populations using camera traps and natural marks. J Wildlife Manage 84(2):301–10. https://doi.org/10.1002/jwmg.21803

Land managers weigh in on weed invasion

Working rangelands and natural areas, which account for about 64% of land in the United States, provide valuable environmental goods and services. Weed invasion in such areas poses significant ecological and economic threats, including reduced livestock forage quality, depleted soil and water resources and reduced plant diversity. Though invasive weed control has been the subject of considerable research, research has largely neglected to tap the very extensive weed-management experience of restoration practitioners and land managers.

To redress this gap, researchers from UC Cooperative Extension (UCCE), the UC Davis Department of Plant Sciences and the University of Arizona, with support from the California Department of Pesticide Regulation, surveyed more than 250 rangeland managers and restoration practitioners in California. The practitioners were asked to identify their land management goals; to rate the effectiveness, vis-à-vis weeds, of management practices such as prescribed fire, grazing, herbicide use and seeding; and to identify barriers to implementing specific practices.

Practitioners identified 196 problematic plants. The two most often mentioned were yellow starthistle and medusahead. The highest-rated management practice was herbicide use — but respondents identified several barriers to using herbicides, including cost and public perception. Many respondents expressed interest in grazing as a management tool for invasive and woody species, but 19% of those who had tried it did not believe it was effective. The researchers found that, across management practices, issues such as permitting and livestock water availability represented barriers to implementation. The researchers suggest that, because the land management goals and issues of concern identified by respondents were similar across the state, targeted research and outreach efforts involving both scientists and land managers can provide benefits across California's rangelands and natural areas.

Schohr TK, Gornish ES, Woodmansee G, et al. 2019. Practitioner insights into weed management on California's rangelands and natural areas. Environ Manage 65:212–9. https://doi.org/10.1007/s00267-019-01238-8

Enhancements to promote bee pollination of crops may help bees more than crops

Efforts to support ecosystem services — that is, the ecosystem functions on which human well-being relies — are often portrayed as compatible with efforts to conserve biodiversity. But if just a few species are adequate for local delivery of ecosystem services, support for those services may benefit only a small set of common species. For example, some bees provide ecosystem services in the form of crop pollination — but if agricultural conservation efforts benefit only the bee species that pollinate crops, these efforts may fail to protect bee diversity broadly.

A national team including four researchers from the UC Davis Department of Nematology and Entomology conducted research over two years at farms in California, Michigan and Oregon to determine whether abundance of wild bees is increased by enhancing the richness and abundance of flowers in habitat adjacent to crops. At each study site, the researchers seeded some field edges with flowering forbs and left other edges unenhanced. Across the four regions, the researchers collected nearly 4,200 wild bee specimens. They found that bee communities in enhanced field edges, compared to those in control edges, were more abundant, taxonomically and functionally diverse and compositionally different. At the same time, they found that enhancements did not increase the abundance or diversity of bees visiting crops — that is, enhancement did not change the supply of pollination services. They conclude that attempts to promote crop pollination may deliver multiple biodiversity benefits but may not benefit crop pollinators, at least over the duration

In a survey of California rangeland managers and restoration practitioners, medusahead (along with yellow starthistle) was identified as the most problematic invasive plant.

Elena Zhukova

considered in this study (previous work in Michigan has shown that the benefits to crops from enhancing habitats can take years to accrue). It is important to safeguard biodiversity and ecosystem services. More research will show how best to comanage pollinators and crop pollination.

Nicholson CC, Ward KL, Williams NM, et al. 2020. Mismatched outcomes for biodiversity and ecosystem services: testing the responses of crop pollinators and wild bee biodiversity to habitat enhancement. Ecol Lett 23(2):326–35. https://doi.org/10.1111/ele.13435

E. coli survival on romaine depends in part on time of inoculation

Eating plant-based foods contaminated with pathogenic strains of *E. coli* can lead to gastroenteritis; leafy lettuce in particular has been implicated in outbreaks of gastroenteritis around the world. Some outbreaks in the United States have been traced to California and Arizona, where most of the nation's leafy greens are grown.

Contaminated water is often the route by which plants are exposed to *E. coli*. Knowing the rates at which pathogens such as *E. coli* die off, after they have contaminated plants, is useful for making microbial risk assessments and for developing strategies to reduce the risk posed by pathogens in agricultural water.

Low solar radiation, high humidity and moisture on leaves are thought favorable for the persistence of *E. coli* on plant surfaces. At night, in California's Salinas Valley, humidity levels rise and water condenses on leaf surfaces. In the daytime, factors such as higher temperatures and lower humidity cause leaf surfaces to dry. Researchers from the UC Davis Department of Food Science and Technology, the Western Center for Food Safety at UC Davis and UCCE in Monterey County conducted experiments over three years to determine the effect that time of inoculation, age of plants and inoculum levels exert on *E. coli* survival.


Tyann Blessington

Researchers inoculate four-week-old romaine lettuce plants with *E. coli*, a pathogen associated with outbreaks of gastroenteritis. *E. coli* survival can be affected by time of inoculation, age of plants and inoculum levels.

The researchers inoculated romaine lettuce plants with the attenuated pathogen (a form that cannot cause illness). Plants were either four or six weeks old; inoculation occurred either at night or in the morning; and inoculation levels were either low or high. They found that *E. coli* populations declined faster when inoculation occurred in the morning than at night — but that after two days and seven days, similar numbers of *E. coli* cells could be retrieved from plants. After seven days, *E. coli* cell numbers were significantly higher on six-week-old than on four-week-old plants — indeed, the researchers found that the age of the plant influenced pathogen survivability more than did time of inoculation. They further report that, even if low levels of pathogen are introduced to plants, the risk of pathogen survivability is greater when contamination occurs under humid conditions, near harvest or at night.

Moyne A-L, Blessington T, Williams TR, et al. 2020. Conditions at the time of inoculation influence survival of attenuated Escherichia coli O157:H7 on field-inoculated lettuce. Food Microbiol 85:103274. https://doi.org/10.1016/j.fm.2019.103274

Tool developed, suitable for citizen scientists, to assess drinking water access in schools

Under the provisions of the Healthy, Hunger-Free Kids Act, schools that serve meals must provide students free access to drinking water in cafeterias at mealtimes, in part because intake of sweetened beverages can cause obesity and tooth decay. A high proportion of schools reports compliance with the law's provisions, but direct observation by researchers has indicated that only 48% to 58% of schools comply. Furthermore, the presence of drinking water might not result in greater water consumption if the water itself is unappealing, the flow of water is poor or drinking vessels are not provided.

The gold standard for assessing drinking water availability in schools is direct observational auditing by researchers, but audits of this kind are resource-intensive. Researchers including Lorrene Ritchie, the director of UC ANR's Nutrition Policy Institute and a UCCE specialist, and Christina Hecht, a senior policy advisor at the Nutrition Policy Institute, undertook to develop a more cost-effective photography-based tool, based on the Harvard Water Audit tool and usable by citizen scientists, that could provide accurate information about water access in schools. Their research also entailed efforts to assess the validity and feasibility of the tool.

Researchers using the tool photographed water sources at schools, including features that researchers hypothesized to be associated with students' intake of water. These features included locations of water sources, evidence of wear on drinking water sources, cleanliness and water flow. Researchers also performed observational audits of drinking water conditions at the same schools. The tool was reviewed by experts, pilot-tested, adapted as necessary and ultimately used at 30 schools in the San Francisco Bay Area. The photographs were then coded, and the information derived from them was compared to information gathered through observational audits. The results of the two methods were found to agree very well on almost all characteristics measured (though agreement was less strong for cleanliness of and wear on water sources). According to the researchers, the evidence suggests that the photo-evidence tool provides a valid, more cost-effective assessment of drinking water access in schools, and holds excellent promise for use by citizen scientists.

Patel AI, Podrabsky M, Hecht AA, et al. 2020. Development and validation of a photo-evidence tool to examine characteristics of effective drinking water access in schools. J School Health 90(4):271–7. https://doi.org/10.1111/josh.12873

OUTLOOK

California's agritourism operations expand despite facing regulatory challenges

Surveys show that agritourism operators in California need increased support from their local governments and the state regarding regulatory requirements.

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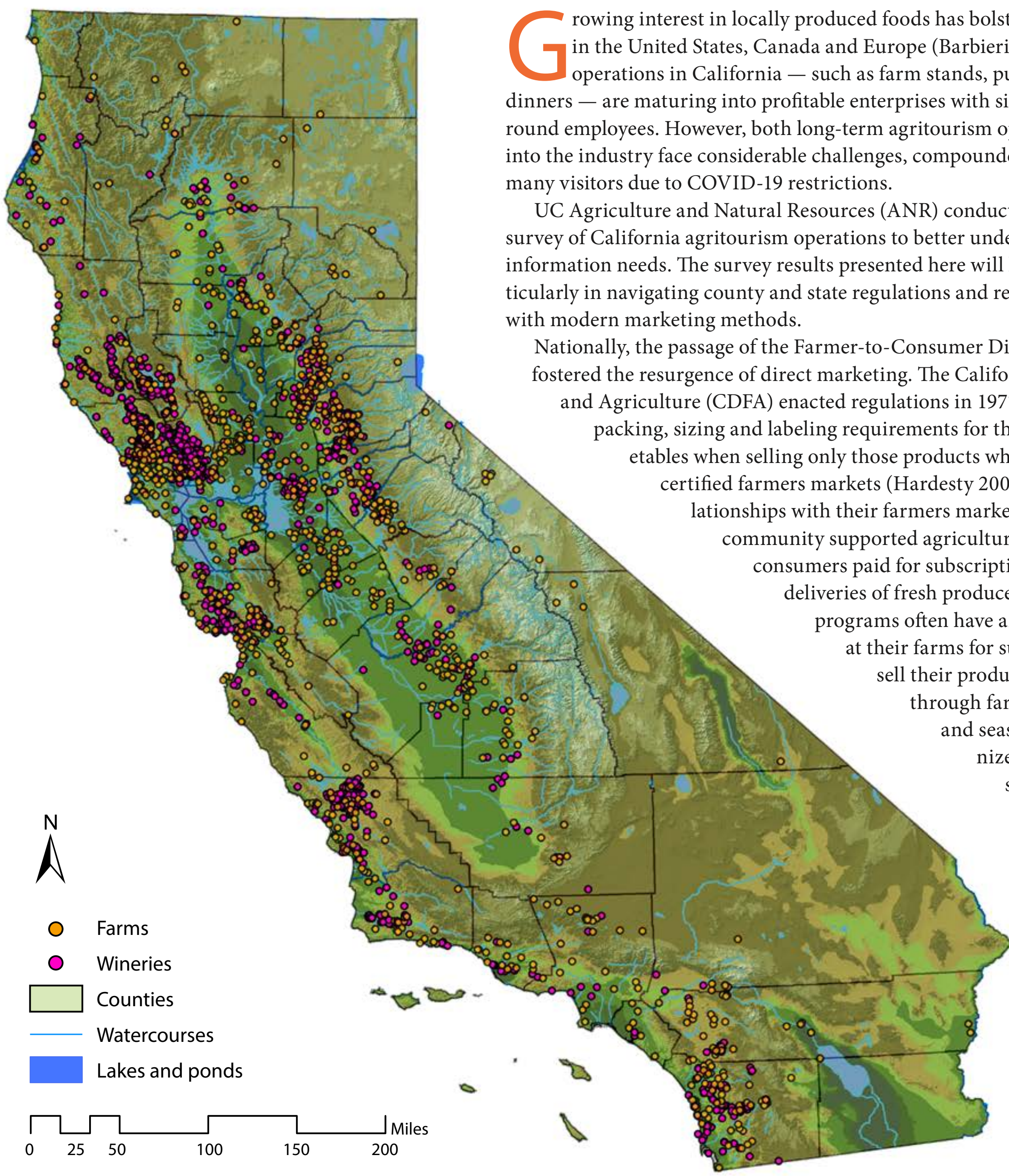
Online: https://doi.org/10.3733/ca.2020a0026

Growing interest in locally produced foods has bolstered demand for agritourism in the United States, Canada and Europe (Barbieri 2013). Many agritourism operations in California — such as farm stands, pumpkin patches and farm dinners — are maturing into profitable enterprises with significant revenue and year-round employees. However, both long-term agritourism operators and new entrants into the industry face considerable challenges, compounded by the inability to host many visitors due to COVID-19 restrictions.

UC Agriculture and Natural Resources (ANR) conducted its second statewide survey of California agritourism operations to better understand their challenges and information needs. The survey results presented here will help to target outreach, particularly in navigating county and state regulations and reaching potential customers with modern marketing methods.

Nationally, the passage of the Farmer-to-Consumer Direct Marketing Act of 1976 fostered the resurgence of direct marketing. The California Department of Food and Agriculture (CDFA) enacted regulations in 1977 that exempt farmers from packing, sizing and labeling requirements for their fresh fruits, nuts and vegetables when selling only those products which they grow themselves at certified farmers markets (Hardesty 2007). As farmers developed relationships with their farmers market customers, many initiated community supported agriculture (CSA) programs, in which consumers paid for subscriptions for weekly or bi-monthly deliveries of fresh produce from the farm. These CSA programs often have an annual or bi-annual event at their farms for subscribers. Many farms also sell their products directly to consumers through farm stands, U-pick operations and seasonal festivals. Some organize farm dinners, tours, workshops, demonstrations and children's day camps, or offer their farms as wedding or retreat facilities, and some have even developed farmstay programs.



California agritourism and winery operations. Data collected and map produced in May 2015 by the UC Small Farm Program.

UC ANR's agritourism efforts

The University of California's Small Farm Program (SFP) began supporting agritourism in the mid-1990s with two purposes: (1) enhance the economic viability of smaller-scale farms by diversifying their market channels; and (2) connect the urban population to agriculture. It defined agritourism as "any income-generating activity conducted on a working farm or ranch for the enjoyment and education of visitors". In a 1999 newsletter, the then-director, Desmond Jolly, noted that agritourism involves linking agriculture to consumers, which ". . . requires a new set of skills that are somewhat different from those typical of more conventional agriculture." In 2000, the SFP launched its CalAgTour.org website, which continues on today to provide a searchable directory of 767 agritourism operations across the state, along with a calendar of agritourism events. Farms can list their agritourism operations on CalAgTour.org at no cost. In 2011, the then-leaders of the UC ANR Agritourism Work Group, UC ANR Advisors Holly George and Ellie Rilla, published the second edition of the UC ANR handbook *Agritourism and Nature Tourism in California*, which has been distributed extensively to participants at UC ANR agritourism workshops.

Surveys of California agritourism operations

The SFP conducted the first statewide survey of agritourism operations in 2009 after compiling a list of 1,940 potential agritourism operations. The overall purpose of the survey was to provide data for determining agritourism extension program priorities, by quantifying the extent of agritourism activities and identifying major opportunities and challenges that agritourism operators are facing. The results were published in 2011 in this journal (Rilla et. al. 2011).

In 2015, the SFP partnered with Colorado State University on a USDA National Institute for Food and Agriculture project to conduct a similar survey of agritourism operations in both states. A list of more than 2,000 potential agritourism operations in California was compiled. From this list, 750 nonwinery operations and 500 winery operations were randomly selected to be surveyed. The questionnaire was mailed in March 2015; an online survey was also sent.

The following information relates to the 164 respondents who indicated that they generated revenue of at least $1,000 from their agritourism operation in 2014. The lack of a comprehensive database of agritourism operations in California continues to be a barrier to analyzing the representativeness of the survey respondents.

Like California agriculture in general, agritourism operators tend to be older than the general population; 55% were between the ages of 46 and 65, 28% were 66 or older, 15% were between 26 and 45 years old, and 2% were 25 years old or younger. Ninety-three percent had some college education, with over a quarter of the respondents having graduate degrees. Forty-one percent of the operations were located on the coast, 31% in the Central Valley and 28% in the foothill, mountain and desert regions.

Forty-one percent of the operations generated at least $100,000 in gross annual agritourism revenue (fig. 1). This is a considerable increase from the 27% reported in the 2009 survey; most of the increase is probably attributable to the fact that 40% of the 2015 survey questionnaires were sent to wineries, which sell higher value product than most agritourism operations. Unfortunately, the number of winery respondents in the 2015 survey cannot be determined.

While more than one-third of the agritourism operations had been operating for 20 or more years, one-fourth were less than 5 years old. Experience tends to increase an agritourism operation's revenues; 47% of those with agritourism operations for 20 or more years earned at least $100,000 in agritourism revenues, compared to only 25% of those operating less than 5 years.

Twenty-two percent of the operations were open between 101 and 250 days during 2014, while 37% were open more than 250 days. Not unexpectedly, agritourism revenues tend to increase as the number of days they are open rises; two-thirds of the operations that were open more than 250 days generated at least $100,000 in agritourism revenues while only two operations open 35 days or less earned at least $100,000.

Most of the visitors to California's agritourism operations are local residents. Almost half (47%) of the visitors were from the same county while one-fourth

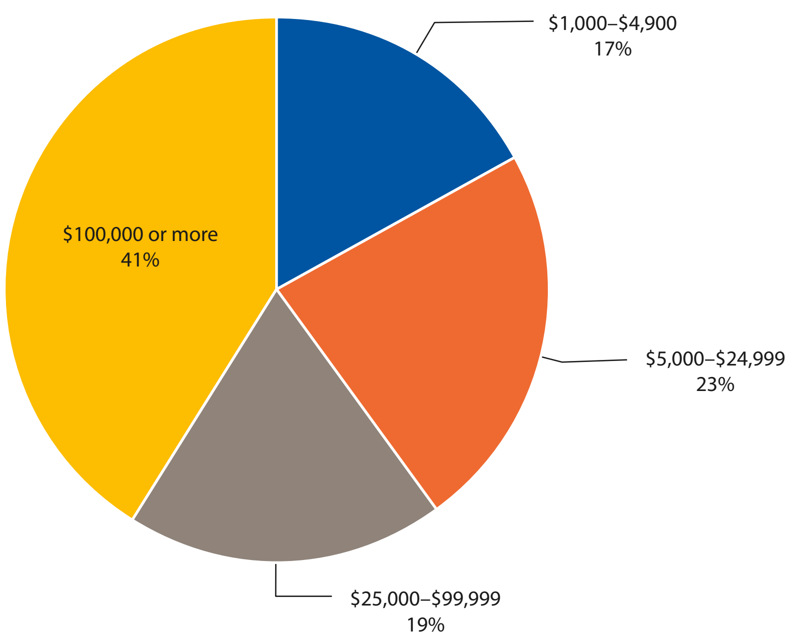


FIG. 1. Agritourism revenue distribution among agritourism operations (percent of respondents earning $1,000 or more).

were from a neighboring county; 10% were from other states and 4% were from other countries.

Agritourism operations continue to offer a very diverse range of activities. Respondents were asked to indicate what percentage of their agritourism revenues came from each of the following five categories:

- On-farm direct sales (U-pick, farm stand, farm store selling fresh fruits, nuts, vegetables, herbs, nursery products, Christmas trees, flowers, meats, eggs or processed fruit or vegetable products, dairy, fibers, wine, beer, spirits, juices, oil, baked goods, soaps, lotions or any other products)
- Accommodations/lodging (farm stays, bed and breakfast inn, vacation rental, guest ranch, camping, cabins, yurts, sheep wagons)
- Entertainment/special events (weddings, farm dinners, family reunions, retreats, festivals, barn dances, corn or other mazes, haunted houses, sports events, games, concerts, pig races, pony rides, hay rides, train rides, etc.)
- Outdoor recreation (bicycle rides, picnicking, swimming, hunting, fishing, bird watching, photography, snowmobiling, horseback riding, skeet shooting)
- Educational activities (farm or ranch work experience, camps, classes, tours, tastings, demonstrations, workshops, petting zoos, egg gathering, etc.)

By far, the most frequently offered agritourism activity is direct sales of agricultural products, with 89% engaged in this activity; the next most popular activities were education (44%) and entertainment/special events (43%). The least prevalent activities were accommodations (17%) and outdoor recreation (12%). Almost two-thirds (63%) of respondents reported receiving 50% or more of their agritourism revenue from direct sales; this 50% threshold was used to define an operation's primary activity. Not surprisingly, direct sales were the most common primary activity (fig. 2). In addition to having a primary revenue source, most agritourism operations also offer other activities that attract customers and generate revenue. The newest entrants into the agritourism industry (less than 5 years old) are trending toward offering more experience-based activities, such as entertainment/special events, education and accommodations, while the older agritourism operations are more likely to focus on direct marketing of their farms' products.

Marketing and challenges

Agritourism operations need to engage in marketing to attract visitors and generate revenues. The two most used marketing tools are also those that they rated as most effective — word of mouth and website (table 1). Social media has increasingly become a critically important promotion tool for agritourism operations (since this survey was conducted, it is highly likely that Facebook and Twitter have increased significantly in usage among agritourism operations). Social media experts have described how potential visitors usually search first using Google or YouTube, visit websites, Facebook pages or YouTube videos to learn about the operation, and then will still check out the reviews on TripAdvisor or Yelp. Increasingly, potential visitors use mobile devices to search, both at home and while traveling. The CalAgTour.org website was redesigned to be mobile responsive; it automatically resizes when used on a cell phone. During the year ending June 30, 2020, 43% of new CalAgTour.org visitors used a mobile device, whereas in the year ending June 30, 2014, only 20% of new visitors used a mobile device.

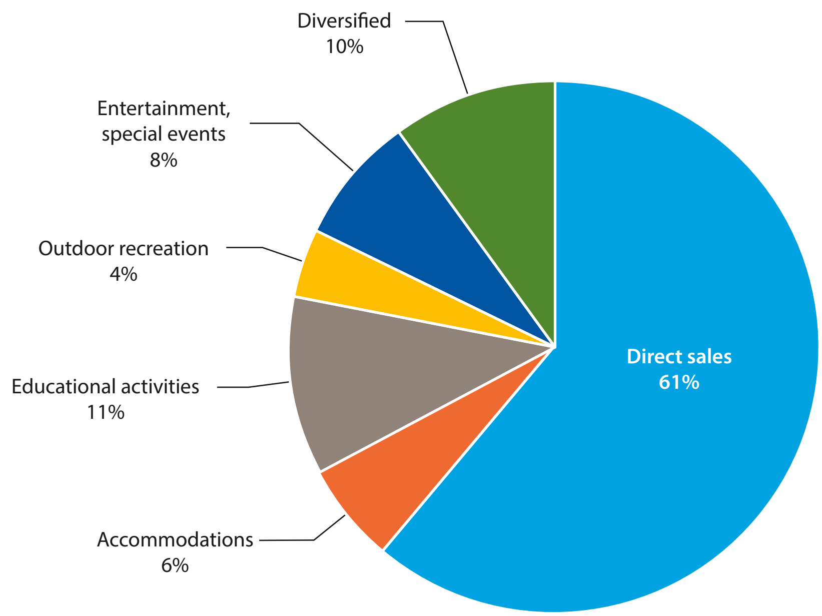


FIG. 2. Primary activity of California agritourism operations (percent of respondents).

TABLE 1. Marketing tools used by agritourism operations

Marketing Tool	% used	% rating very effective
Word of mouth	98	64
Website	95	42
Feature story	85	37
Direct mail or email	74	35
Referrals from other businesses	92	32
Facebook and/or Twitter	85	26
Farm or wine trail association	81	26
Highway sign	54	24
Sign outside business	87	23
Trip Advisor and/or Yelp	71	20
Paid advertising	73	19
Regional or state tourism guide	82	14
Print brochures, posters, fliers	81	14
Chamber of commerce or visitor bureau referrals	82	12

Agritourism enables farms to diversify their revenue sources; however, this diversification can involve multiple challenges. The most significant challenges reported in 2015 by California's agritourism operators were similar to those in the 2009 survey. The challenge that was most frequently rated as "very challenging" in 2015 was "city/county permitting and zoning" (34%), followed by "other state and local regulations" (28%). In the same survey conducted in Colorado, these issues were considerably less problematic, with 17% and 19%, respectively, of Colorado's agritourism operations reporting them as "very challenging" (Gaede et al. 2015).

The preliminary findings from the 2019 National Agritourism survey also confirm that regulations are more challenging to California's agritourism operations than to those in other states.

The preliminary findings from the 2019 National Agritourism survey also confirm that regulations are more challenging to California's agritourism operations than to those in other states (Chase et al., unpublished data). In that survey, 49% of California's agritourism operations reported that "city/county zoning and permitting" were "very challenging", compared to 23% of the agritourism operations nationwide. Similarly, 47% of California's agritourism operations reported that "state/local regulations" were "very challenging", compared to 28% of the agritourism operations nationwide. In California, counties differ considerably regarding the strictness/cost of their zoning and permitting requirements, as well as how rigorously they enforce the state's environmental health regulations. County officials are often invited to attend UC ANR agritourism workshops, in an effort to promote dialog and understanding between regulators and agritourism operators.

The COVID-19 pandemic is the most recent challenge facing agritourism operations; many — including wineries — have canceled on-site activities and sales. On May 8, CDFA issued a detailed set of COVID-19 guidelines for farms with farm stands and U-pick operations (CDFA 2020). Nevertheless, the pandemic has also been described as generating a rebirth of the local farm movement. Demand for fresh local produce has increased as new customers are learning to cook instead of eating out (Hiller 2020). Numerous agricultural organizations have responded with ways to assist smaller-scale farms. F.E.E.D. Sonoma, a micro-regional food distributor, transformed itself from serving Bay Area restaurants into a CSA for Sonoma County residents. Sonoma County Farm Trails created an online portal to enable its members to market their products through the following channels: farm stands, CSAs accepting new members, local delivery and drop points, and online orders and delivery. The CalAgTour.org directory (UC ANR 2020) recently added a blog describing the responses of eight agritourism operations to the COVID-19 pandemic. Only one of the eight operations — a pumpkin farm in Contra Costa County — decided to temporarily close its agritourism operations for this fall. The others decided not to offer school tours in the fall. However, they are implementing social-distancing measures, as they promote their farms as safe family attractions in the outdoors.

In conclusion

Agritourism is an important component of California agriculture. UC ANR has been conducting agritourism research and outreach for almost 30 years. While agritourism enterprises are a viable source of diversification for California's farms and ranches, they also contribute to rural economies and educate the public about agriculture and the food that they eat. Some counties have added agritourism into their general plans. However, these survey results indicate that California's agritourism operations need increased support from their local governments and the state regarding regulatory requirements.

More information about agritourism in the western United States is available at: https://ucanr.edu/sites/agritourism and https://agritourism.localfoodeconomics.com. CA

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LETTER

Complexity in 4-H youth enrollment: A response to Davy et al. (2020)

Online: https://doi.org/10.3733/ca.2020a0025

California Agriculture, April–June 2020 issue

In "Traditional market-animal projects positively influence 4-H enrollment", Davy et al. (April-June 2020) use a general linear model to explore the influence on 4-H enrollment of several variables: year, region, population density, and whether the young person enrolled in a beef, sheep or swine project. Their core finding is a statistically significant relationship between swine, sheep and cattle project and 4-H community club enrollment.

My critique of the paper is not with the finding that animal projects have a relationship with 4-H enrollment (previous analyses also show they do; Lewis et al. 2015), but rather that the authors do not build on the extensive literature and oversimplify the complex human dynamics involved in 4-H enrollment. These flaws have important consequences, as I detail here.

First, the research findings are not generalizable to 4-H enrollment processes (that is, they do not have "ecological validity"; see Wegener and Blankenship 2007). The authors ignore (or omit) a variety of important factors known to be involved with youth participation in 4-H, including individual psychological factors (of the youth and their parents), 4-H programmatic factors, as well as social and cultural influences. They also did not include in their analysis other common 4-H projects (e.g., foods, arts and crafts, rabbits, poultry or environmental education) that also positively correlate with enrollment. By not attending to these dynamics, their core finding — that animal projects correlate with enrollment — is not, on its own, actionable by 4-H professionals who wish to increase enrollment.

A second issue is potential adverse consequences given the context of 4-H in California today. The Davy et al. (2020) paper comes at a crucial moment. Due to UC ANR's new funding formula for 4-H staff positions — in which funding for county-based community educators depends partially on that county's 4-H enrollment — as well as concerns about resuming in-person programming during the COVID-19 pandemic, pressure to increase enrollment is high. A possible negative consequence of Davy et al. is that our colleagues may urge a shift away from non-livestock subject matter, even when other subject areas would be more meaningful and relevant to a target youth population (e.g., reaching diverse youth with culturally relevant curriculum; or in areas where raising livestock animals may be less relevant or feasible). For example, California 4-H enrollment data shows that while the number of young people undertaking animal projects has grown 42% over the past decade, youth enrollment in health projects has increased 726%, civic engagement by 168% and technology/engineering by 125% (Lewis 2018).

The literature shows that participation in 4-H is a fluctuating and dynamic process.

Before joining 4-H, youth and families must become aware of 4-H, requiring marketing and outreach. Youth join 4-H for a variety of reasons: a desire to have fun, to meet new friends, participate in projects, engage in community service, etc. (Harrington et al. 2011; Wingenbach et al. 2000).

Attention to retaining members is important in minimizing dropouts. Reasons cited for dropout include: families not understanding the 4-H program, feeling unwelcome and that they do not belong, reduced time availability, not having the financial ability to pay for activities, and not having a positive learning experience in their projects (Defore et al. 2011; Harrington et al. 2011).

Drawing on a decade of California 4-H enrollment data, Russell and Heck (2008) found that "long-term 4-Hers are the minority within the program, and that there is significant 'churning' in enrollment across all the ages" (p. 8). Lewis (2018) found the average retention rate was 62% across all members (excluding youth who "aged-out" at 19 years of age). Almost half (49%) of 4-H membership are first year members (Lewis et al. 2015). The prevalence of first year dropout is well-documented by existing literature (Hamilton et al. 2014; Harder et al. 2005; Russell and Heck 2008).

Important questions remain to be explored regarding 4-H enrollment; some include: (a) examination into the recruitment and retention of youth of color, (b) investigation into recruitment of adolescents and ensuring the program meets their developmental needs, and (c) inquiry into retention and the first-year member dropout phenomenon. While these are phrased as questions of enrollment, they really are questions of program quality, which will require 4-H professionals to make organizational, cultural and programmatic adaptations to better attract and serve youth.

The first strand of research was undertaken with the UC 4-H Latino Initiative (see Worker et al. 2019). The second strand is a high priority in the 4-H Strategic Plan 2018-2028, although no active statewide projects are underway. The third strand is being researched by 4-H academics who initiated the youth retention study, a multi-state research project to explore the first-year dropout phenomenon and the challenges new members encounter. Preliminary findings from an analysis of a decade of California 4-H enrollment data are that youth were more likely to return a second year when they were involved in leadership roles (e.g., club officer, teen leader), involved in more than one project, or were younger, male, white or lived in a rural area or farm (Lewis et al. 2015). Additionally, project participation was tested to determine its influence on reenrollment; for example, youth enrolled in an animal project (livestock, small animal or animal-related projects such as veterinary science or embryology) were 55% more likely to reenroll another year than youth who did not undertake an animal project.

In closing, Davy et al.'s findings may lead our colleagues to believe that cattle, swine or sheep projects are a "quick fix" to increasing 4-H enrollment, when in actuality enrollment is a multifaceted phenomenon. They should have moderated their claim to acknowledge the inherent limitations in their analysis and the complexity of their subject.

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Reply to: Complexity in 4-H youth enrollment: A response to Davy et al. (2020)

The core misunderstanding of the rebuttal of the article "Traditional market-animal projects positively influence enrollment" is the notion that this paper lacks practical application.

Our paper investigated the importance of three livestock projects — beef, sheep and swine — on enrollment. The paper does not say these are the only factors influencing 4-H enrollment.

Much of the research presented in the rebuttal reports averages to survey responses with standard deviations. The author apparently would prefer to use these methods to investigate the various socioeconomic factors that influence 4-H enrollment — which is fine, but a different topic. To illustrate, Worker notes that "For example, California 4-H enrollment data shows that while the number of young people undertaking animal projects has grown 42% over the past decade, youth enrollment in health projects has increased 726%, civic engagement by 168%, and technology/engineering by 125% (Lewis 2018)." These numbers as a percent increase are relatively meaningless without some context. For example, if the number of youth interested increased from 10 to 73, the increase would be 730%, but would still be small in terms of project numbers.

It is true that other variables potentially could have been explored. We chose to examine the three market animal projects referenced above. How these projects influence enrollment was the question that we wanted answered, and our analysis offers a clear answer. The literature cited in the rebuttal does not answer this question. Most of the other topics brought forth in the rebuttal are not germane to the topic of how these market animal projects influence enrollment.

Our paper presents practical and actionable data. Although these projects are traditional, it is important to make sure they are attended to, and, because of their multiplicative effect on enrollment, to increase their numbers when possible. In short, these three market animal projects absolutely warrant attention.

Attention to these projects can easily be made in the day-to-day management of 4-H. For example, if a barrier to participating in a project exists, we can — and in many cases already do — offer solutions to these barriers. If a leader doesn't exist to assist in a project, find one. If it is difficult to be a leader or takes too much time, develop avenues to make it easier or take less time to be a leader. In one county where funding was an issue, a no-interest loan program for project steers was developed. These efforts don't have to take all our time, but a little time spent can yield results.

The 4-H program does not have a monopoly on market animal projects. Such projects can also be completed in FFA, Grange or independently. The ecological validity of this paper is that we can now quantify these livestock projects' importance to enrollment, and we ignore them at the peril of 4-H enrollment.

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Larry Forero
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Nate Caeton
UC Youth Development Advisor, Shasta, Trinity and Tehama counties

RESEARCH ARTICLE

Surveys of 12 California crops for phytoseiid predatory mites show changes compared to earlier studies

In phytoseiid samples from 25 counties from 2000 to 2018, the western predatory mite, long recognized as an important biological control agent, was found in relatively low numbers.

by Elizabeth E. Grafton-Cardwell, Walter Bentley, Mary Bianchi, Frances E. Cave, Rachel Elkins, Larry Godfrey, Ping Gu, David Haviland, David Headrick, Mark Hoddle, James McMurtry, Maria Murrietta, Nicholas Mills, Yuling Ouyang, Carolyn Pickel, Stephanie Rill, Menelaos C. Stavrinides and Lucia G. Varela

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Abstract

Phytoseiid mites are key predators in agricultural crops. However, not all species regulate pest populations below economic thresholds, and therefore knowledge of which species are associated with particular crops aids pest control recommendations. Surveys of 12 crops across six geographical regions of California demonstrated that phytoseiid species varied by crop and geographical location, with subtropical crops exhibiting the lowest species diversity and grape the greatest. The western predatory mite, *Galendromus occidentalis*, long cited as a dominant species in California crops, was not found to be the major species in most situations. *Euseius stipulatus*, a species introduced in the 1970s, was found in the surveyed crops in many areas of the state and appears to be displacing *E. hibisci* along the south coast.

Predatory mites in the family Phytoseiidae are important predators of pest mites in agricultural crops, regulating to varying levels populations of pest spider mites (Tetranychidae), as well as small insects such as immature thrips (McMurtry and Croft 1997). There are more than 2,000 described species of phytoseiids, and probably many more are yet to be discovered. The extensive monograph of Schuster and Pritchard (1963) on the Phytoseiidae of California described 52 species, and about 16 additional species have been discovered or introduced since.

The food habits and lifestyles of phytoseiids vary considerably but can be categorized as follows: Type I phytoseiids are highly specialized predatory mites in the genus *Phytoseiulus* that feed almost exclusively on heavy-web–spinning tetranychid spider mites. Type II phytoseiids are specialized predatory mites

Phytoseiulus persimilis, a predatory mite (left), next to a twospotted spider mite. This highly specialized predator was most common in raspberries and strawberries.

Jack Kelly Clark

represented by *Galendromus* species and some species of *Neoseiulus*; they tolerate webbing and prefer spider mites but also prey on other groups of mites such as eriophyids (rust or bud mites), tarsonemids and tydeiids, as well as feed on pollen. Type III phytoseiids in the genera *Amblyseius*, *Typhlodromalus*, *Typhlodromus* and *Metaseiulus* avoid the heavy webbing produced by *Tetranychus* species and instead feed on mites such as *Panonychus* species (red mites), eriophyids, tarsonemids and tydeiids and also on thrips, whiteflies and other small insects, and on pollen, fungi and plant exudates. Type IV phytoseiids in the genus *Euseius* are highly adapted to pollen and leaf sap feeding, often showing rapid population increases during leaf flush and flowering periods, but may help suppress non-web-spinning spider mites and thrips (McMurtry and Croft 1997; McMurtry et al. 2013).

Type I and II phytoseiids have adaptations to move through spider mite webbing and have demonstrated

TABLE 1. Species of phytoseiid predatory mites found in 12 permanent or semipermanent cropping systems in California

Host plant	Collection years	Counties	Site-years*	Seasonal samples†	No. of mites	I *Phytoseiulus persimilis*	I *Typhlodromina eharai*	II *Galendromus occidentalis*	II *Galendromus annectens*	II *Neoseiulus californicus*	III *Neoseiulus aurescens*	III *Neoseiulus cucumeris*	III *Neoseiulus brevispinus*	III *Neoseiulus barkeri*
Citrus	2006–2018	Fresno, Tulare, Kern, Santa Barbara, Riverside, San Bernardino	21	No	994	0	0	0	0	0	0	0	0	0
Avocado	2000–2007	San Luis Obispo, Orange	11	Yes	1,892	0	1	3	37	4	0	0	0	0
Cherimoya	2006–2007	Santa Barbara, Ventura	3	Yes	104	0	0	2	0	0	0	0	0	0
Blackberry	2006–2007	San Luis Obispo	2	Yes	106	0	9	14	24	49	0	0	0	0
Raspberry	2006–2007	San Luis Obispo, Ventura	10	Yes	239	50	2	0	0	26	0	0	0	0
Strawberry	2006–2010	Santa Cruz, Santa Barbara, Ventura	18	Yes	1,570	271	0	0	0	612	403	204	19	5
Grape	2005–2010	Lake, Napa, Mendocino, Sonoma, Madera, San Joaquin, Kern, Ventura, San Luis Obispo, Monterey	78	Yes	5,604	13	5	415	0	87	12	1	0	1
Peach/ nectarine	2006–2007	Butte, Fresno, Kings, Tulare, Kern	19	No	576	0	0	35	0	1	0	0	0	0
Plum/ prune	2006–2007	Butte, Kern	4	No	67	0	0	3	0	0	0	0	0	0
Pear	1996–2008	Lake, Mendocino, Sacramento, Yolo	30	Yes	800	0	0	71	0	4	0	0	0	0
Almond	2006–2018	Kern, Butte	9	No	174	0	0	6	0	0	0	0	0	0
Walnut	2006–2013	Tehama, Butte, Yuba, Yolo, Sutter, Solano, San Joaquin, Kings, Tulare	24	Yes	2,533	0	0	362	0	5	0	0	0	2
				Total number	**14,659**	**334**	**17**	**911**	**61**	**788**	**415**	**205**	**19**	**8**

* Sites × years sampled.

† Yes = samples collected at intervals throughout the crop season. No = one or a few samples collected.

a high level of regulation of this group of spider mites due to their specialized feeding habits. However, when spider mites are scarce their populations decline. Type III and IV phytoseiids are able to survive when mite prey are scarce because of their generalized feeding habits.

During the 1970s and 1980s, *Galendromus occidentalis* (formerly called *Typhlodromus occidentalis* or *Metaseiulus occidentalis*), commonly known as the western predatory mite, was demonstrated to be a significant biological control agent of tetranychid spider mite pests, especially in almond (Hoy et al. 1979) and grape (Kinn and Doutt 1972). Based on these and other studies (McMurtry and Flaherty 1977; McMurtry et al. 1971; Rice and Jones 1978), the UC Integrated Pest Management (IPM) pest management guidelines listed *G. occidentalis* as a key beneficial predator for tetranychid spider mites (*Tetranychus* and *Eotetranychus* species) in almonds, apples, apricots, cherries, grapes, nectarines, peaches, pears and walnuts.

	III	III	III	III	III	III	III	III	III	III	III	III	III	III	III	IV	IV	IV	IV
	Typhlodromus pyri	*Typhlodromus caudiglans*	*Typhlodromus rhenanoides*	*Metaseiulus smithi*	*Metaseiulus citri*	*Metaseiulus johnsoni*	*Metaseiulus arboreus*	*Metaseiulus flumenis*	*Proprioseiopsis fragariae*	*Proprioseiopsis lindquisti*	*Amblyseius similoides*	*Amblyseius andersoni*	*Amblydromalus limonicus*	*Typhlodromalus peregrinus*	*Graminaseius graminis*	*Euseius tularensis*	*Euseius stipulatus*	*Euseius hibisci*	*Euseius quetzali*
	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	755	36	182	19
	0	0	10	0	0	0	0	0	0	0	17	0	0	0	0	0	123	1,694	3
	0	0	0	0	0	0	0	0	0	0	4	0	1	0	0	0	92	0	5
	0	0	0	0	0	1	1	0	0	0	0	0	7	0	0	0	1	0	0
	0	0	2	0	0	10	0	0	0	0	0	0	84	0	0	0	65	0	0
	0	0	0	0	0	0	22	0	0	0	0	0	0	0	28	0	6	0	0
	3,236	169	104	0	37	280	315	22	2	0	4	29	18	1	39	5	67	10	732
	0	168	0	0	2	0	0	0	0	0	74	0	0	0	0	213	0	1	82
	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0	2
	0	82	0	0	52	0	0	0	0	1	3	1	0	0	0	6	0	0	580
	0	0	0	0	12	0	0	0	0	0	104	0	0	0	0	14	27	0	11
	0	223	0	1	90	0	0	0	0	0	919	0	0	0	0	78	596	10	247
	3,236	**658**	**116**	**1**	**195**	**291**	**338**	**22**	**2**	**1**	**1,125**	**30**	**110**	**1**	**67**	**1,117**	**1,013**	**1,897**	**1,681**

Pest control advisers (PCAs) learned to use spider mite/predatory mite ratios as thresholds for treatment in many of these crops to minimize pesticide use. Because phytoseiid species are difficult to distinguish with a hand lens, there was often a presumption by PCAs that any phytoseiid seen in these crops was *G. occidentalis*. Yet, not all phytoseiids are equally reliable in maintaining pests below an economic threshold.

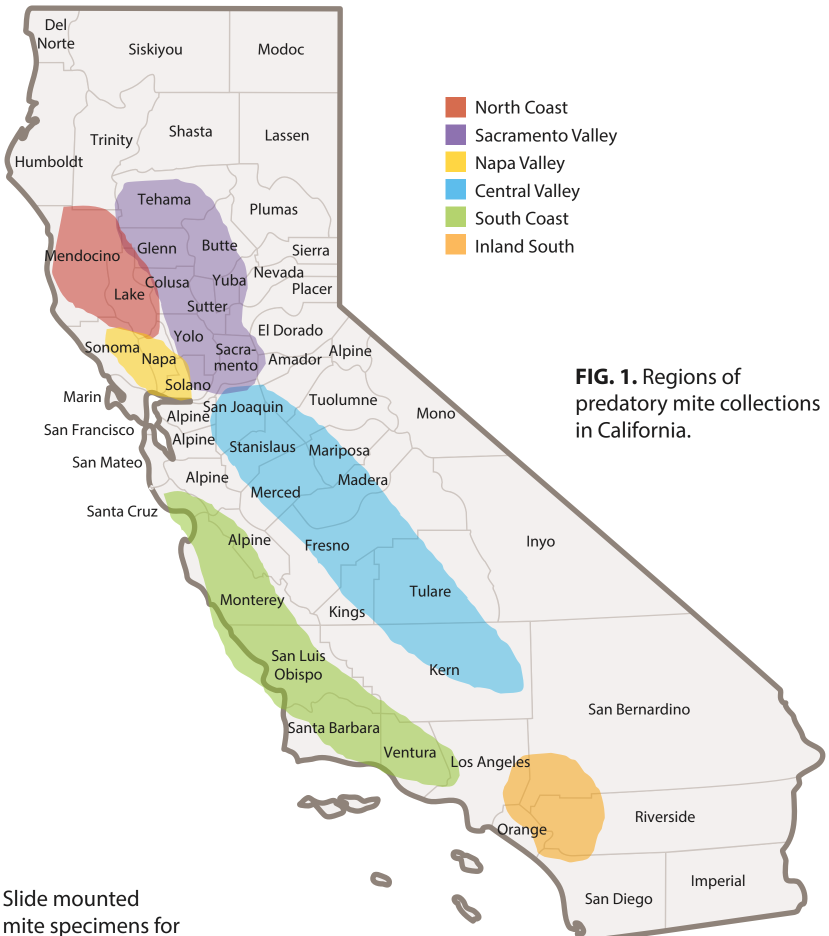
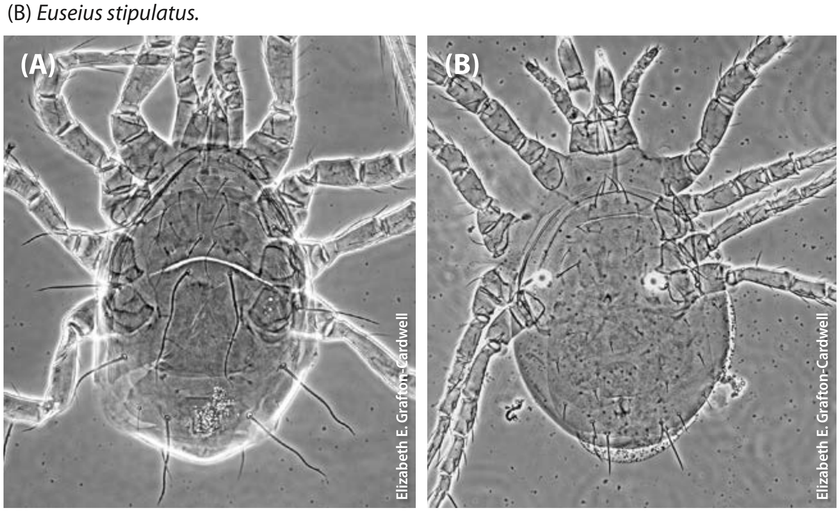


FIG. 1. Regions of predatory mite collections in California.

Slide mounted mite specimens for identification: (A) *Phytoseiulus persimilis* and (B) *Euseius stipulatus.*



A survey of several crops by a high school student in the Ag Futures Internship Program at UC Kearney Agricultural Center in 1992 surprisingly revealed that the western predatory mite was not the dominant species.

That discovery led to the acquisition of funding from the UC Exotic/Invasive Pests and Diseases Research Program for us to survey a number of major crops — from 2005 to 2008 to determine predatory mite species frequency and diversity. We obtained additional collections of data on mites over the years from studies funded by commodity organizations.

14,659 predatory mites, 12 crops, 25 counties

From 2000 to 2018, UC Cooperative Extension (UCCE) advisors and specialists, UC faculty, UC technicians and a Cal Poly, San Luis Obispo, graduate student collected and identified 14,659 predatory mites from 12 crops — almonds, avocados, blackberries, cherimoyas, citrus, grapes, pears, peaches/nectarines, plums/prunes, raspberries, strawberries and walnuts — in 25 counties of California encompassing six geographical regions (table 1, fig. 1). Mites were collected directly from leaves using an artist brush or a mite brushing machine, placed into 70% ethyl alcohol and slide mounted using Hoyers medium (Krantz and Walter 2009).

Identification of slide-mounted specimens of female mites was accomplished with the aid of a taxonomic key (Key to the Phytoseiid Predatory Mites of California Crops, developed by J. McMurtry and E.E. Grafton-Cardwell, in progress) and a phase contrast microscope. Some mite collections (in grapes, walnuts, strawberries, citrus, caneberries and cherimoyas) were made repeatedly in the same sites through one or more seasons. Other collections were made on one or a few dates during a season. Collectively, a total of 229 site-years were sampled.

Subtropical fruit: Dominated by *Euseius* species

Three subtropical fruit crops were studied: avocados, cherimoyas and citrus (table 1, fig. 2). Surveys demonstrated that subtropical crops had low predatory mite species diversity (five to nine species total) and a strong tendency to support type IV *Euseius* species (93.3% to 99.8% of specimens).

A total of 994 mites representing five species were identified from citrus in Fresno, Tulare, Kern, Santa Barbara, Riverside and San Bernardino counties from 2006 to 2018, and 99.8% were in the genus *Euseius* (table 1, fig. 2). The Central Valley supported *E. tularensis* (96.8%) and *E. quetzali* (3.1%). In contrast, in the south coast area only *E. stipulatus* was found, and in inland Southern California a mixture of *E. tularensis* (46.5%), *E. stipulatus* (3.3%) and *E. hibisci* (50.1%) was found.

Previous studies described the distribution of *E. tularensis* and *E. hibisci* in California citrus (Congdon and McMurtry 1985, 1986; McMurtry et al. 1971, 1992). *E. stipulatus* was introduced to citrus in Southern California in 1972 (McMurtry 1977). The current study suggests that *E. stipulatus* has displaced *E. hibisci* in the southcoast area. The UC IPM guidelines for citrus (Dreidstadt 2012; Grafton-Cardwell et al. 2019) recommend conservation of *Euseius* species to aid in control of pest mites and thrips.

A total of 1,892 phytoseiids representing nine species were collected from avocado in San Luis Obispo and Orange counties from 2000 to 2007, and 96.2% of these mites were in the genus *Euseius* (table 1, fig. 2). *E. hibisci* was the dominant species (95.8% of *Euseius* species) found on inland Southern California avocados, and *E. stipulatus* was the dominant species (96.0% of *Euseius* species) found on south coast avocados. Again, the abundance of *E. stipulatus* in the south coast area is a significant change from the 1960s through the 1980s, when *E. hibisci* dominated that region (Congdon and McMurtry 1985; McMurtry and Johnson 1965, 1966). The UC IPM guidelines for avocado (Dreidstadt 2008; Faber et al. 2018) list *Neoseiulus californicus, E. hibisci, Galendromus annectans, G. helveolus* and *Amblydromalus limonicus* as important predators of pest mites.

A total of 104 phytoseiids representing five species were identified from cherimoya in the south coast area (Santa Barbara and Ventura counties) during 2006 and 2007, and 93.3% of these mites were in the genus *Euseius* (table 1, fig. 2), including *E. stipulatus* (88.5%) and *E. quetzali* (4.5%). This is the first report of phytoseiids in cherimoyas (Murrietta 2015) and provides further evidence that *E. stipulatus* has established in south coast California subtropical crops.

Berries: Specialized spider mite predators

In contrast to the subtropical crops that hosted primarily type IV phytoseiid species, blackberries, raspberries and strawberries supported a high percentage of type I and II specialized spider mite predators: *Phytoseiulus, Typhlodromina*, *Galendromus* and *Neoseiulus* species (fig. 3). Collections in our study were likely affected by augmentative releases of these phytoseiids by growers for tetranychid pest mites.

A total of 106 mites representing eight species were collected from blackberries in San Luis Obispo County, and 90% were identified as type I *Typhlodromina ehari* (8%) and type II species: *N. californicus* (46.2%) and *Galendromus* species (35.8%) (table 1, fig. 3). A previous study in blackberry by McMurtry and Show (2012) revealed lower diversity (only two species) compared to our untreated commercial site or the wild blackberries in their study, indicating pesticide effects on diversity.

A total of 239 mites represented by seven species were collected from raspberries in San Luis Obispo and Ventura counties, including type I *P. persimilis* (20.9%), type II *N. californicus* (10.9%), type III *Amblydromalus limonicus* (35.1%) and type IV *Euseius*

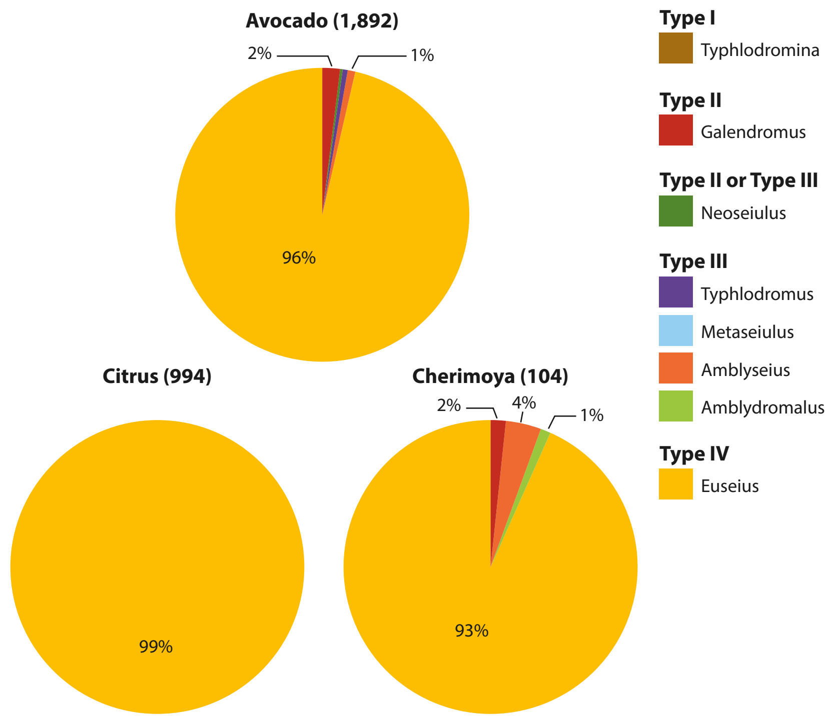


FIG. 2. Percentage of each phytoseiid predatory mite genus found in citrus, avocado and cherimoya (number of specimens).

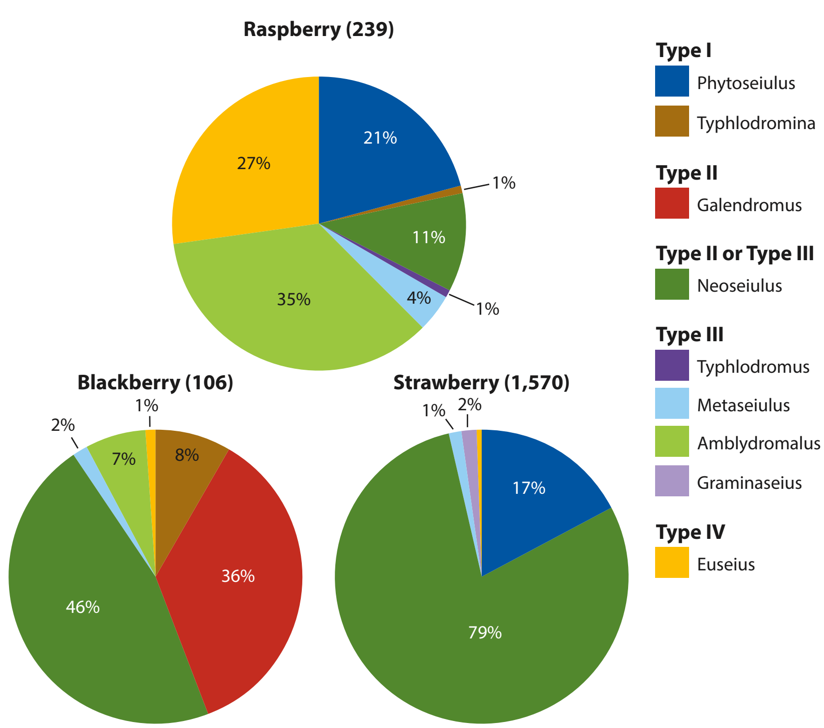


FIG. 3. Percentage of each phytoseiid predatory mite genus found in blackberry, raspberry and strawberry (number of specimens).

stipulatus (27.2%) (table 1, fig. 3). Significant numbers of *E. stipulatus* found in south coast raspberries again demonstrate establishment of this species in this region. Raspberries had a greater number of type III and IV phytoseiids than blackberries; however, the blackberry crop was represented by only one surveyed site. The UC IPM guidelines for caneberries discuss releases of *P. persimilis* for control of mites (Bolda et al. 2018b).

A total of 1,570 mites representing nine species were collected from strawberries in Santa Barbara, Ventura and Santa Cruz counties, including type I *P. persimilis* (17.3%) and type II and III *Neoseiulus* species (79.2%) (table 1, fig. 3). Because of early research demonstrating the efficacy of releases (Oatman et al. 1977), growers regularly use phytoseiid releases for tetranychid mite control in strawberries. The UC IPM guidelines for strawberry state that *P. persimilis* and *N. californicus* have established in south coast strawberries, and these were the two dominant species found in Santa Barbara and Ventura county surveys (Bolda et al. 2018a; Strand 2008). The Santa Cruz County survey revealed five species of *Neoseiulus*: *N. californicus* (35.6%), *N. aurescens* (41.1%), *N. cucumeris* (20.8%), *N. brevispinus* (1.9%) and *N. barkeri* (0.5%), suggesting greater species diversity of *Neoseiulus* in this county. Our study revealed *E. stipulatus* in south coast strawberries.

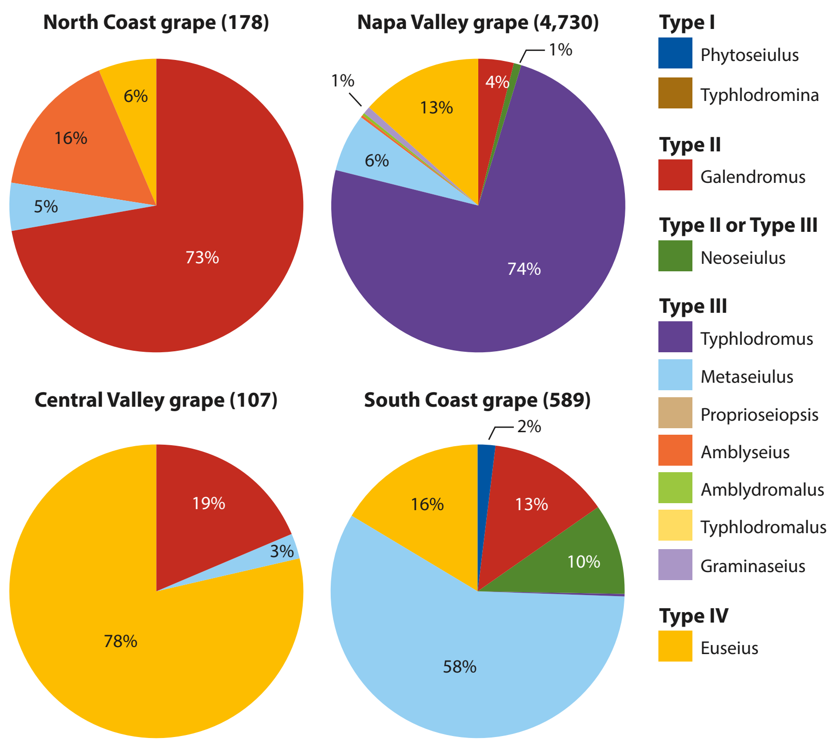
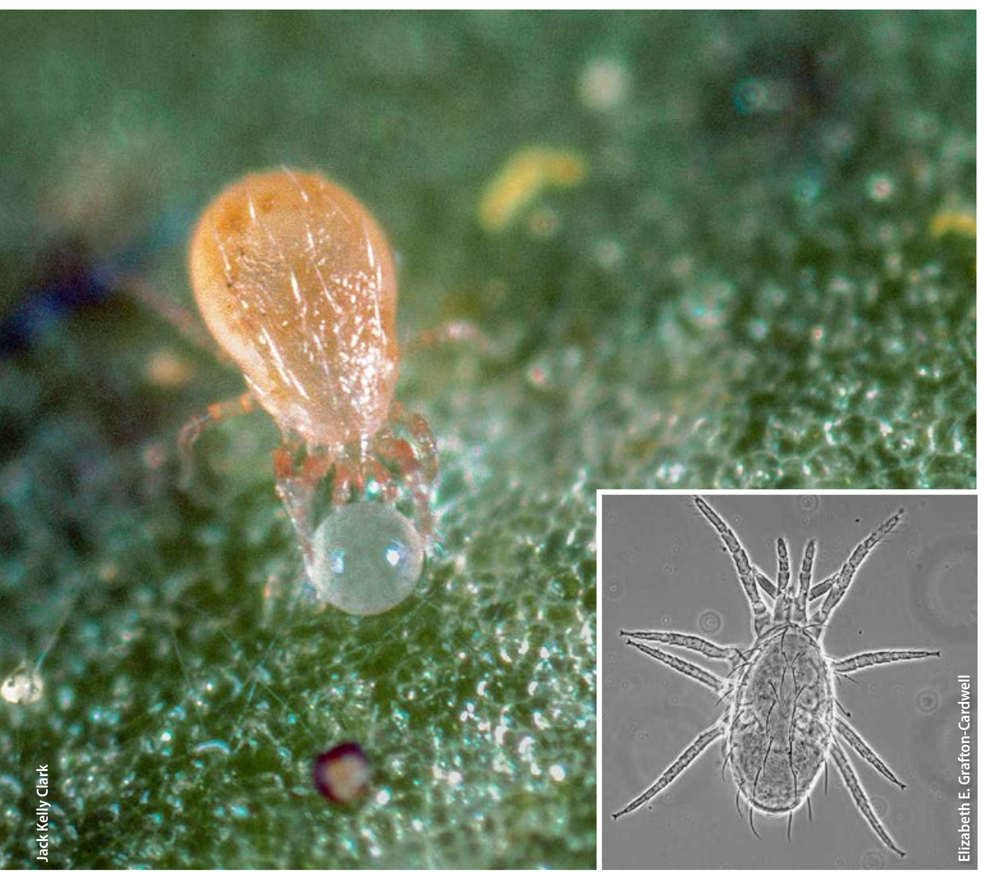


FIG. 4. Percentage of each phytoseiid predatory mite genus found in grape sampled from four regions (number of specimens).



Adult western predatory mite *Galendromus* (*Metaseiulus) occidentalis* attacking a twospotted spider mite egg. Inset: *Galendromus occidentalis* specimen as seen under a compound microscope.

Grapes: Greatest phytoseiid diversity

Grapes (table 1, fig. 4) had the greatest diversity of phytoseiids (24 of 28 total species collected from all crops). However, the greater diversity found may be due to the higher number of ecological niches sampled. A total of 5,604 mites were collected from 10 counties, and species composition varied greatly by region. The dominant genera in north coast vineyards were type II *Galendromus* (72.5%) and type III *Amblyseius* (16.3%) species; in the Napa Valley, type III *Typhlodromus* (74.2%) and type IV *Euseius* (13.2%) species dominated; in the Central Valley, type II *Galendromus* (18.7%) and type IV *Euseius* (78.5%) were most common; and in south coast vineyards, type II *Galendromus* (13.2%), type III *Metaseiulus* (58.1%) and type IV Euseius (16.1%) species prevailed. The UC IPM guidelines for grape, updated based on the surveys described in this study, list *G. occidentalis*, *T. pyri*, *E. quetzali*, *E. tularensis*, *E. stipulatus*, *Neoseiulus fallacis*, *N. californicus* and *M. mcgregori* [*M. flumenis*] as beneficial species, with species dominance varying from region to region (Bettiga 2013; Haviland et al. 2019).

The differences in species composition could be explained by a number of factors, including variations in climate, prey species, neighboring crops and pesticide treatments (Hanna et al. 1997; Stavrinides and Mills 2009). Previous research (Flaherty and Huffaker 1970) in the Central Valley revealed a similarly high level of species diversity in grape and listed *E. hibisci* as the sole *Euseius* species collected. However, at that time, *E. tularensis, E. stipulatus* and *E. quetzali* had not yet been described (Congdon and McMurtry 1985). Our collections revealed all four species of *Euseius*, with *E. stipulatus* present in the south coast and Napa Valley regions, *E. hibisci* in the south coast, *E. tularensis* in the Central Valley and south coast and *E. quetzali* statewide.

Stone fruit and pears: Additional species found

A previous survey of peaches, nectarines and plums (Rice and Jones 1978) indicated that *Typhlodromus caudiglans*, *Metaseiulus citri*, *Galendromus occidentalis* and *Euseius hibisci* were the key phytoseiids in the Central Valley. Our study provided evidence of these but also additional species such as *Amblyseius similoides*, and the previously undescribed *E. tularensis* and *E. quetzali*.

A total of 576 mites representing eight species were collected from peaches and nectarines in Butte, Fresno, Kings, Tulare and Kern counties. The dominant species found were type II *G. occidentalis* (6.1%), type III *T. caudiglans* (29.2%) and *A. similoides* (12.8%) and type IV *Euseius* species (51.4%) (table 1, fig. 5). The UC IPM guidelines for peaches and nectarines list *G. occidentalis* as the key phytoseiid for control of key pest spider mites (Day et al. 2017a, 2017b; Strand 1999), yet this species accounted for only 6.1% of the specimens collected.

A total of 67 mites representing four species were collected from plum and prune orchards in Butte and Kern counties (table 1, fig. 5). The major species found were type II *G. occidentalis* (4.5%), type III *T. caudiglans* (23.9%) and type IV *E. tularensis* (71.6%). The UC IPM guidelines for plums and prunes suggest *T. caudiglans* and *Galendromus* species as effective control agents for key pest mites (Adaskaveg et al. 2017; Bentley et al. 2017).

A total of 800 mites representing nine species were collected from pear orchards in Lake, Mendocino, Sacramento and Yolo counties (table 1, fig. 5). The predominant species were type II *G. occidentalis* (8.9%), type III *T. caudiglans* (10.3%) and *M. citri* (6.5%) and type IV *E. quetzali* (72.5%). This is the first published survey of phytoseiids in pear. The UC IPM guidelines for pear list *G. occidentalis* for the control of key pest mites (Elkins et al. 2017; Ohlendorf 1999), yet this species represented < 9% of mites collected.

Nuts: Few phytoseiids in almonds

A total of 174 mites representing six species were collected from almond orchards in Kern and Butte counties (table 1, fig. 6). The predominant species were type III *Amblyseius similoides* (59.8%) and type IV *Euseius* species (29.9%). The UC IPM guidelines for almond list *Galendromus occidentalis* as the key predacious mite for tetranychid pest mite control (Flint 2002; Haviland et al. 2017). However, *G. occidentalis* represented a minor percentage (3.4%) of species collected. It should be noted that we searched almond sites for several years

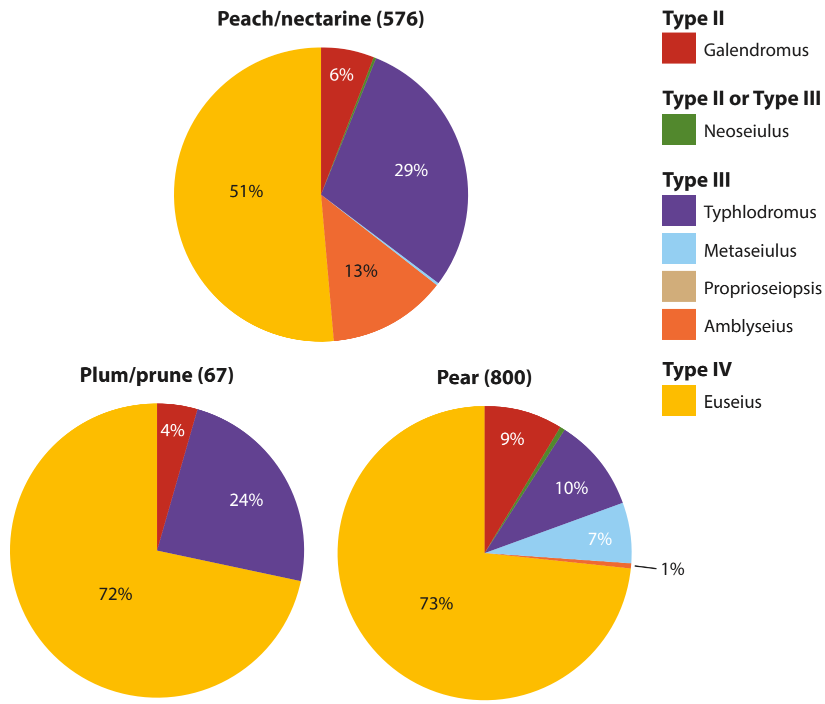


FIG. 5. Percentage of each phytoseiid predatory mite genus found in stone fruit and pear (number of specimens).

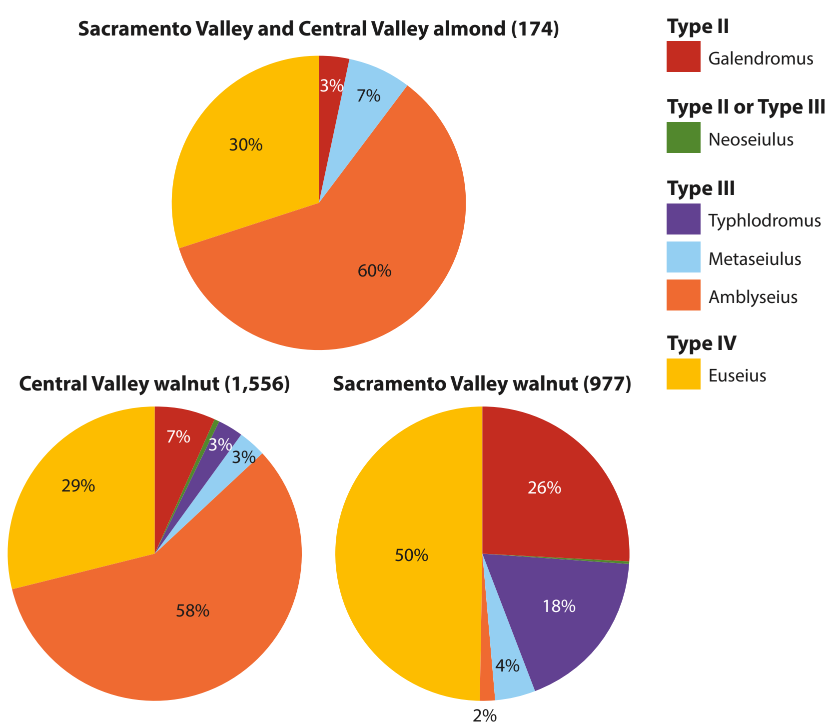
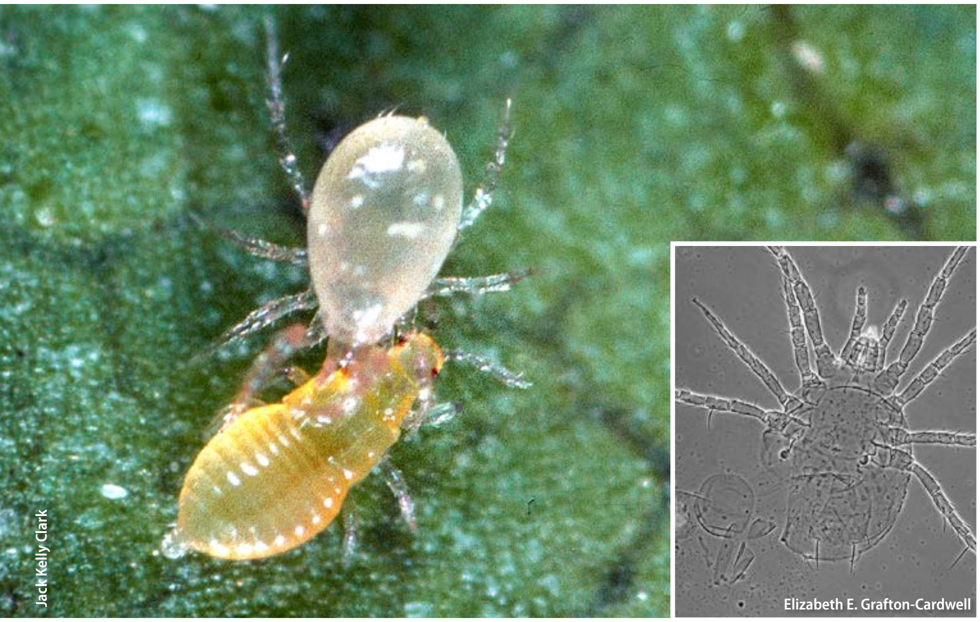


FIG. 6. Percentage of each phytoseiid predatory mite genus found in nut crops, with walnut sampled from two regions (number of specimens).



Euseius tularensis predatory mite, *top*, feeding on a citrus thrips nymph, *bottom*. Inset: *Euseius tularensis* specimen as seen under a compound microscope.

to obtain these collections and routinely found very few phytoseiids. The low populations of phytoseiids compared to decades ago may be explained by changes in chemical control programs that favor a second-level predator, the sixspotted thrips, *Scolothrips sexmaculatus*, which feeds on both tetranychids and phytoseiids.

A total of 2,533 mites representing 11 species were collected from walnut orchards in Tehama, Butte, Yuba, Yolo, Sutter, Solano, San Joaquin, Kings and Tulare counties (table 1, fig. 6). When we examined the results by geographical region, the predominant genera in the Central Valley were very similar to almonds, with type III *Amblyseius* species (58.0%) and type IV *Euseius* species (28.7%) dominating. In contrast, walnuts grown in the Sacramento Valley had a much higher percentage of type II *G. occidentalis* (26.1%) and type III *Typhlodromus* species (18.1%), in addition to type IV *Euseius* species (49.5%) and very low numbers of type III *Amblyseius* (1.7%) species. The UC IPM guidelines for walnut indicate that *G. occidentalis* is the key predator of walnut pest mites (Grant et al. 2017; Strand 2003). However, it was found in much lower abundance in the Central Valley region than the Sacramento Valley.

Diversity levels, changes

The surveys in this study were undertaken to determine the level of diversity of phytoseiids in perennial crops in six regions of California and look for changes in species composition compared to earlier studies (Congdon and McMurtry 1985, 1986; Hoy et al. 1979; Kinn and Doutt 1972; McMurtry and Flaherty 1977; McMurtry and Johnson 1965; McMurtry et al. 1971; McMurtry et al. 1979; McMurtry and Show 2012; Oatman 1971; Rice and Jones 1978; Rice et al. 1976). Similar to these other studies, our surveys found low phytoseiid diversity in subtropical crops, extremely high levels of diversity in grapes and moderate levels in tree fruits, nuts and berries. Berries hosted the greatest proportion of type I *Phytoseiulus persimilis* and type II *Neoseiulus californicus*, likely due to augmentative releases and/or establishment from prior releases of the commercially available predators.

The presence of *Euseius stipulatus* in citrus, avocados, cherimoyas, grapes, strawberries, blackberries, raspberries, almonds and walnuts is interesting because this species was introduced to citrus in Southern California in 1972 (McMurtry 1977) for the control of citrus red mite. It is now found as far north as the Sacramento Valley in walnut orchards and Napa Valley, and it appears to have displaced *E. hibisci* to a great extent in south coast subtropical crops.

The western predatory mite, *Galendromus occidentalis*, has long been recognized as an important biological control agent in California crops, as evidenced by its mention in many of the UC IPM guidelines. Our survey demonstrated that *G. occidentalis* was often a minor component of the phytoseiid complex, playing a major role only in grape, Sacramento Valley walnut and south coast blackberries. Previous authors noted that *G. occidentalis* populations decline when tetranychid prey are lacking and this species is sensitive to insecticides (Hoy et al. 1979; Rice and Jones 1978).

The predatory mite complexes differed significantly between geographical regions for walnuts and grapes, and studies need to be undertaken to determine the underlying basis for these differences. In addition, studies are needed to evaluate the roles and effectiveness of the abundant type III and type IV phytoseiid species, such as *Typhlodromus*, *Amblyseius* and *Euseius* species, in the stone, pear and nut crops. Are these species regulators of key pests such as mites and thrips? Or are they feeding on pollen or nonpest mites such as tydeiids, eriophyids and tarsonemids and insignificant for agricultural pest control? Most of our surveys were carried out without monitoring plant-feeding prey, but clearly there are host plant and prey influences. Additional work is needed to elucidate the impact of pest phenology, climate, crop variety, alternative prey and crop management activities on the abundance of phytoseiid species and their ability to regulate pest populations.

A significant impediment to evaluating the role of predatory mites in field situations is that they are difficult to identify to species using a hand lens because of their rapid movement, small size and similar appearance. Yet, there are large differences in their ability to regulate pest populations. As mentioned, a taxonomic key is being prepared for publication, but it requires slide-mounted specimens and a phase-contrast microscope. Consequently, phytoseiid identification may be limited for professionals who have no access to specialized equipment. Future work may take advantage of rapid advancements in and declining costs of field-usable molecular tools to quickly identify mites. If future research establishes the efficacy of the various phytoseiid species and a rapid identification method becomes available, then PCAs can make real-time decisions and avoid unnecessary pesticide applications.

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RESEARCH ARTICLE

Strawberry growers are unlikely to forgo soil fumigation with disease-resistant cultivars alone

A UC survey found that disease resistant cultivars have not yet become a priority for strawberry growers, mainly because of economic pressures.

by Julie Guthman

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Abstract

A major collaborative project launched in 2017 to accelerate the development of disease-resistant strawberry cultivars is responding urgently to two developments: increasing restrictions on fumigant use and the appearance of two novel pathogens not evidently manageable with allowed fumigants. As part of that project, I sought to understand the factors that guide growers' cultivar choice and assess their willingness to choose a pathogen-resistant cultivar to reduce or potentially replace fumigation. From a survey completed by 33 strawberry growers and in-depth interviews with 20 growers, I found that most growers prioritize yield in choosing cultivars, despite the industrywide problem with low prices. Few growers said they would be willing to substitute disease-resistant cultivars for fumigation without fail-safe disease control methods. Many growers, even those with existing organic programs, would opt for soilless systems in a tighter regulatory environment. This study thus suggests that disease resistance breeding must be coupled with support for other disease management techniques, and the economic situation that makes growers feel that they cannot forgo yield also needs attention.

Under the leadership of the UC Davis strawberry breeding team, with strong support from the California Strawberry Commission and several major strawberry shippers and nurseries, a major collaborative project was launched in September 2017. The overall objectives for the project are to identify natural sources of resistance to pathogens affecting strawberries and to accelerate the development of commercial cultivars resistant to a broad spectrum of soilborne and aboveground pathogens.

The urgency of this project, called the Next-Generation Disease Resistance Breeding and Management Solutions for Strawberry, stems from two developments. One is the increasing restrictions on the use of soil fumigants that have long been used to manage soilborne disease; the most reliably effective fumigant, methyl bromide, has finally been phased out except for nursery uses, in compliance with the international Montreal Protocol on Substances that Deplete the Ozone Layer, and other chemical fumigants, such as chloropicrin and 1,3-dichloropropene (brand name Telone), have seen more stringent application protocols,

Field day introducing new university-bred strawberry cultivars to stakeholders . A recent survey of California strawberry growers found that most prioritize yield over pathogen resistance when they select cultivars.

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such as larger buffer zones and township caps. The other development is increased disease pressure from two novel fungal pathogens, *Macrophomina phaseolina* and *Fusarium oxysporum* f. sp. *fragariae*, which colonize the plant, causing it to collapse and die.

The two developments are related. The virulence of the two novel fungal pathogens is widely believed to be associated with the end of methyl bromide use, since they began to appear in 2005 when growers started reducing the use of methyl bromide, even though they continued to fumigate with other chemicals, like chloropicrin (Koike et al. 2013; Lloyd and Gordon 2016; Tourte et al. 2016). While the extent of die-off from these two pathogens has yet to be documented, fears are increasing of significant production loss.

UC breeders started with disease resistance

UC has been developing strawberry cultivars since the 1940s, when UC scientists first identified the problem of *Verticillium* wilt. Although disease resistance was the original raison d'être of the program, breeders soon incorporated other qualities as well, such as yield, size, firmness and the ability to withstand freezing, for the frozen food market. Once fumigation became routine, disease resistance diminished as a priority (Darrow 1966; Wilhelm and Sagen 1974). Since that time, the UC breeding program has seen many changes; its varieties once comprised 95% of the plants sold (Wilhelm and Sagen 1974), but today it competes with private breeders, including Driscoll's, for the royalties from cultivar licenses.

UC varieties, nevertheless, remain very important, especially for growers who cannot or prefer not to pay the higher license fees for proprietary varieties (Baum 2005). Commonly used UC varieties, developed and patented before 2016, before the new breeding team came on board, include the day-neutral varieties Albion, Cabrillo, Monterey, Portola and San Andreas, which tend to be grown in the Pajaro Valley and Salinas regions, and the short-day varieties Benicia, Petaluma and Fronteras grown in the cooler months farther south in the Santa Maria/Guadalupe and Oxnard regions. Although some show mild resistance to disease, they were primarily bred for yield, size, color and firmness, with attention to flavor as well, especially in Albion.

Breeding for disease resistance has since returned as a high priority, which was recognized by the U.S. United States Department of Agriculture (USDA) in its decision to fund the UC project. The social science research I conducted is part of the project; I sought to understand the factors and institutions that guide growers' cultivar choice and assess their willingness to choose a pathogen-resistant cultivar to reduce or potentially replace the use of fumigation.

Grower perspectives collected

In collaboration with Professor Rachael Goodhue, Agricultural and Resource Economics, UC Davis, who was researching related questions, I initially opted to conduct a survey of growers. Developed in consultation with the key stakeholder group, the California Strawberry Commission, the survey was lengthy and complex. It mainly consisted of binary and multiple-choice questions useful for quantitative analysis, although it also solicited comments and open-ended responses that might be used in a qualitative analysis.

Written in both English and Spanish, the survey was administered in spring 2018 through the electronic platform Qualtrics (Qualtrics, Provo, UT) and by standard mail. In accordance with their policy of not sharing their mailing list, the commission distributed the surveys. They publicized in their newsletter an anonymous link to the Qualtrics version; an anonymous link collects no identifying information on responders, such as name or email, which therefore makes targeted follow-up impossible. In addition, they sent 236 surveys in the mail. We were unable to obtain information on the overlap of their newsletter and mailing lists.

The initial response to the survey was poor. Ten growers completed the mailed survey and none completed it online. Reasons that the response rate to our survey might have been particularly low include growers' skepticism about its intent, which may have been read as discouraging soil fumigation, their annoyance with the number of requests they are receiving from researchers and journalists — anecdotal reports from other social science researchers attest to strawberry growers being a difficult-to-contact research population — and annoyance with the length of the survey. However, there is additional evidence to suggest that the dissemination methods were not optimal. In our subsequent contact with growers at

Verticillium die-back in an experimental field.


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field days and by phone, many reported never having seen the surveys.

To augment participation, we called or emailed growers using contact information that I had obtained from publicly available sources in a prior research project (Guthman 2017). This yielded 21 online surveys and two additional mail surveys, all arriving within a few days. Altogether, we received 21 online surveys and 12 mail surveys, for a total of 33 surveys. I estimate this to be an 11% response rate, based on an estimate from California Strawberry Commission representatives that there were approximately 300 strawberry growers in California. If, however, the 236 hard copies initially sent out reflected the total grower population, the response rate would be 14%, closer to the 15% to 20% response rate social scientists consider good. It is difficult to confirm the number of strawberry growers through the Pesticide Use Reporting system, the typical source of grower contact information, because one operation can apply for multiple permits under various names.

Likely owing to the length of the survey, many of the surveys were incomplete and very few respondents provided qualitative data. With limited data to achieve my research objectives, especially to understand the nuances of growers' cultivar choices, I opted to augment the survey by conducting in-person interviews. Without access to contact information from the commission, I sought out growers who had participated in my prior project and who had welcomed additional follow-up. In constructing the sample, I emphasized growers who used UC varieties, to learn about breeding priorities, although not to the exclusion of growers who used proprietary cultivars, to understand the range of concerns and needs around cultivars. Since my goal for the interviews was to achieve depth rather than establish statistically significant patterns, a small sample was appropriate (Crouch and McKenzie 2006).

I was able to conduct interviews with 20 growers, 15 of whom grew nonproprietary varieties. All but six had some acres in organic production, although only one was a dedicated organic grower, growing multiple crops. The nature of this sample suggests a significant, but not surprising, overlap between those growers more generally willing to work with researchers and those experimenting with various production techniques. Importantly, many growers I attempted to contact were not reachable and/or had gone out of business, and even three of those I did interview had retired or all but exited strawberry production.

In the interviews, conducted in 2018 and 2019, I was able to reframe questions that had not quite worked in the surveys, as well as probe on the more difficult questions (Legard et al. 2003). Before completing them, I reached saturation, such that additional interviews were no longer producing more themes or deepening understanding, which substantiated that the sample size was sufficient (Hennink et al. 2016). Research assistants transcribed and coded interview data with NVivo qualitative research software (QSR International, Burlington, Mass.), identifying ideas and themes that further elucidated the more bounded questions asked in the survey.

Alongside these two primary sources of data (the survey and the interviews), I reviewed limited discussions about cultivars from my previous project and notes taken from short discussions with growers at field days and follow-up phone calls for the survey. These additional data were thoroughly in keeping with survey and interview data, providing further triangulation of the findings.

TABLE 1. Most important traits in strawberry cultivar

Trait	No. of responses
Yield	11
Marketability (appearance, size, taste)	7
Resistance to soilborne diseases	6
Long, steady yield relative to other available cultivars	4
Suitability to local conditions	4
Harvest timing (early)	3
Shipper requirements	2
Cost	1
Other	1
Total responses	**39**

TABLE 2. Cultivars planted for 2016 marketing year

Cultivar	No. of responses
Monterey	8
Cabrillo	8
Fronteras	6
San Andreas	4
Portola	4
Proprietary	4
Radiance	2
Albion	1
Other	1
Total responses	**38**

Growers emphasize yield

While the strawberry industry has long enjoyed the benefits of strawberries bred with multiple aims, emphasis in one area often comes at the expense of another (Darrow 1966). Since UC began its breeding program in the 1940s, growers have generally adopted those varieties with high productivity traits (Wilhelm and Sagen 1974). An important question, therefore, was within the current context of fumigant restrictions and the emergence of novel diseases, to what extent disease resistance had become a desirable trait. The survey thus queried growers about what traits they considered in choosing a cultivar. To prevent them from choosing all, it asked them for their top three priorities.

As seen in table 1, growers mostly wanted high yields, especially if a variation on the same theme, long steady yields, was included. While interest in resistance to soilborne diseases and in marketability (appearance, size, taste) were not negligible, they appeared as secondary priorities. These preferences were corroborated by answers to a question about which cultivars had been planted for the 2016 marketing year (table 2). Of the UC varieties, Cabrillo, Monterey and Fronteras were the most planted and they are high yield performers. In a recent trial involving equal plot sizes, Fronteras produced an average cumulative marketable fruit weight of 11,000 grams per plot, with Monterey producing close to 9,500 per plot. Of these two cultivars, Monterey allegedly has better flavor. San Andreas, the next most widely planted cultivar, is most associated with Fusarium resistance, but in that same experiment yielded only a little over 7,000 grams per plot. The notably flavorful Albion, which is popular among growers selling in farmers markets, although was not often planted by survey respondents (table 2), yielded only about 6,500 grams per plot (Cole et al. 2018).

Answers to a third question further clarified the dimensions of the trade-off between yield and disease resistance. Asked about the maximum decline in yield a grower would accept in a cultivar with high levels of resistance to soilborne diseases and no change in production costs, most growers reported that no or only a minimal yield decline was acceptable (table 3).

Qualitative responses and interviews provided additional evidence that growers tended to choose yield over pathogen resistance and helped clarify their rationale. Of the 20 growers interviewed, 15 said yield was a high priority, albeit not without some hedging. Many recognized the importance of marketability characteristics, acknowledging that a strawberry that lacks flavor, for example, would turn off consumers. For that reason, they were more likely to grow Monterey than even higher yielding varieties, and some shippers insisted that they grow a marketable variety such as Monterey.

Growers who use proprietary varieties because they sell to shippers who require them to (Driscoll's and WellPict) have somewhat less choice in what they grow. The shipper sets priorities, and Driscoll's, in particular, has allegedly prioritized flavor and disease resistance over yield in their breeding. Growers who favor working with these shippers do so because they obtain higher prices, making up for the loss of yield. Still, my interview data showed that when given a choice these growers, too, favor yield, especially because they are paid the same no matter what they grow.

When I pressed on questions of why yield remained a priority for those selling in wholesale markets when they also complained of low prices, I learned of a significant collective action problem. Most growers recognized that it made sense for the industry to reduce supply but felt that it was folly personally to choose a lower-yielding variety. This is the technological treadmill problem first identified by agricultural economist Willard Cochrane in 1958.

Cochrane noted the tendency of farmers to adopt technologies that reduce costs because early adopters make additional profits as their expenses decline (Cochrane 1958). As he also noted, such tendencies eventually negatively affect crop prices because other farmers join in, supply increases overall and price competition ensues, driving some out of business. In the case of adoption of a higher-yielding variety, rather than reducing cost, the output increases with little additional effort, making such a strategy nearly irresistible. As one grower put it, "We're in a competitive environment. We like to say we don't grow a commodity, but there are commodity-like characteristics. So if you have a variety and neighbor selling into same market, if he's more productive he will have an edge."

In addition to low prices, fixed costs such as land leases and land preparation are extremely high and increasing in strawberry production. Labor costs, though variable, have risen considerably with labor shortages and new minimum wage and overtime laws. Therefore, growers feel they need to sell as many berries as they can to be economically viable. As another grower said, "You could have the best fruit around, but if you don't have yield you can never make any money. . . . I mean our costs are going through the roof. The only way we can bring some of the costs down is through yield."

TABLE 3. Acceptable decline in yield for a cultivar with high levels of disease resistance

Acceptable level of decline	No. of responses
0%	3
1–5%	5
6–10%	2
11–15%	0
15–20%	1
More than 20%	1
Total responses	**12**

At the same time, growers also questioned this logic, asserting that the industry was undermining itself by continuing to breed and grow ever more high-yielding varieties: "So we want these varieties to give out more numbers and last longer, but it's hurting us in the long run. . . . It seems like people think that if I plant 100 acres and make such amount of dollars, if I put 200 acres in, I'm going to make double that, but it doesn't work that way." This observation is corroborated by the most recent statistics on historical trends reported by the USDA National Agricultural Statistics Service. Utilized production of strawberries (i.e., the volume of marketed strawberries) grown in California increased from 539 million pounds in 1974 to 3,015 million pounds in 2012, an increase of 559%; grower prices increased only from 29 cents per pound to 80 cents per pound, an increase of 276%, in that same time period (USDA NASS 2013).

"Our costs are going through the roof. The only way we can bring some of the costs down is through yield."

It is not that growers were oblivious to the need for disease resistance, but some were making a calculated decision that the yield benefits of a cultivar outweighed the risk of plant loss. As one grower said, "We can have 30% die out of Radiance (in Mexico) due to soilborne pathogens and still beat the yield on San Andreas." More often, growers had not experienced enough plant loss to make disease resistance a priority: "If we begin to see more Vert or other pathogens, we will worry more. Right now, all is cool."

Several growers emphasized the need to know the soil history to determine what cultivar to grow. Some growers, though, who had experienced disease loss were more inclined to let go of leases on diseased land than give up on the yield or marketability advantages of a cultivar. There were exceptions, too. One grower spoke of having planted Monterey and losing 40% of the plants one year. After that, he "switched soils," but that soil was infested too, and he lost 32% of Monterey that year. He then turned to growing almost entirely San Andreas. Not surprisingly, it was growers with organic fields who were most interested in disease-resistant varieties. With fumigation still available, growers with conventional fields remained relatively uninterested in these varieties.

Growers reluctant to forgo fumigation

Understanding that most growers were unwilling to trade off yield for pathogen resistance because soil fumigants were available, I wanted to explore in more depth what role pathogen-resistant cultivars could play in reducing the use of soil fumigation. The survey included two questions about what prevents growers from reducing their use of preplant soil fumigation and what currently encourages them to reduce their use of preplant soil fumigation. It asked them to choose all answers that applied.

Answers to these questions aligned with previous studies and reports (Guthman 2017; Lloyd and Gordon 2016; Tourte et al. 2016). Growers most often chose "crop loss/potential crop loss" as the condition that prevented them from reducing their use of preplant fumigation (table 4). Buyer and lease conditions played a role, as well — for instance, some leases require that growers fumigate so that the lessors, often vegetable growers, get the benefits of fumigation. On the flip side, regulatory pressures, including restrictions on fumigation in the form of buffer zones, were most encouraging growers to reduce fumigation, with opportunities such as entry into organics or land with low disease pressure (e.g., previous pasture) also playing roles (table 5).

TABLE 4. Conditions that prevent reduction of preplant soil fumigation

Conditions discouraging reduction	No. of responses
Crop loss/potential crop loss	13
Lack of disease-resistant cultivars	10
Lack of profitable alternative technologies (e.g., hydroponics, substrate/soil substitute, anaerobic soil disinfestation)	6
Lease requirements	5
Lack of support/information regarding alternative technologies	4
Shipper or retailer requirements	2
Total responses	**40**

TABLE 5. Conditions that encourage reduction of preplant fumigation

Conditions encouraging reduction	No. of responses
Proximity to housing or schools outside buffer zones	10
Existing regulations/label restrictions/use permit conditions (including buffer zones)	9
Possibility of new regulations	8
Access to land with low disease pressure (owned or leased)	5
Public pressure	3
Concern with public health	3
Organic price premium	2
Other	1
Total responses	**41**

Qualitative responses and interviews corroborated and nuanced the latter answers. Several growers emphasized how fumigant restrictions had pushed them to find alternative means to grow strawberries and discussed organic certification and the accompanying price premium as a way of offsetting the potential costs and crop losses of forgoing fumigation. In these instances, they saw disease-resistant varieties as enabling such a transition: "Without disease-resistant varieties, conventional strawberries require the use of fumigants. If they become unavailable, organic is the best alternative." The trade-off is noteworthy given that growers have to give up other pesticides besides fumigants to be certified organic.

A few growers mentioned their willingness to give up fumigation without converting to organics, simply because of fumigation costs. And a few growers noted that organic prices might be too weak to make that trade-off. One wrote in the survey, "If I were organic [I'd reduce fumigation use], but they don't have the price either right now." Even the many interviewees who have organic programs were not at this time considering transitioning their entire operation; instead, they were choosing fields for their organic programs where soil conditions make them viable, often areas with low disease pressure.

That organic markets were nevertheless the main factor incentivizing fumigant reduction was confirmed by answers to a question about whether there were any conditions in which growers would consider eliminating the use of preplant soil fumigation, not including transitioning to organic. Only 10 growers replied to this question, but seven said no, with two maybes and one yes. When asked to comment about what, if any, conditions might lead growers to eliminate preplant soil fumigation altogether within the next 5 years, surveyed growers mentioned cultivars completely resistant to all major soilborne diseases — not just simply tolerant to diseases, which is what the best cultivars are today.

Growers basically wanted alternatives that wouldn't forgo yield, quality or higher profit — in other words, something foolproof. In an interview, one grower was emphatic on this point: "It has to be proven to me, I gotta see it. . . . But I'm not going to do it because [the UC breeder] says 'Oh, by the way, I have this variety that's resistant to *Macrophomina*, you don't need to fume.' Well, let me see that, you know what I mean?"

The more personalized setting of the interviews also allowed me to explore what growers would do if fumigants were taken away. Here I learned that while such a possibility heightened interest in disease-resistant varieties, several said that they would leave strawberries or retire early, and many said they would move to soilless regimes. As it happens, one of the challenges of soilless systems is finding cultivars that work in those settings. The performance of existing varieties is reportedly subpar.

Those interested in remaining "on ground" clarified that disease-resistant varieties would be helpful, but they would need to adopt other tools as well, such as nonchemical modes of soil disinfestation, making breeding for disease resistance only a partial solution.

One grower said, "Just having a variety that is tolerant of x, y or z only does so much. . . . . That would be just like added insurance."

Several growers noted the long pipeline to the development of good varietals, because of the lengthy time needed for testing and propagation. Some were also aware of the difficulty in breeding for multiple diseases and were skeptical that a truly disease-resistant variety could be developed. Some growers even suggested that industry and ecological conditions might be too dynamic for cultivars bred for specific conditions to be of use by the time they are developed.

The last survey question asked about the policies or practices that would encourage planting of a disease-resistant cultivar instead of fumigating and asked respondents to choose all answers that applied. Here again it appeared that additional regulatory restrictions would increase interest in disease-resistant cultivars (table 6), although it was clear that few growers would wish for such a situation. Were it to come about, support from UC Cooperative Extension could help aid the transition, as could financial support in terms of higher prices or subsidies. As of now, however, with fumigation still allowed, albeit restricted, most growers were concerned with other challenges: "To be honest, right now our focus is definitely in other factors. If the economics don't work, we can have the disease-resistant variety but we're not going to be able to farm it."

Is disease resistance a priority?

Overall, while there was still keen interest in seeing disease-resistant cultivars developed, disease resistance has become less of a priority for growers, mainly because other pressures have overtaken concerns with disease. It is also clear that disease-resistant varieties alone are unlikely to replace fumigation or, more to the point, convince growers to take the risks of reducing or forgoing fumigation.

As emphasized in a report issued by the California Department of Pesticide Regulation (DPR 2013) encouraging research into fumigation alternatives, without the magic bullet of chemical fumigation, disease management is more complex, and strawberry growers would need to incorporate a combination of complementary methods and technologies to address the changing economic, ecological and regulatory environment of strawberry production (also Lloyd and Gordon 2016). These complementary methods need continuing research support and testing in combination with each other. Consideration should also be given to ways of mitigating the costs of growing berries in this ever more challenging economic environment.

Does that mean breeders should turn to other priorities than disease resistance? Not at all. Regulation is unlikely to become less restrictive or pathogens less virulent, and at some point disease resistance will become imperative. Given the difficulty of breeding effectively for all desirable traits, it is arguable breeders should even double down on disease resistance and lighten up on yield. Although growers want yield, breeders responding to that are perpetuating the technology treadmill that contributes to low prices. Indeed, it is important that super-industry forces, those whose interests surpass those of individual growers, including university scientists, shippers and policy makers, aim to curb this prioritizing of yield by attending to the economic exigencies that make yield so important for growers. CA

TABLE 6. Factors that would encourage use of disease-resistant cultivars over fumigation

Factors encouraging disease-resistant cultivars	No. of reponses
Tighter restrictions on fumigants	8
Higher prices from buyers	6
Information from UC Cooperative Extension advisor or other UC personnel	5
Availability of data on cultivar yield when pathogens are present at different levels	4
None	3
Information from Cal Poly	2
Crop insurance against disease outbreaks	2
Direct cash subsidy	2
Subsidized field trial on farm	2
Other cost support	1
Total responses	**35**

J. Guthman is Professor of Social Sciences, UC Santa Cruz.

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RESEARCH ARTICLE

Agricultural managed aquifer recharge — water quality factors to consider

AgMAR could counteract groundwater overdraft, yet impacts to water quality must be considered — current growing season N management and historical legacy nitrate in the subsurface need to be taken into account.

by Hannah Waterhouse, Sandra Bachand, Daniel Mountjoy, Joseph Choperena, Philip A.M. Bachand, Helen E. Dahlke and William R. Horwath

Online: https://doi.org/10.3733/ca.2020a0020

Abstract

The resilience and productivity of California's agriculture is threatened by groundwater overdraft, reduction in aquifer water quality, increased land subsidence damage to infrastructure and an irreversible reduction in groundwater storage capacity. Intentionally flooding agricultural fields during winter — a practice referred to as agricultural managed aquifer recharge (AgMAR) — can help counteract overdraft. However, the potential for AgMAR to exacerbate nitrate/salt leaching and contamination of at-risk aquifers remains a critical concern. To quantify the risk of groundwater contamination with AgMAR, we took 30-foot-long soil cores in 12 almond orchards, processing tomato fields and wine grape vineyards on low- and high-permeability soils, measured nitrate and total dissolved solids concentrations and calculated stored nitrate-N. Wine grape vineyards on permeable soils had the least nitrate leaching risk observed. However, almond orchards and tomato fields could be leveraged for AgMAR if dedicated recharge sites were established and clean surface water used for recharge. Historical land use, current nitrogen management and soil permeability class are the main factors to consider before implementing AgMAR.

Agricultural managed aquifer recharge (AgMAR) is a concept in which farmlands are leveraged to capture legally and hydrologically available flood flows to recharge groundwater (Kocis and Dahlke 2017). In semi-arid regions, including much of California, there is great interest in AgMAR among water management and conservation districts. Although California contains some of the most productive agricultural regions in the United States, with over 400 crops, 9.8 million acres of cropland and $46 billion in agricultural output (CDFA 2018; USDA NASS 2017), much of the state is severely water limited. Many growers rely on groundwater to meet their irrigation needs, especially during drought years, when surface water is less available.

Groundwater supplies 40% of total water demand in California during nondrought years, and demand for groundwater is increasing as perennial crop acreage, such as almonds, increases (DWR 2014; Massoud et al. 2018). From 2005 to 2010, the Central Valley aquifer experienced between 5.5 and 13 million acre-feet of groundwater overdraft, and, in many locations,

Paolo Vescia

Flooding agricultural fields can help recharge depleted aquifers. Of the three crops the authors studied, wine grapes grown on highly permeable soils had the least risk for nitrate leaching.

groundwater levels declined more than 100 feet below previous historic lows, driven by the 2007–2009 drought (DWR 2014).

These water challenges are expected to increase in the coming decades as climate models predict more variation in average precipitation, resulting in earlier snowmelt, more precipitation as rain, increased frequency of extreme events, including droughts and floods, and earlier and more extreme runoff events (Thorne et al. 2012). Some of these changes are already apparent in the observational record, including a larger fraction of annual precipitation falling in a smaller number of more intense events (Russo et al. 2013). It is imperative that California's water infrastructure be able to capture and convey sufficient water to meet municipal, agricultural and environmental water needs.

In 2014, California passed the Sustainable Groundwater Management Act (SGMA) in response to dropping groundwater levels exacerbated by the 2012–2016 drought. The aim of the legislation was to maintain adequate groundwater resources in perpetuity. SGMA mandates that groundwater sustainability agencies, responsible for 95% of statewide groundwater pumping, develop and implement plans for critically overdrafted groundwater basins to achieve sustainable groundwater use by 2040. These plans will provide new opportunities for groundwater recharge and storage.

Traditional recharge methods such as dedicated infiltration basins and injection wells are usually costly, time consuming to construct and spatially limited. For those reasons, and because there is a large amount of irrigated cropland acreage available in California, many water management and irrigation districts are considering AgMAR as a more cost effective and potentially higher impact form of groundwater recharge than traditional methods. Additionally, AgMAR has many potential benefits, including increasing water tables, which would decrease pumping costs for growers, flushing salts from the root zone, mitigating subsidence and increasing groundwater storage capacity, which could act as a buffer through future droughts.

Recently, the California Department of Water Resources (DWR) established a research advisory committee to develop expertise to aid in the expansion of AgMAR. The Kings River Conservation District plans to enroll 16,000 acres, with the capacity to divert 500 cubic feet per second of flood flows, potentially diverting 30,000 acre-feet of water monthly (Bachand et al. 2016). To assist planners and water agencies in targeting appropriate lands to implement AgMAR, O'Geen et al. (2015) developed the Soil Agricultural Groundwater Banking Index (SAGBI), which identifies potentially suitable agricultural land for AgMAR based on NRCS (USDA Natural Resources Conservation Service) digital soil survey data. SAGBI determines soil suitability based on five factors: deep percolation, root zone residence time, topography, chemical limitations (such as salts) and soil surface condition. These five factors were used to classify lands into six categories ranging from "very poor" to "excellent." Absent from SAGBI, however, are the factors of historical land use and current management practices, which deserve consideration before implementation of AgMAR.

Only a few pilot studies of AgMAR, limited to collaborative research projects between UC Davis, local water management and conservation districts, environmental consulting companies and landowners, have been conducted (Bachand et al. 2016; Dahlke et al. 2018). However, although small, those studies (on alfalfa, tomatoes, wine grapes, almonds and pistachios) found promising results for AgMAR in terms of its cost effectiveness, scaling potential, capacity for increasing groundwater storage and compatibility with grower operations.

Effects on groundwater quality

Uncertainty remains on how AgMAR efforts could impact groundwater quality. Residual contaminants, such as nitrates (NO_3^-), from historical fertilizer applications (i.e., legacy contaminants) could be mobilized and transported to groundwater. AgMAR could also mobilize salts present in the vadose zone of agricultural fields, the unsaturated portion between the surface and the water table; and, if the groundwater is already contaminated, AgMAR could also mobilize contaminated pore water left in the vadose zone by falling groundwater levels.

Contaminants may also be moving past the root zone as a result of poor fertilizer management in a current season. Crop nitrogen (N) use efficiency

A Geoprobe push-drill system was used to collect soil cores to 30 feet in depth in fields planted in almonds, tomatoes and wine grapes in the Kings groundwater subbasin.

varies across crop type, soil type, fertilizer application method and irrigation practice, with plants typically taking up less than 50% of N applied and the rest leaching below the root zone (Tomich et al. 2016). Additionally, inorganic fertilizers and manure provide N in the form of salts, such as sodium nitrate, ammonium chloride or ammonium sulfate. These salts, combined with naturally occurring salts and salts from irrigation water, increase residual total dissolved solids (TDS) in the soil pore water and could leach to the groundwater.

Harter et al. (2012) quantified nutrient loading to groundwater in the Tulare Lake Basin and the Salinas Valley from various agricultural crops and other sources, such as septic systems, animal corrals and manure storage lagoons. In total, the study concluded that 215,000 tons N/year is leached from cropland to groundwater, accounting for 94% of all NO_3^- leaching in the study area. Furthermore, they estimated NO_3^- leaching intensity by crop, with vineyards leaching, on average, 31 pounds N/acre/year, tree crops leaching 80 to 90 pounds N/acre/year and vegetables leaching over 90 pounds N/acre/year (Harter et al. 2012).

In the Central Valley, three significant regulatory programs have been implemented to regulate groundwater quality: the Central Valley Dairy General Order, the Irrigated Lands Regulatory Program and the Central Valley Salinity Alternatives for Long-Term Sustainability. All three programs necessitate groundwater quality monitoring and development of management plans to reduce contaminant discharge to groundwater. With efforts under way to increase groundwater recharge on agricultural land, understanding the effect of AgMAR on NO_3^- and salt leaching and the risk of increased groundwater contamination is essential for growers to benefit from this practice while remaining in compliance with regulations.

To determine the potential risk of NO_3^- and salt leaching under AgMAR, we analyzed soil core data from 12 fields, with significant differences in soil texture and crops, within the Kings groundwater subbasin. Our goal was to quantify the potential risk of groundwater contamination from legacy and current concentrations of NO_3^- and TDS that different cropping systems and soils could pose under AgMAR. The study focused on three common specialty crops — almonds, processing tomatoes, wine grapes — and two different soil groups — low- and high-infiltration soils. Our two central hypotheses were (1) vadose zone chemistry is affected by crop type and land management and (2) soil infiltration characteristics affect residual NO_3^- and TDS concentrations in the vadose zone and overall leaching potential.

Kings subbasin

The study area is within the Kings groundwater subbasin west of Fresno, which was designated as critically overdrafted by DWR in 2014. Depth to groundwater in the basin is 20 to 220 feet, with an estimated annual decrease in storage of 288,000 acre-feet based on changes in storage from 2003 to 2014 (KRCD 2014). DWR determined that 20% of wells sampled were above the 10 milligrams nitrate–N (NO_3^-–N)/liter and 16% were above the 500 milligrams TDS/liter recommended drinking water quality standard (SWRCB 2018).

The subbasin is characterized by fertile, alluvial soils supporting over 500,000 acres of irrigated land. Fresno County grows a diversity of crops with a gross total value of $6.58 billion (CDFA 2017). In this study, we targeted the three specialty crops with the largest acreage, which are in the top 10 agricultural commodities in the area: almonds, processing tomatoes and wine grapes.

Soil cores, analysis

Replicate cores ($n = 3$) were collected to 30 feet in depth in fields planted in almonds, tomatoes and wine grapes, and representing two different NRCS hydrologic soil classes: Class A and Class C/D. Class A soils are defined as having low surface runoff potential and a relatively high saturated hydraulic conductivity, greater than 5.67 inches/hour (USDA NRCS 2016); Class C soils have moderately high surface runoff potential and relatively low to medium saturated hydraulic conductivity, of 0.14 inch/hour to 1.42 inches/hour. Class D soils have a high runoff potential and a low saturated hydraulic conductivity, of less than 0.14 inch/hour.

Class A soils correspond to SAGBI soils rated as "excellent," "good" and "moderately good," whereas Class C and Class D soils correspond to "very poor," "poor" and "moderately poor." C and D soils were included in this study because in farmland situations — especially in orchard and vineyard systems, which were considered in SAGBI — they are often deep tilled to remove restrictive soil horizons and to increase infiltration and deep percolation (O'Geen et al. 2015).

A total of 36 soil cores were collected with the following sampling scheme: three cores from each of the three crops and two soil classes with two field replicates. The cores were collected from six farms in total, not uniformly distributed by grower but collected based on field accessibility. Cores were taken with a Geoprobe push-drill system (Geoprobe Systems, Salina, Kansas) and analyzed in the lab for soil NO_3^-–N, texture, water content and salts. Stored NO_3^-–N was calculated on a per-acre basis considering the entire 30-foot profile.

Farm practices survey

Grower surveys were conducted to understand historical and current agricultural management practices, including previous cropping systems, irrigation practices and amount, and fertilizer sources and amount of N applied (table 1).

Annual applied N loads and irrigation amounts in almonds ranged from 180 to 300 pounds N/acre and 3.0 to 3.9 acre-feet water applied; in tomatoes, 50 to 275 pounds N/acre and 2.3 to 4.0 acre-feet of water applied; and in wine grape systems, 40 to 215 pounds N/acre and 2.5 to 3.0 acre-feet of water applied. Most sites used microirrigation systems such as buried drip irrigation or microsprinklers; however, a few sites still used flood irrigation.

TABLE 1. Crops and farm management practices at 12 study sites

Site code	Alm A1	Alm A2	Alm CD1	Alm CD2	Tom A1	Tom A2
Crop	Almond	Almond	Almond	Almond	Tomato	Tomato
Soil hydrologic group	A	A	C/D	C/D	A	A
Fertilizer use						
Stored NO_3^-–N mean and standard deviation (kg–N/ha)	714.02 (247.32)	942.48 (264.93)	1,239.58 (582.38)	420.22 (42.92)	737.40 (62.96)	966.35 (203.56)
Type of fertilizer	NA*	CAN-17	NA	UAN-32, chicken manure	NA	UAN-32
Method of application	Fertigation	Fertigation	Chiseled	Synthetic: fertigation Manure: spread on ground	Fertigation	Fertigation
Quantity (lb–N/ac)	180	190	250	Synthetic: 250 Manure: 5 tons	250–275	50
Last application	Oct	Oct	Oct	Dec	Late Aug	Mid Aug
Annual application timing	Feb through end of May as needed; fall application in Oct	4–6 applications starting in Jan and finishing in Jun; fall application starts in Sep	3 applications: fall, spring, summer	Synthetic: 3: Feb, Apr, Jun Manure: Dec	1 per week	1 every 2 weeks
Production						
2nd crop	NA	NA	NA	NA	Onions	Carrots
2015 yield (ton/ac)	0.64	1.10	0.94	1.65	68	62
5-year average yield (ton/ac)	1.30	1.13	0.89	1.60	68	60
Field preparation						
Tillage depth	NA	NA	NA	6 in, every other year	Beds: 10 in Rows: 16 in	30 in
Deep ripped	Yes	No	No	Yes	No	No
Cover crop	No	No	No	No	No	No
Irrigation						
Method	Double-line surface drip, microsprinkler, and flood	Surface drip, flood 1 time per year	Flood	Surface drip	Subsurface drip	Subsurface drip/ sprinklers
Water source	Groundwater, surface water when available	Surface water, groundwater	Surface water, groundwater	Groundwater	Groundwater	Groundwater
Annual amount (ac-ft)	3.6	3.0	NA	3.9	4.0	2.3
Timing		Feb–Nov	Feb–Oct	Feb–Nov	Apr–Jul	Apr/May–Jul
Frequency	Daily during summer peak	Daily during summer peak	Every 2 weeks	Daily during summer peak	3 days on, 2 days off during summer peak	1 per week, daily during summer peak
Last irrigation of season	Oct	Nov	Oct	Nov	Sep	Mid Aug
Ever flooded	Yes	Yes	No	No	No	No
Crop history						
Age of orchard/vineyard (yrs)	7	18	20	9	NA	NA
Prior crop	Almonds	Cotton/wheat	Alfalfa	Wheat	Carrots	Tomatoes

* NA = not available.

Soils effects on NO_3^- distribution

Soils vary in their ability to convey water and solutes to the vadose zone, and ultimately groundwater, and thus will behave differently under AgMAR. We found that C/D soils had significantly higher stored NO_3^-–N (732 pounds N/acre) than A soils (542 pounds N/acre) across the entire 30-foot profile (fig. 1). The same pattern was found in the root zone only (0 to 3 feet), with C/D soils having statistically higher stored NO_3^-–N (291 pounds

TABLE 1 (continued). Crops and farm management practices at 12 study sites

Site code	Tom CD1	Tom CD2	WGr A1	WGr A2	WGr CD1	WGr CD2
Crop	Tomato	Tomato	Wine grapes	Wine grapes	Wine grapes	Wine grapes
Soil hydrologic group	C/D	C/D	A	A	C/D	C/D
Fertilizer use						
Stored NO_3^-–N mean and standard deviation (kg–N/ha)	736.60 (109.89)	826.40 (443.22)	74.85 (16.94)	209.55 (123.96)	326.25 (129.91)	1,370.82 (705.11)
Type of fertilizer	NA	UAN-32	UAN-32	UAN-32	NA	NH_3
Method of application	Fertigation	Fertigation	Fertigation	Chiseled	NA	Chiseled in/ fertigation
Quantity (lb–N/ac)	250–275	246	215	40	NA	75
Last application	Late Aug	Mid Aug	Jun	Oct	NA	Early spring
Annual application timing	1 per week	1 every 2 weeks	As needed in spring	Spring and postharvest	NA	1 time
Production						
2nd crop	Onions	Tomatoes	NA	NA	NA	NA
2015 yield (ton/ac)	68	62	3.15	3.50	NA	13.92
5-year average yield (ton/ac)	68	60	2.75	2.36	NA	11.09
Field preparation						
Tillage depth	Beds: 10 in Rows: 16 in	30 in	24 in	6 in	NA	8 in
Deep ripped	No	No	Yes	Yes	NA	Yes
Cover crop	No	No	No	No	NA	No
Irrigation						
Method	Subsurface drip	Subsurface drip	Surface drip and furrow flood	Flood	NA	Surface drip
Water source	Groundwater	Groundwater	Surface water, groundwater	Surface water, groundwater	NA	Groundwater
Annual amount (ac-ft)	4.0	2.3	3.0	2.5	NA	3.0
Timing	Apr–Jul	Apr/May–Jul			NA	
Frequency	3 days on, 2 days off during summer peak	1 per week, daily during summer peak	4 days per week during summer peak	Every 3 weeks during summer peak	NA	Daily during summer peak
Last irrigation of season	Sep	Mid Aug	Oct	Oct	NA	Oct
Ever flooded	No	No	Yes	No, except for normal irrigation practices	NA	No
Crop history						
Age of orchard/vineyard (yrs)	NA	NA	25	19	NA	20
Prior crop	Carrots	Tomatoes	Almonds	Wine grapes	NA	Cotton

* NA = not available.

N/acre) than A soils (164 pounds N/acre). However, no statistical difference was found between soil classes below the root zone (3 to 30 feet), as the classifications are applicable only to 3.0 to 6.6 feet.

Class A soils may be well suited for conveying large amounts of recharge water to an underlying aquifer due to their high infiltration rates, but these soils tend to be more prone to NO_3^- loss below the root zone during normal irrigation events (Bergström and Johansson 1991). These coarser-textured soils are also associated with lower microbial biomass and thus lower fertility compared to finer-textured soils (Chau et al. 2011). Together, these factors may lead to overfertilization of A soils, and over many growing seasons higher rates of NO_3^- loss to the vadose zone and a greater impact on underlying groundwater than with C/D soils.

In contrast, C/D soils are characterized by low infiltration rates and low permeability due to their higher clay content, so they hold more water and thus retain more NO_3^- in small pores (Thomas 1970). These finer-textured soils are also associated with higher microbial biomass and often higher fertility, with the potential for less N inputs, if budgeted for, and lower compounding rates of overfertilization (Chau et al. 2011). However, they may be less suitable for conveying large amounts of water to the underlying aquifer.

With efficient methods of irrigating (drip and sprinkler), water movement and NO_3^- leaching below the root zone are limited. During AgMAR events, however, the infiltrating water can bring soils quickly to field capacity, allowing for faster water flow and movement of the stored NO_3^- into deeper depths, as the soil macropores are activated (Harter et al. 2005; Jarvis 2007; Thomas 1970). Both classes of soil have distinct challenges with respect to mitigating NO_3^- loss, necessitating specific growing season nutrient management guidelines tailored to soil type prior to an AgMAR event, as well as careful management of the flooding event. To minimize NO_3^- contamination of groundwater, further studies (table 2) are needed on how the amount and the frequency of floodwater applications affect NO_3^- movement in contrasting soil types.

Crop effects on NO_3^- distribution

Crop systems vary in their nutrient and water use efficiencies and requirements, which affects the concentration of NO_3^- in the vadose zone. It's essential before implementing AgMAR to understand the complex set of variables that interact to affect NO_3^- leaching and to target those crops with the lowest NO_3^- footprints.

While NO_3^-–N concentrations decreased with depth across both soil classes and all crops, 17% of all samples were above the 10 milligrams NO_3^-–N/liter EPA drinking water quality limit, a majority of which were below 3 feet (fig. 2). We found that mean stored NO_3^-–N in almond (740 pounds N/acre) and tomato (729 pounds N/acre) cropping systems were significantly higher than in wine grape (442 pounds N/acre) cropping systems throughout the entire 30-foot profile, with no significant statistical difference between almonds and tomatoes (fig. 3A). Within the root zone (0 to 3 feet), wine grapes (182 pounds/acre) had statistically lower stored NO_3^-–N than tomatoes (269 pounds/acre); however, no statistical difference was found between wine grapes and almonds (164 pounds/acre), or almonds and tomatoes. Below the root zone, the same pattern as the entire profile was observed, with almonds and tomatoes having significantly higher stored NO_3^-–N than wine grapes. In summary, we found that land use at the surface affects the nitrate footprint in the vadose zone.

Cropping systems have unique nutrient and water requirements that need to be considered in relation to

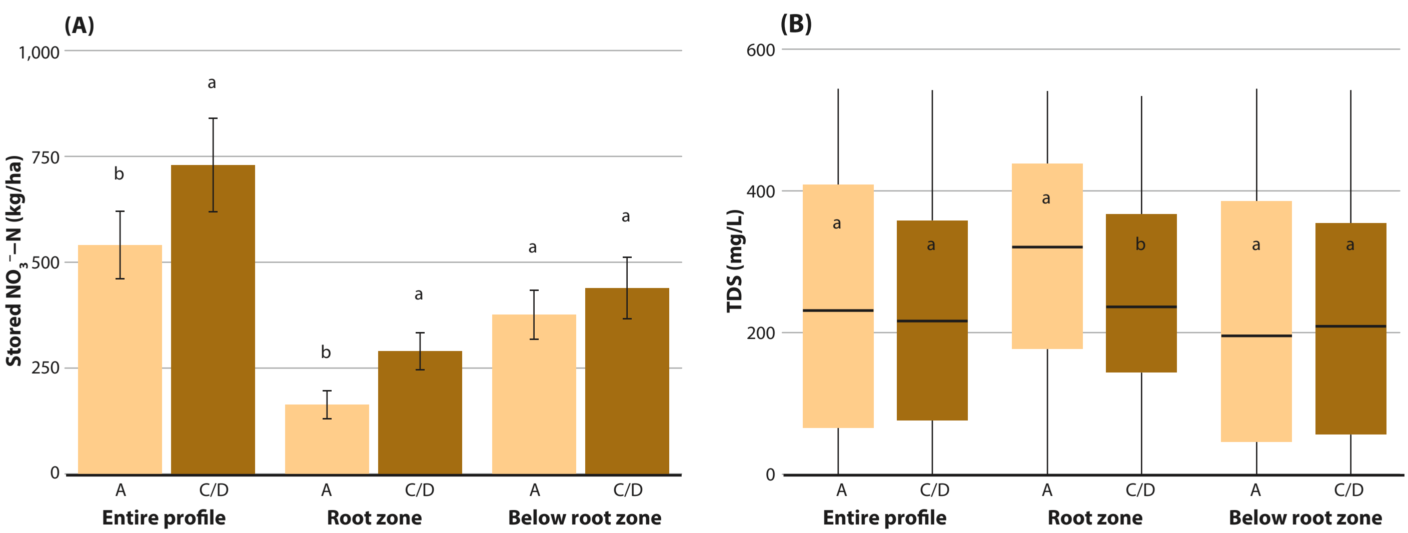

FIG. 1. (A) Mean stored NO_3^-–N (lbs/ac) with standard error bars shown (n = 36) and (B) TDS concentrations (mg/L) with bars representing range of data (n = 36) by soil class at varying sections of the profile: across the 30-foot profile, within the root zone (0 to 3 feet) and below the root zone (3 to 30 feet). Letters represent significant differences ($p < 0.05$) between soil classes within each section.

TABLE 2. Potential concerns about AgMAR, suggested precautionary steps and future research needs by soil class, crop type and water and N management

Soil type	Potential concerns	Precautionary steps	Future research
A (permeable soils)	• More prone to NO_3^- loss • Historical overfertilizing due to lower fertility	• Understand historical fertilizer application rates • Test root zone for NO_3^- prior to AgMAR • Ensure recharge water is free of NO_3^- • Assess root zone total N storage and soil mineralization potential, account for in nutrient budgeting • Implement soil-specific crop N applications	• Whether groundwater underlying permeable surface soils is more contaminated with NO_3^- than groundwater under less-permeable surface soils • Effect of AgMAR flood amount and frequency on NO_3^- movement • Understanding of water conveyance potential of less-permeable soils that have been deep ripped • Decision support tools to assess impacts of AgMAR on groundwater quality and quantity
C/D (less-permeable soils)	• Water conveyance could be low if soil is not previously deep ripped. • Large NO_3^- stores within the root zone could be leached.		
Crop type	**Potential concerns**	**Precautionary steps**	**Future research**
Almonds (perennial crop with high N demand)	• Fall applications of fertilizer make more N available for loss during a subsequent AgMAR event.	• Target low–N crops initially • Fertilizer 4 Rs: right source at the right rate at the right time in the right place (especially, apply N in increments matched to timing of crop uptake) • Account for N in irrigation water and residual N in soil • Apply N for the realistic yield goals • Do not apply N in fall	• Effect of AgMAR on following year N budgeting • Effect of AgMAR on future yields and N use efficiency • Modeling studies examining the amount of water and time needed to dilute incoming NO_3^- to groundwater to improve groundwater quality • Quantity of water needed to dilute incoming NO_3^- to groundwater
Tomatoes (annual crop with high N demand)	• Double cropping can lead to more N applied per year and greater N loss. • Shallow-rooted crops can lead to more NO_3^- loss to the vadose zone.		
Wine grapes (perennial crop with lower N demand)	• Early spring applications of fertilizer can be subject to loss during sprinkler frost protection.		
Management practices	**Potential concerns**	**Precautionary steps**	**Future research**
Water	• Inefficient irrigation can cause leaching of NO_3^- below the root zone. • Drip irrigation can lead to buildup of residual NO_3^- in the root zone at the end of the growing season if not managed properly and could be mobilized under AgMAR.	• Steps listed in precautionary steps for crops • Using cover crops to recapture residual N after the growing season • Using dedicated fields for recharge • Choosing sites with known low–N history	• Research needs listed in future research for crops • Practices during flooding that increase denitrification, the conversion of NO_3^- to N_2, such as buried reactive barriers • How AgMAR events at same time and in same basin on multiple sites and varying cropping systems affect groundwater quality in that basin • Whether water can be injected below the root zone on agricultural land to bypass NO_3^- from the root zone • Winter cover cropping as a way of capturing residual NO_3^- and reducing loss during AgMAR flooding
Nitrogen	• N applied in excess of crop needs or at the wrong time is subject to loss. • Growers' risk aversion to yield loss is a barrier to N rate reductions. • Lack of soil and irrigation N accounting in nutrient plans can lead to overapplication of N.		

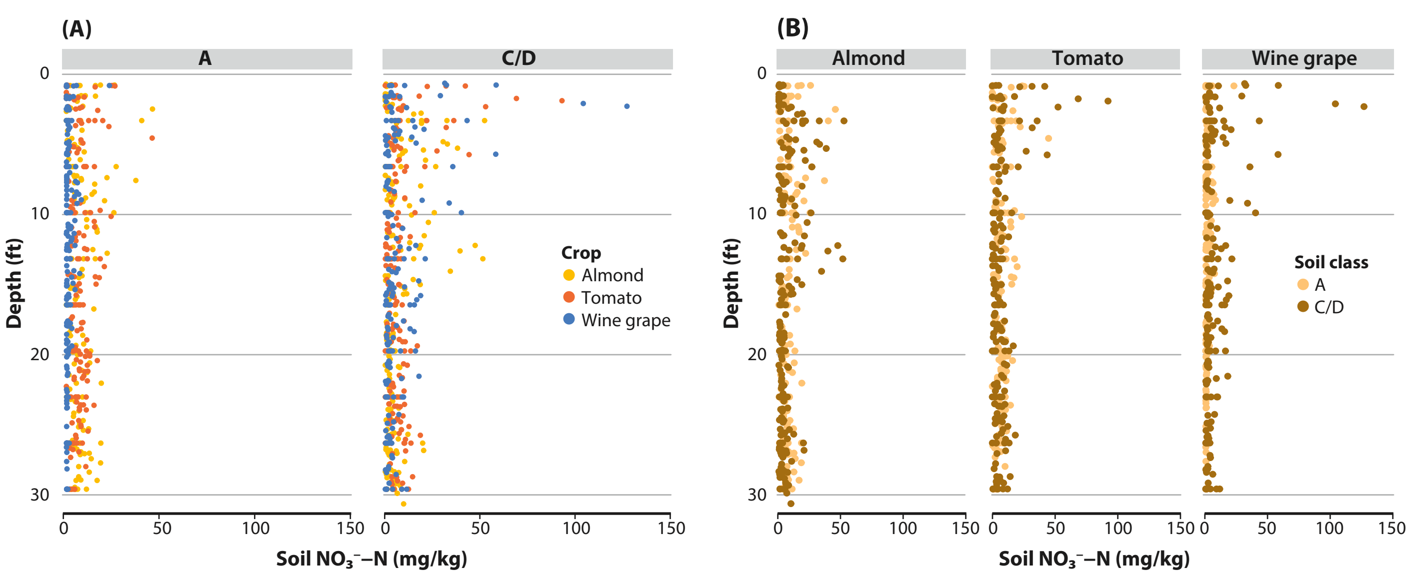

FIG. 2. Soil NO_3^-–N profiles (ug NO_3^-–N/g soil) down to 30 feet by (A) crop and (B) soil class (n = 1,058).

AgMAR. For example, almonds are generally fertilized in multiple applications, including a fall application. This practice should be avoided or delayed if AgMAR is to be implemented. Similarly, annual cropping systems, such as tomatoes, allow for double cropping, which can intensify the yearly N load to the land surface and over time compound the legacy NO_3^- in the vadose zone. Furthermore, annual crops have shallower rooting systems compared to perennial crops, making them more prone to NO_3^- loss to the vadose zone below the rooting depth. Wine grapes require protection from frost in early spring, which is achieved by sprinkler irrigation; however, applications of NO_3^- from fertilizer during this time could be subject to loss. These practices may need to be adjusted under AgMAR (table 2).

Rooting depth and water/nutrient uptake could also influence the depth of NO_3^- leaching (Dzurella et al. 2015). From our results, wine grape cropping systems, with low N inputs and deep roots (5 to 6.5 feet, Smart et al. 2006), were found to have the lowest amounts of N stored in the vadose zone and therefore would be the crop with the least NO_3^- leaching risk among the three crops we studied. Deep-rooted crops extend the zone for recapturing NO_3^- and more efficiently reduce the amount of NO_3^- lost to the vadose zone, perhaps explaining the differences seen below the root zone between the wine grapes and the almonds and tomatoes (Machado and Oliveira 2005). This finding is consistent with the UC Nitrate Groundwater Pollution Hazard Index, which rates wine grapes lower on the hazard index due to the crop's deep roots and low N inputs (Dzurella et al. 2015).

TDS concentrations differed significantly across cropping systems (fig. 3B). Comparing the 30-foot profiles, almonds had the lowest TDS concentrations, with a median value of 166 milligrams/liter, whereas tomatoes and wine grapes had the highest TDS concentrations, with median values of 259 milligrams/liter and 264 milligrams/liter, respectively; there were no significant differences between wine grapes and tomatoes (fig. 3B). Within the root zone, the same pattern existed: almonds showed lower TDS concentrations (176 milligrams/liter) than tomatoes (322 milligrams/liter) and wine grapes (316 milligrams/liter). However, TDS concentrations below the root zone did not show significant differences between cropping systems, indicating that the significant differences found for the entire profiles were influenced by root zone TDS. A potential reason for the TDS differences found between cropping systems could be the fertilizer source, especially those fields which historically used or currently use manure, which contain relatively high levels of salts. Other sources could include irrigation water. However, the reasoning is speculative, as we did not have enough data to test this hypothesis.

Total TDS stored in the entire profile for almonds, tomatoes and wine grapes were 66,000 pounds/acre, 62,000 pounds/acre and 64,000 pounds/acre, respectively. Only 7% of TDS concentrations in our study

Wine grape cropping systems, with low N inputs and deep roots, were found to have the lowest amounts of N stored in the vadose zone and therefore would be the crop with the least NO_3^- leaching risk among the three crops we studied.

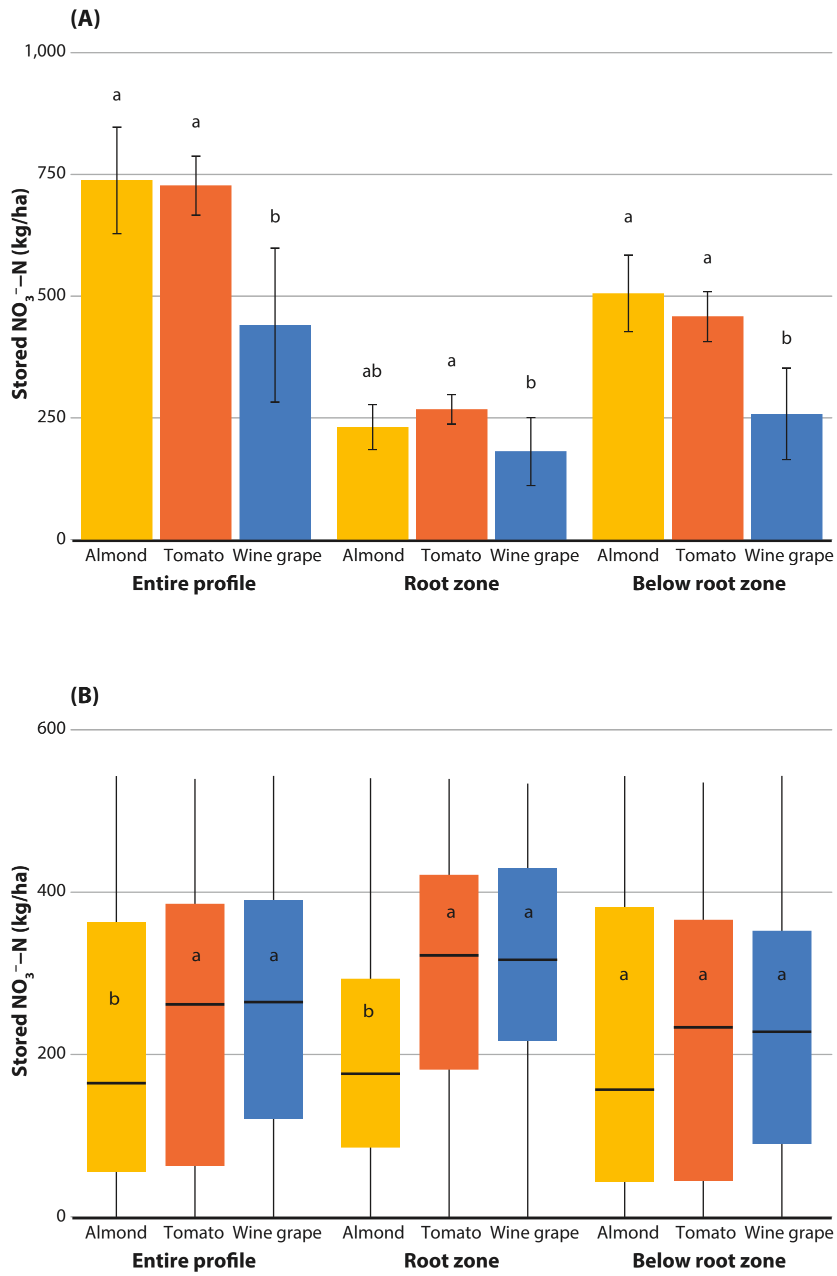

FIG. 3. (A) Mean stored NO_3^-–N (kg/ha) with standard error bars shown (n = 36) and (B) TDS concentrations (mg/L) with bars representing range of data (n = 36) by crop at varying sections of the profile: across the 30-foot profile, within the root zone (0 to 3 feet) and below the root zone (3 to 30 feet). Letters represent significant differences (p < 0.05) between crops within each section.

were above the California State Water Resources Control Board's (2017) recommended secondary maximum contaminant level of 500 milligrams/liter, with almonds, tomatoes and wine grapes having 29, 22 and 20 samples, respectively, above the recommended level.

When considering AgMAR, choosing cropping systems that have the lowest potential for NO_3^- and TDS loading to the underlying aquifer is an important consideration. These cropping systems could be targeted first as more research on AgMAR and water quality is conducted. Well established practices to increase N uptake and reduce NO_3^- loss should be emphasized; such as the fertilizer "4 Rs" (right source of fertilizer, at the right rate, at the right time, and in the right place), accounting for N in irrigation water and residual N in the soil and adjusting fertilizer inputs accordingly, fertilizing for realistic yield goals, and not applying nitrogen in the fall should help reduce N loss under normal conditions and under AgMAR management. Furthermore, using surface water that is relatively free of NO_3^- for recharge on dedicated fields could dilute the incoming NO_3^- to groundwater, even in systems with higher NO_3^- footprints such as almonds and tomatoes (table 2). Future research should focus on the effect of AgMAR on future yields and N use efficiency, on the N budget of the following growing season, and the quantity of water needed to dilute incoming NO_3^- to groundwater. Modeling studies could be well suited to assist groundwater sustainability agencies in determining the timing and quantity of NO_3^- reaching groundwater under AgMAR in varying cropping systems and the effect on groundwater quality.

TABLE 3. Summary of output statistics for hierarchical mixed effects model

Fixed effects	Estimate	Standard error	*t* value	*p* (> |*t*|)
Intercept	0.003	0.2093	−0.01	0.99
Clay	0.06	0.0284	2.17	0.03
Silt	0.15	0.0283	5.21	0.00
Sand	−0.05	0.0293	−1.61	0.11
Moisture	0.26	0.0280	9.14	0.00
Depth	−0.21	0.0242	−8.80	0.00
TDS	0.02	0.0263	0.61	0.54
Random effects*	**Variance**	**Standard deviation**		
Farm	0.23	0.47		
Crop	0.10	0.32		
Soil hydrologic class	0.02	0.14		
Residual	0.64	0.80		
Marginal R^2	0.14			
Conditional R^2	0.44			
df = 1,040				

Hierarchical mixed-effects models account for the hierarchical structure, or clustering, of the data (in this case, "soil group" is nested in "crop," which is nested in "farm"). All estimated coefficients have been standardized.

* Conditional R^2 refers to the overall model, including random and fixed effects; marginal R^2 is for fixed effects only. The variance for random effects indicates how much variation that variable accounts for in relation to the remaining unexplained variance. Higher numbers indicate more variance explained.

Management effects on NO_3^- distribution

While this study did not examine the effect of specific agricultural management practices on NO_3^-occurrence below the root zone, we did find that NO_3^-–N varied by grower, and a hierarchical mixed-effects model determined that individual farms accounted for the largest portion of the variation in the NO_3^- data (table 3). This suggests that management practices, such as irrigation management, fertilizer type and fertilizer application amount, timing and frequency, are the most important variables in affecting NO_3^- losses below the root zone and suggest opportunities to adjust management to reduce leaching.

Between the two sampled almond sites on C/D soils, there was a significant difference in mean NO_3^-N storage down to 30 feet (fig. 4A). While the reasons behind this difference are speculative, we observed that the

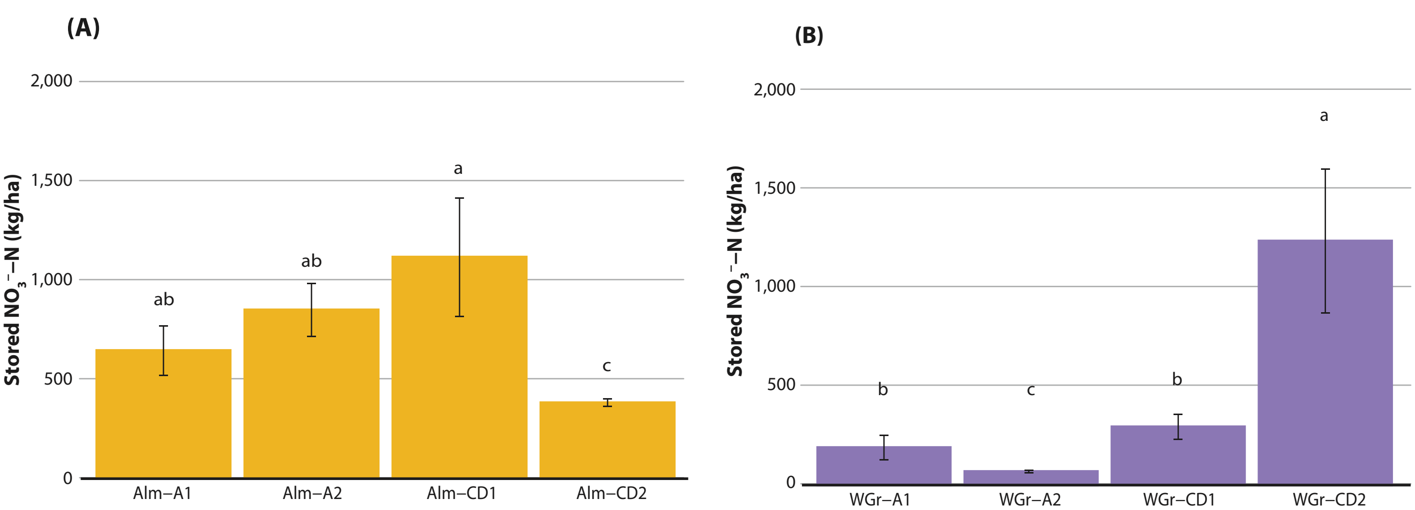

FIG. 4. Mean stored NO_3^-–N (kg/ha) by grower in (A) almonds and (B) wine grapes across the 30-foot profile. Error bars are standard errors. Letters represent significant differences ($p < 0.05$) between growers within each section.

farm with the lower stored NO_3^-–N in the 30-foot profile (Alm CD2) had higher yields and potentially higher N use efficiency than the other farm (Alm CD1), which applied a similar amount of N but had half the yield, indicating the importance of adjusting N applications to realistic yield goals (table 2).

Differences in NO_3^- were also found in the wine grape cropping systems, with WGr CD2 having statistically higher levels than all other farms, highlighting the importance of the impact of individual management on NO_3^- leaching (fig. 4B). This site differed from the other sites in that N fertilizer was applied all at once at the beginning of the season, whereas the other sites fertigated their fields, allowing for better dosage and timing of N availability to crop N demand, potentially increased N use efficiency, and mitigating NO_3^- loss below the root zone (Bar-Yosef 1999). Identifying which management practices lead to increased N use efficiency is imperative under normal irrigation management and in the context of AgMAR. Further studies are needed to examine the relationship between specific agricultural management and the effect on NO_3^- footprints in the vadose zone.

Furthermore, N fertilizer type, rate and method of application, type of irrigation system and amount of water applied in semi-arid and arid climates affect losses of NO_3^- below the root zone (Bar-Yosef 1999; Karandish and Šimůnek 2017; Kirchmann and Bergström 2001; Klocke et al. 1999). NO_3^- leaching was found to be higher in sprinkler-irrigated systems than drip-irrigated systems, with more residual NO_3^- in the root zone at the end of the season in the drip system (Barakat et al. 2016). Residual NO_3^- in a cropping system could be recaptured by a cover crop or accounted for in the following growing season's nutrient budget, improving the N efficiency of the system. Testing for root zone N after a growing season could be implemented prior to AgMAR to help decide whether the site is suitable for AgMAR or if a site with lower residual N would be more appropriate.

Establishing dedicated AgMAR sites for "clean recharge," using water with a low NO_3^- concentration such as snowmelt or rainfall runoff from the Sierra Nevada, may mitigate the impact on groundwater quality of the legacy NO_3^- and residual root zone NO_3^- (Harter and Dahlke 2014). Bachand et al. (2014) estimated that 39 acre-feet of high-quality, low-salinity surface water would be needed to move 2.25 pounds TDS per square foot through the vadose zone into the groundwater (assuming a mean electrical conductivity of 1 decisiemen/meter), and an equal amount of recharge would be needed to return the groundwater to its original background concentration. Assuming NO_3^- leached below the root zone behaves similarly to salts, application of low–N surface water could have similar impacts on NO_3^- concentrations in groundwater.

However, the timing and amount of high-quality surface water needed until groundwater dilution is achieved depends on the initial groundwater quality and management history of the site in relation to N lost below the root zone, and thus the land use and history of the site should be taken into consideration. In a Washington Orange orchard in Riverside County, Pratt et al. (1972) found 100% of soil NO_3^-–N concentrations were above the 10 milligram NO_3^-–N/liter drinking water quality standard set by the EPA. Similarly, Lund et al. (1974) found high levels of soil solution NO_3^-–N under a manure disposal site in Southern California, previously cropland, where beef feedlot manure was disposed of for 4 years, with all soil solution NO_3^-–N concentrations above 10 milligrams NO_3^-–N/liter. In contrast, Harter et al. (2005) found only 10% of soil NO_3^-–N concentrations were above the drinking water quality standard in a nectarine orchard in Fresno County. These legacy NO_3^- differences could be attributed to differing land use and management practices and the history of the site, which have important implications for the selection of groundwater recharge sites. Estimating both historical and current N mass balances could be one approach to understand the NO_3^- footprint of that particular site and the risk it poses to groundwater quality under AgMAR management.

Loss of NO_3^- from the root zone under AgMAR is a concern for growers and other stakeholders with regards to potential reduced yields and water quality. This concern represents a barrier for growers wanting to implement AgMAR on certain soils and with certain cropping systems while remaining in compliance with the Irrigated Lands Regulatory Program's waste discharge requirements. Furthermore, there is potential to compound the NO_3^- leaching problem if NO_3^-, which could have been accounted for in a grower's nutrient management plan, is lost below the root zone during AgMAR, and must be added as an additional external N fertilizer input the following growing season after AgMAR has been implemented. Strategies that reduce N applications (including nutrient management budgets that account for soil and irrigation water NO_3^-), improve the timing between N availability and crop N demand, improve N use efficiencies, promote conversion of NO_3^- into less harmful forms such as dinitrogen gas, and recapture residual NO_3^- in the root zone (i.e., cover cropping) should be implemented to reduce NO_3^- leaching below the root zone and mitigate additional NO_3^- leaching under AgMAR (table 2). Ultimately, careful N management leading up to an AgMAR event, combined with dedicated recharge sites, could reduce the risk of NO_3^- leaching.

AgMAR going forward

AgMAR is a promising practice for replenishing California's groundwater after decades of overdraft. However, historic NO_3^- buildup in the vadose zone and current rates of NO_3^- loss below the root zone represent a potential threat to groundwater quality and a barrier to adoption of AgMAR. We found that wine grapes grown on highly permeable soils have the lowest

NO_3^- footprint of the three cropping systems and two soil classes we studied. While wine grapes potentially represent the best candidate cropping system for AgMAR, other cropping systems could be leveraged for AgMAR if dedicated "clean recharge" sites are established. If only Central Valley grape cropping systems were leveraged for AgMAR and adequate excess flooding water was available, roughly 460 million acre-feet of water per day could be recharged on lands rated by SAGBI as "excellent" and "good," assuming 1 foot per day of infiltration (O'Geen et al. 2015).

Barriers to implementation across cropping systems include a lack of scientific evidence for how AgMAR may affect yields, a lack of capacity to move water from irrigation canals to fields, and floodwater being available only when AgMAR might interfere with growing season operations. Future studies examining the effects on a site's NO_3^- footprint of land use history, climate, or specific management practices such as tillage or irrigation system could be used to improve our understanding of NO_3^- leaching risk under AgMAR. Furthermore, work should be conducted on management of floodwater during an AgMAR event and the interactive effect with soil type on NO_3^- movement to groundwater. CA

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RESEARCH ARTICLE

Terminated marketing order provided resources to California peach and nectarine growers

The authors found that industry information provided via marketing orders was a significant factor for respondents who voted to continue the orders.

by Zoë Plakias, Rachael Goodhue and Jeffrey Williams

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Abstract

Marketing orders allow farmers to collectively fund industry-wide services that may be difficult to provide through a voluntary approach. But not all farmers support collective approaches. We employed ballot data from U.S. Department of Agriculture and survey data we collected to explore why farmers in California voted to terminate the federal fresh peach and nectarine marketing orders in 2011 and the implications of this termination. Even after controlling for other factors, we found that farmers who produced more were significantly less likely to vote for continuation. We also found that detailed industry information provided via the marketing orders was significantly more important to respondents voting for continuation, and respondents with more organic production were significantly more likely to vote for continuation. These results suggest farmers may have lost important production and marketing resources due to termination of the orders, with evidence that smaller farms were more affected. This termination may thus have accelerated the exit of farmers from this industry.

In 2011, growers of fresh peaches and nectarines in California voted in a referendum to terminate the two federal marketing orders that enabled collective funding of marketing and production research, market development and enforcement of quality standards. These marketing orders, formed and continued through regular grower votes and U.S. Department of Agriculture (USDA) approval, had existed for more than 50 years (Federal Register 2011a). The goal of these marketing orders was to stimulate consumer demand for the crops via marketing and production research, to lower production costs via production research, and to maintain a positive industry reputation among consumers via quality standards. The orders were terminated after they failed to meet the voting threshold needed for continuation. The USDA cited increases in on-farm research and private quality standards imposed by retailers as reasons for the lack of sufficient grower support (Federal Register 2011b).

Modern marketing orders must adapt to meet the diverse and evolving needs of the growers in their industries.

Evett Kilmartin

Continuation of the marketing orders required support from either (1) two-thirds of those voting or (2) producers of two-thirds of the output of those voting. This voting rule is the standard rule for federal marketing orders; the rules differ for federal research, commodity and promotion programs and similar types of state-level organizations. Among both fresh peach and nectarine growers, more than 60% of farmers voting in the referendum voted for continuation, but in each case they represented just over 30% of the total output of those voting (Federal Register 2011a). Although very close to meeting the first voting threshold, because neither threshold was met, the marketing orders for both crops were terminated. When voting, producers could select either "continue" or "terminate" on their ballot for each crop, so we refer to the "continuance referendum" in line with USDA terminology and the "termination vote" to indicate the referendum's outcome for both crops.


Evett Kilmartin

The results from this referendum suggest an important link between the value of the marketing orders to farmers and farm size (specifically, farms' production of fresh peaches and nectarines). However, farm size was not the only factor in farmers' votes. We examined which characteristics of both farms and farmers predicted farmers' support for these marketing orders, and whether these factors are consistent with the reasons for termination the USDA highlighted in their justification for the termination (Federal Register 2011b). We also analyzed farmers' behavior after the termination of the orders. To carry out this work, we used survey data collected from farmers about their fresh peach and nectarine production and USDA ballot data from the 2011 referendum containing farmers' votes.

Marketing orders and related programs (often collectively referred to as "check-offs") are under increasing political scrutiny for the role they play as government-enforced, industry-led organizations (for example, Sen. Elizabeth Warren specifically referenced check-off programs in her agricultural policy platform during her presidential campaign, suggesting they should be made voluntary [Warren 2019]). This scrutiny comes in part from the fact that these organizations have distributional consequences and may, whether unintentionally or intentionally, favor a subset of producers. A U.S. Supreme Court justice even recently suggested during oral arguments that check-offs are an antiquated form of policy (U.S. Supreme Court 2013). Nevertheless, even as existing check-offs are challenged or terminated, new ones are being established. For example, pecan growers in 15 states voted in March 2016 to approve a new federal marketing order in their industry (Menayang 2016). As industries become more varied in terms of size, marketing channels and production practices, understanding the tensions arising from the use of industry-wide mandatory organizations and the potential benefits and costs of these organizations is increasingly important. Additional information on the history of check-offs and their controversy can be found in Crespi and Sexton (2001) and Williams and Capps (2006).

Our work is of particular relevance to diversified California farmers, who may grow multiple crops with mandatory check-off programs. In fact, there are currently 50 state-level commissions and councils (administered by the California Department of Food and Agriculture, or CDFA), 11 federal marketing orders (administered by the USDA) and 16 federal research and commodity promotion boards (also administered by the USDA) operating in nearly as many agricultural industries within the state. These check-off programs differ slightly in how they are administered depending on the administering body and the type of organization, but they all follow a similar process for formation and continuation. Their formation is initiated via petition by a group of farmers or handlers (a packer or shipper of peaches and nectarines, sometimes affiliated with a specific grower). This petition is followed by an administrative review (by the USDA, or by the equivalent state agency in the case of a state group). If the administering agency deems the organization potentially beneficial to farmers in the industry, formation is then put to a vote in a referendum of affected growers and/or handlers. The marketing order is officially formed if a certain voting threshold is met, with final approval in the hands of the secretary of agriculture (state or federal, depending on the organization).

In the years that follow, regular referendum votes (generally every 5 years) are then required by law and administered by the USDA or equivalent state agency to determine whether or not farmers continue their support. Referendum votes are also held if farmers and/or handlers want to make significant changes to the orders (called a major amendment). Continuation of the organization or changes to the organization are contingent on the outcome of these votes and subject to final approval by the relevant secretary of agriculture. Although federally administered, federal marketing orders can applied to a limited geographic area (e.g., a single state), which was the case with the peach and nectarine marketing orders we studied.

Our work contributes to a growing academic literature on the mandatory nature of check-offs and their use. One set of analyses has used theory and/or simulations to measure the expected behavior of farmers or voting outcomes in check-off referenda (e.g., Plakias and Goodhue 2015). Other theoretical work explores the differential benefits of generic promotion among diverse farmers but does not consider other check-off activities (e.g., Zheng, Bar and Kaiser 2010). Additional relevant literature explores voting and the mandatory nature of check-offs using experimental techniques (e.g., Liaukonyte et al. 2014). Finally, there are empirical analyses that use data collected from farmers to explore hypothetical or real voting outcomes (e.g., McLaughlin et al. 2014). Our work contributes to this literature by providing an analysis of a real organization, combining survey and ballot data, and considering the situation at the termination of a marketing order.

Termination vote in context

Federal marketing orders for peaches (no. 917) and nectarines (no. 916) were established in 1939 and 1958, respectively, and were administered under the California Tree Fruit Agreement (CTFA), established in 1933. These orders were focused on peaches for fresh markets specifically, generally varieties known as “freestone” peaches (“cling” varieties of peaches, which were used more commonly in processing due to the challenges of separating the pit from the flesh of the fruit, had their own separate marketing order). Figure 1 highlights some key dates in the history of the marketing orders. Over time, certain provisions were added to the orders as the industry’s focus shifted; in particular, the role of maturity became increasingly important. As any consumer of peaches knows, the taste difference between a juicy, ripe peach and a mealy, unripe peach is substantial, and growers and marketers of peaches recognized the importance of maturity.

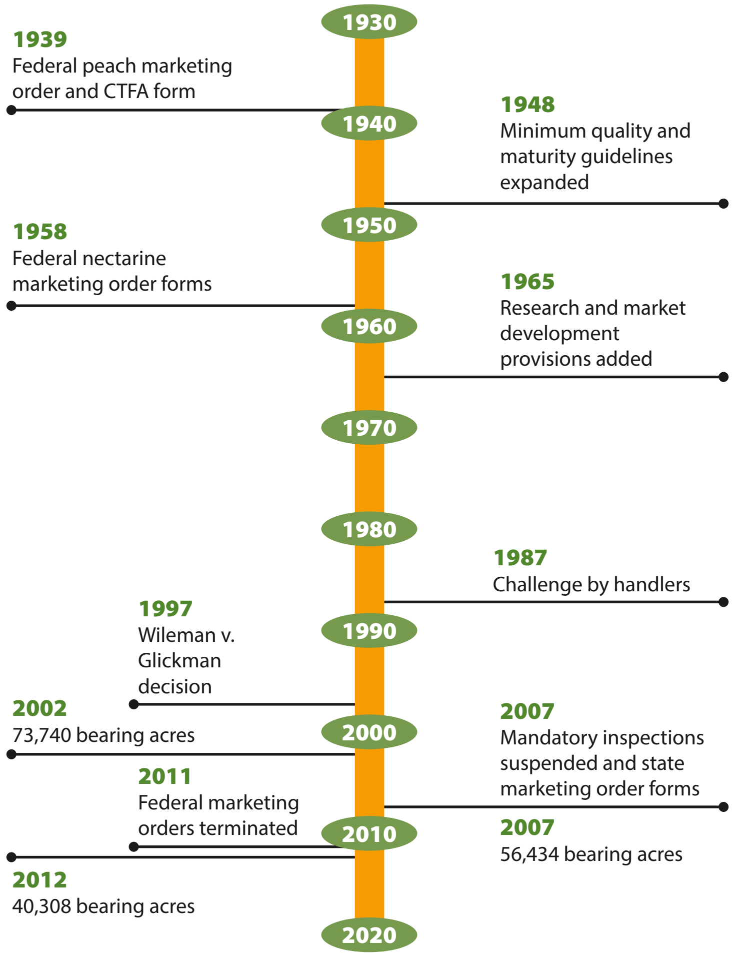

FIG. 1. Fresh peach and nectarine industry and marketing order timeline.

By the 1980s, the focus of both marketing orders was generic promotion plus maturity and size standards as indicators of quality (CTFA 1983). Then, in 1987, a group of handlers petitioned the U.S. secretary of agriculture, challenging both the promotion and quality standard provisions of the marketing orders (Crespi 2003). Although the challenges to quality standards were dismissed, the First Amendment challenge to the orders’ generic promotion provisions went to the Supreme Court, which ruled in 1997 the provisions were constitutional (U.S. Supreme Court 1997). Despite this ruling, over time the industry discontinued some of its promotion activities as more and more growers and handlers engaged in their own marketing.

In the decade leading up to the termination of the orders, the industry was changing. Respondents to our survey and industry leaders indicated high production levels and low prices reduced profits, which led to consolidation and acreage reduction (Sparks 2014). Figure 1 shows the freestone peach acreage bearing from the 2002, 2007 and 2012 USDA Censuses of Agriculture to highlight this contraction in acreage over time (NASS 2020). Concurrently, retailers, who were engaging directly with the largest producers and handlers, were adopting private quality standards, which were sometimes at odds with the standards of the marketing order. Conversations with some industry members and statements from several of our survey respondents suggest that for growers and handlers engaged with these large buyers, this made the order restrictive rather than helpful. However, for growers without direct relationships with buyers and their own recognizable brand, collective standards enforced by the marketing order likely still provided an effective mode for signaling quality to potential buyers. There was a cost to these standards, however — growers and handlers were required to pay for inspections and audits associated with the standards via a small per unit assessment on output, which may have seemed particularly large when industry profitability was at a low.

Not surprisingly, this high cost of the marketing order relative to profit margins highlighted by some survey respondents and the perceived (or actual) differences in the benefits of the marketing orders across growers led the industry to suspend mandatory inspections under the federal orders in 2007. The mandatory inspections were replaced by voluntary inspections administered by a new state-administered marketing order for the same crops. However, farmers who voluntarily labeled their output as "California Well Matured" were still required to meet the grade and size requirements of the federal standard (Federal Register 2007). This allowed those growers or handlers who were not engaged in their own marketing to send a quality signal to prospective buyers while lifting restrictions on those who wanted to meet private quality standards.

In addition to the activities of the marketing orders it administered, the CTFA annual report provided detailed industry information. The purpose of this report was to inform farmers, handlers and regulators so they could better manage quality (CTFA 1958). The information collected expanded over time. By 2007, the annual report provided disaggregated information on shipments by variety, container size, time period, region size and maturity grade and information on variety sales, rootstock varieties and harvest dates (CTFA 2007).

The state marketing orders were terminated in 2010 after a failed continuance referendum. The federal marketing order referendum occurred several months later in 2011. At the time, the marketing orders' activities included marketing and production research and regulation of voluntary standards as described above. Assessment rates were $0.028 per 25-pound container of nectarines and $0.026 per 25-pound container of peaches, which represent 0.40% and 0.46%, respectively, of the 2010 average prices received (Federal Register 2010a; NASS 2020). The failed continuance referendum led to termination of the marketing orders and the CTFA closed up shop shortly thereafter.

Ballot and survey data collected

We used two data sets to examine the votes in these industries. One consists of all referendum ballots collected by the USDA's Agricultural Marketing Service (AMS) — a population of 104 growers. This data set is not a sample but encompasses all voters. Why so few voted is a key question.

The second data set was collected via a 2015 mail survey of California peach and nectarine farmers; we sent a pre-survey letter to each farmer and then sent the full survey twice (a copy of the survey is available by request from the authors). Of the 380 unique farmers surveyed (all peach and nectarine farmers with up-to-date addresses in 2015 who were eligible to vote in the 2011 referendum), we received 65 responses, for a response rate of 17.1%. Fifty-seven of the 65 surveys we received were complete enough to be used in our analysis in some way, resulting in a final response rate of 15.0%. Although this number is low, it is in line with other recent research in this area (e.g., McLaughlin et al. [2014] report a response rate of only 8%).

Of the responses to questions about participation in the referendum, 23% growing each crop either did not vote, could not remember if they voted or preferred not to say. Lack of response was likely driven by the length of the survey (11 pages total) and the lack of current relevance to farmers, given that the marketing orders were terminated several years prior to data collection, and there was structural change in the industry that led to exit, as discussed in the previous section. However, when we consider the respondents who said they voted in the 2011 referendum as a share of all 2011 referendum voters, the response rate was considerably higher, with 30.7% and 30.3% of peach and nectarine voters in the 2011 referendum responding, respectively. These numbers suggest that farmers who were more likely to have voted were also significantly more likely to respond to the survey. Thus, in our analysis we only consider survey respondents who reported how they voted.

Table 1 presents these voting results tabulated directly from the USDA AMS ballot data as well as the

TABLE 1. Referendum votes, 2011

	Ballot *N*	Share	Survey *N*	Share
Vote for peach order continuation (V)	102	0.61	37	0.38
Vote for nectarine order continuation (V)	99	0.63	30	0.37
Vote for peach order continuation (Q)	101	0.36	31	0.35
Vote for nectarine order continuation (Q)	99	0.41	27	0.21

V = number of farmers voting, Q = quantity produced by those voting.

Compared to the population of referendum voters, survey respondents who voted were less likely to report voting for continuation and represented a smaller share of volume among those voting for nectarines only.

self-reported votes of the survey respondents by the number of farmers voting for continuation (V) and their share of all voters' production (Q). Among survey respondents who voted, nearly 40% growing each fruit reported voting for continuation. Compared to the population of referendum voters, survey respondents who voted were less likely to report voting for continuation and represented a smaller share of volume among those voting for nectarines only. All respondents who produced both peaches and nectarines voted to continue both or terminate both (not shown).

Table 2 displays additional summary statistics for the ballot and survey data. Results from two different statistical tests used to compare the ballot and survey data sets suggest that relative to the population of referendum voters, survey respondents had significantly lower peach and nectarine yields, were significantly less likely to vote for continuation of the marketing order, and were significantly less likely to produce both freestone peaches and nectarines, measured in annual production of 25-pound containers. These differences further suggest that survey respondents may not be representative of referendum voters, an issue we attempt to address in our analysis.

The operator in table 2 refers to the voter (ballot data) or survey respondent (survey data). In addition to the data reported in table 2, some voters provided information about their farms' business structures and locations on their ballot. Corporation is the most common business structure, reported by more than half of voters who reported their business structure (not shown). Referendum voters were primarily located in Fresno, Tulare and Kings counties, and nearly 90% of them had peach and/or nectarine production in one of these counties at the time of the referendum. In the survey, more than 30% of farm operations reported having more than $1 million dollars in gross farm income in 2010; this is the modal income category. Approximately two-thirds of respondents had a bachelor's degree or higher at the time of the survey in 2015.

Data sets combined to reduce bias

We empirically analyzed the relationship between farm and farmer characteristics and the probability of farmer voting for continuation using a method called binomial logit regression. We first estimated the relationship of variables available from the USDA referendum ballots to the probability of voting for continuation, then conducted a similar procedure using the survey data. Analyzing both data sets has two advantages. First, while the ballot data set represents the population of voters, it does not include all the variables that might be expected to predict farmers' votes. The survey data set enabled us to incorporate these additional characteristics. Second, although the ballot data and survey did not allow us to exactly match individuals across the two data sets, we were able to match survey respondents to similar voters and to see which referendum voters were the most likely to be in our set of survey respondents.

We then used this information to weight the survey observations to partially account for survey respondents' probability of responding to the survey. Matched referendum/survey voters with a lower predicted probability of responding to the survey who responded anyway were given greater weight to account for the fact that they were underrepresented in our survey data. This procedure allowed us to address some of the bias that comes from the differences we observed between the survey respondents and the population of referendum voters (further details of this empirical procedure, called propensity score weighting, are available by request). For the regressions using ballot data, we report

TABLE 2. Peach and nectarine operation and operator characteristics in 2010

Operation and operator characteristics	Ballot			Survey		
	N	Mean/%	Std dev	*N*	Mean/%	Std dev
Containers of peaches (1,000s)	101	121.54	242.89	48	66.57	200.13
Containers of nectarines (1,000s)	98	109.92	212.72	48	29.05	52.73
Acres of peaches/nectarines	108	287.58	584.91	50	146.98	222.81
Markets peaches only (%)	111	11.71		46	23.91	
Markets nectarines only (%)	111	8.11		46	13.04	
Markets both fruits (%)	111	81.08		46	63.04	
Organic peach and nectarine production (%)				46	22.63	41.67
Income from peaches and nectarines (%)				47	56.07	34.67
Age				52	60.31	11.96
Years of experience growing peaches and nectarines				56	29.09	14.20
Male (%)				54	98.15	
Farming is sole occupation (%)				57	64.91	

the model with and without the business type variable, as not all voters provided this information on their ballot. For the regressions using survey data we provide the results with and without the weights we calculated to address bias.

Size is one factor in farmer votes

Columns 1 and 2 (table 3) report the results of the regressions exploring the relationship of peach and nectarine farm and farmer characteristics to vote choice using ballot data. The reported values tell us the change in the probability of voting for continuation given a one-unit change in the variable indicated in that row at its average (known as the marginal effect at the mean). The first column includes all referendum voters, while the second includes only the subset of referendum voters who reported information about their business type. From both columns, we see that voters with more containers of peach and nectarine production were less likely to support continuation of the marketing order after controlling for other factors. In column 2, we see that voters using a corporation structure (the omitted business type category) were less likely to vote for continuation than voters using partnerships and other business structures. This result suggests that business type was important or it was related to other characteristics that might have influenced vote choice. Surprisingly, we found the relationship between business type variables and quantity of peach and nectarine production to be relatively weak (with a correlation of 0.22 at most), which suggests that a relationship between these variables is not driving this result. This finding that business type is significant on its own suggests an area for future research. In general, corporations are becoming more common in California agriculture and represented about 10% of California farms in the 2017 Census of Agriculture, up from about 6% in 1997. However, the share of these corporations that are family-held has remained study at about 84%.

We report the results from unweighted and weighted regressions using the survey data in columns 3 and 4 (table 3). We included containers of peaches and nectarines and an indicator of gross income from farming. Similar to the ballot regressions, the survey regressions point to a significant negative relationship between the quantity of peach and nectarine production and the probability of voting for continuation. We also found a significant and negative relationship between the percentage of farm income from the peach and nectarine operation (a measure of farm specialization) and the probability of voting for continuation. These results provide evidence that farm size and specialization both relate to vote choice. However, the indicator of gross income from farming is not significant — we did not see much difference between the results in columns 3 and 4. This is likely because the reweighting procedure we used mitigates only some of the nonresponse bias.

We also found that survey respondents producing a greater share of their peach and nectarine production organically were significantly more likely to support continuation. The reasons for this result are unclear from the qualitative survey responses. One possible reason could be that production research conducted by the CTFA had specific positive benefits for organic operations. For example, research on pest pressures conducted by the CTFA could perhaps benefit organic operations who were more restricted in their pest mitigation practices than conventional operations. This result could also be due to the low number of organic respondents. Only nine of the 11 organic producers who responded to our survey provided information about their vote choice. Of these nine, six voted for continuation of the marketing orders.

In our examination of farmer characteristics, we found that neither specialized experience in peach

TABLE 3. Effects of farm and farmer characteristics on probability of voting for continuation of peach (P) and nectarine (N) marketing orders†

Farm and farmer characteristics	Marginal effects at mean from logit regressions			
	Ballot data		Survey data	
	(1)	(2)	(3)	(4)‡
Containers of P&Ns (1,000,000s)	-0.636*** (0.210)	-1.138*** (0.431)	-2.528*** (0.953)	-2.154*** (0.967)
Yield (containers/acre)	0.208 (0.195)	0.111 (0.343)		
Grows peaches only	-0.096 (0.151)		-0.445 (0.454)	-0.264 (0.443)
Grows nectarines only	0.125 (0.253)		0.170 (0.318)	0.275 (0.331)
Grows Ps or Ns only		0.338 (0.269)		
Business type is partnership		0.497* (0.276)		
Other business structure		0.512** (0.242)		
Income from P&Ns (%)			-0.021** (0.009)	-0.017* (0.009)
P&N output that's organic (%)			0.008* (0.005)	0.007* (0.004)
Farm income > $500k			–0.032 (0.596)	0.126 (0.501)
Years growing P&Ns			0.017 (0.019)	0.018 (0.014)
Farming is sole occupation			–0.136 (0.370)	–0.092 (0.282)
Education is less than bachelors			–0.273 (0.490)	–0.387 (0.479)
County controls	Y	Y	N	N
N	104	47	33	33
Pseudo R^2	0.12	0.34	0.54	

† Dependent variable: 1 = votes for continuation, 0 = votes against continuation.
‡ Weighted to account for nonresponse bias. Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Y = yes, N = no.

and nectarine production nor level of education had a significant relationship with the probability of voting for continuation. Farming as a sole occupation was also not significant.

Changes made after termination

These results point to distinct differences in farmers' perceptions of the benefits provided by the marketing orders, which raises the question of whether — and which — farmers changed their behavior post-termination. Accordingly, we compared post-termination activities of respondents voting for and against continuation using several statistical tests (details available upon request). It is important to note that these changes were not necessarily a result of marketing order termination; other factors that have affected the industry since then very likely played a role as well.

One aspect of production the survey asked about was fruit quality. Although not specifically defined in the survey, in the marketing orders fruit quality had long been measured in terms of grades, which are determined by a combination of maturity, shape, color and amount of physical damage (e.g., cracking, bruising or physical damage from pests, harvesting or other external sources). About 19% of respondents (seven out of 36) indicated they produced a greater range of peach and nectarine qualities after the marketing orders were terminated. Another (potentially overlapping) 25% (nine out of 36) indicated they produced higher quality fruits on average. Only one respondent reported decreasing average quality. About 16% of respondents (six out of 38) increased their advertising post-termination, while only one respondent reported decreasing advertising. About 25% of respondents (10 out of 40) increased their research post-termination, and only 10% (four out of 40) decreased it.

Only the change to produce higher qualities of fruit on average was significantly different across voting groups; those producing higher qualities of fruit on average after termination were less likely to have voted for continuation. This result is consistent with the trend toward higher quality that preceded marketing order termination but a little perplexing, given that restrictions on growers had been lifted in 2007 and only inspections associated with the voluntary California Well Matured label remained in effect in 2011 when the marketing orders were terminated. We can think of two possible reasons for this result. First, since the survey data were collected several years after termination, respondents could be responding to the question as if it was asking about behavior after termination of the mandatory inspections in 2007 and not after termination of the orders in 2011. Alternatively, it may be that the absence of an assessment payment and inspection costs resulting from the termination of the marketing order freed up resources for farmers to improve their fruit quality. Furthermore, in the absence of the California Well Matured label, producers who were using this label and the associated quality standard may have needed to increase their qualities to meet buyers' needs.

In addition, more than two-thirds of survey respondents (25 out of 35) indicated the CTFA was an important source of information, and more than 46% of respondents (16 out of 35) had not found a source to replace it by 2015. However, nearly all those voting for continuation (13 out of 14) found the CTFA to be an important information source, compared with only 57% of those voting for termination (12 out of 21). Differing levels of access to information has significant implications. Firms that have more information may have an advantage, or even if everyone has information they may not be able to take advantage of it easily. Furthermore, peaches and nectarines are perennials and do not produce fruit immediately once planted, so these percentages may understate the share of producers (some of whom may not have been eligible to vote in the referendum) who would value this information, which may have been important for long-term production planning

Finally, we will note that of the 65 original responses received in 2015, 16 (or 24.6%) indicated they had stopped producing fresh peaches and nectarines or exited the stone fruit industry entirely since the 2011 termination vote, highlighting the continued consolidation in the industry discussed earlier. Although all these results should be interpreted with caution due to our small sample size and the length of time elapsed between the vote and survey data collection, our data on the population of referendum voters collected at the time of the referendum, together with our survey data, can provide some useful insights.

Resources lost in termination

Several important results bear further consideration. First, even after controlling for other factors, the findings that (1) farmers who produced more and (2) farmers who had a higher percentage of gross income from peaches and nectarines were less likely to vote for continuation are consistent with the narrative that farmers were bringing the activities of the marketing orders inhouse, which reiterates the different impacts marketing orders can have on different sizes and types of farms. Second, the result that referendum voters using a corporation business structure were less likely to vote for continuation, even after controlling for size, was unexpected. This suggests the business structure that farms choose is inextricably linked to its marketing decisions and highlights the possibility that farms incorporated as corporations face different incentives.

Third, our survey data suggest that the CTFA was significantly more important as a source of information to respondents voting for continuation. The termination of the orders and dissolution of the CTFA that followed led to the end of this information collection. Finding new sources of information likely has been challenging for these farmers; some respondents reported having not found a replacement 4 years after termination of the orders. The post-termination information environment could have further contributed to decline in the industry, as the lack of information forced farmers to face more uncertainty and risk in marketing.

Finally, respondents with more organic production were significantly more likely to vote for continuation. This result suggests that despite efforts to create separate organizations supporting the organic industry alone, such as the failed 2018 attempt to implement a multi-crop Organic Promotion Check-Off, the peach and nectarine marketing orders may have provided benefits to organic farmers.

These findings together suggest important resources may have been lost due to termination of the two marketing orders, and not all of these resources have been replaced by other entities. While many of our results are consistent with those of the USDA, our results suggest a more complex and nuanced story in the industry and help explain some of the reasons that such a large share of growers — nearly two- thirds — actually voted for continuation of the marketing orders. In the case of this particular marketing order, it would appear to be smaller farms that lost out from termination, although this is by no means true across all marketing orders (Plakias and Goodhue [2015] provide examples where the opposite is true as well). In industries diverse in terms of farm size, production type and more, these tensions will always be present in mandatory organizations. Modern organizations that seek to continue operations must adapt to meet the diverse and evolving needs of the growers in their industries. CA

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RESEARCH ARTICLE

Brown spot in table grape Redglobe controlled in study with sulfur dioxide and temperature treatments

A popular export table grape variety showed no disease development for 32 days at 2°C after being treated with 200 ppm-h SO_2.

by Cassandra A. Young, Robin A. Choudhury, Carlos H. Crisosto and W. Douglas Gubler

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Abstract

Brown spot is a postharvest disease of grapes caused by *Cladosporium* species in the San Joaquin Valley of California. It spreads during cold storage and transport, resulting in severe economic losses to late table grape cultivars, which are grown mainly for export to countries such as China and Mexico. We examined the effect of temperature and sulfur dioxide (SO_2) treatments on fungal growth and infection of Redglobe berries by three *Cladosporium* species: *Cladosporium ramotenellum*, *C. cladosporioides* and *C. limoniforme*. Redglobe is especially popular for export. Fungal colonies growing on potato dextrose agar in petri plates stored at −2°C grew slower than those stored at 2°C, and an 400 ppm-h SO_2 treatment significantly reduced fungal growth of all three species and at all temperatures tested. Redglobe berries inoculated with the *Cladosporium* species, treated with SO_2 concentrations of 100 ppm-h, 200 ppm-h and 400 ppm-h and incubated in high relative humidity chambers for 28 to 32 days at 2°C, showed little incidence of disease. The development of brown spot on berries was entirely prevented with the treatment of 200 ppm-h SO_2 for all *Cladosporium* species tested.

California is the leading producer of table grapes. In 2019 table grapes accounted for 130,000 acres of the 918,000 acres of grapes grown in the state, with 6,588 acres grown with the variety Redglobe (CDFA 2020). The cultivar Redglobe is a variety popular for export markets, including China and Mexico, because of its flavor and long shelf life (Dokoozlian et al. 1996). Brown spot can cause major postharvest fruit loss in Redglobe and other late-harvest cultivars such as Crimson Seedless and Autumn King (Swett et al. 2016). No reliable control of brown spot has been found.

A study by Swett et al. (2014) showed 100% of Redglobe clusters collected from a commercial field in Delano, in the San Joaquin Valley, had latent infections of *Cladosporium* species responsible for brown spot disease. Redglobe clusters may be stored for 2 to 3 months before they are shipped to Asia. When symptomless berries are in cold storage conditions for long periods, brown spot disease begins to emerge and spread (Swett et al. 2016). While initial infections occur

Harvested Redglobe table grapes. This variety is popular for export but can develop brown spot disease while in cold storage and transport. Laboratory test results indicate that sulfur dioxide treatments of at least 200 ppm-h can prevent the disease.

Mike Poe

in the field, once in post-harvest, infection can also easily spread from berry to berry through epidermis contact with no wounding necessary and in temperatures as low as −2°C (Swett et al. 2016). Brown spot is a major source of economic loss for grapes during long distance transport.

Attempts to manage brown spot have relied on strategies developed for the control of gray mold, a severe postharvest disease caused by the fungus *Botrytis cinerea* (Cantín et al. 2011; Coertze et al. 2001; Crisosto et al. 1994; Lee et al. 2015; Palou et al. 2001). Gray mold (*Botrytis cinerea*) and brown spot (*Cladosporium* spp.) have similar biology, such as infection timing, occurrence of a latency period and timing of symptoms expression (Coertze et al. 2001; Crisosto et al. 2002; Crisosto et al. 1994; Fourie 2008; Palou et al. 2001; Swett et al. 2014). However, the common practice of using 100 to 200 parts per million per hour (ppm-h) sulfur dioxide (SO_2) treatments used to control gray mold during cold storage and during transport has not been effective for the control of brown spot (Lee et al. 2015; Palou et al. 2001; Serey et al. 2007; Smits et al. 2003; Teles et al. 2014).

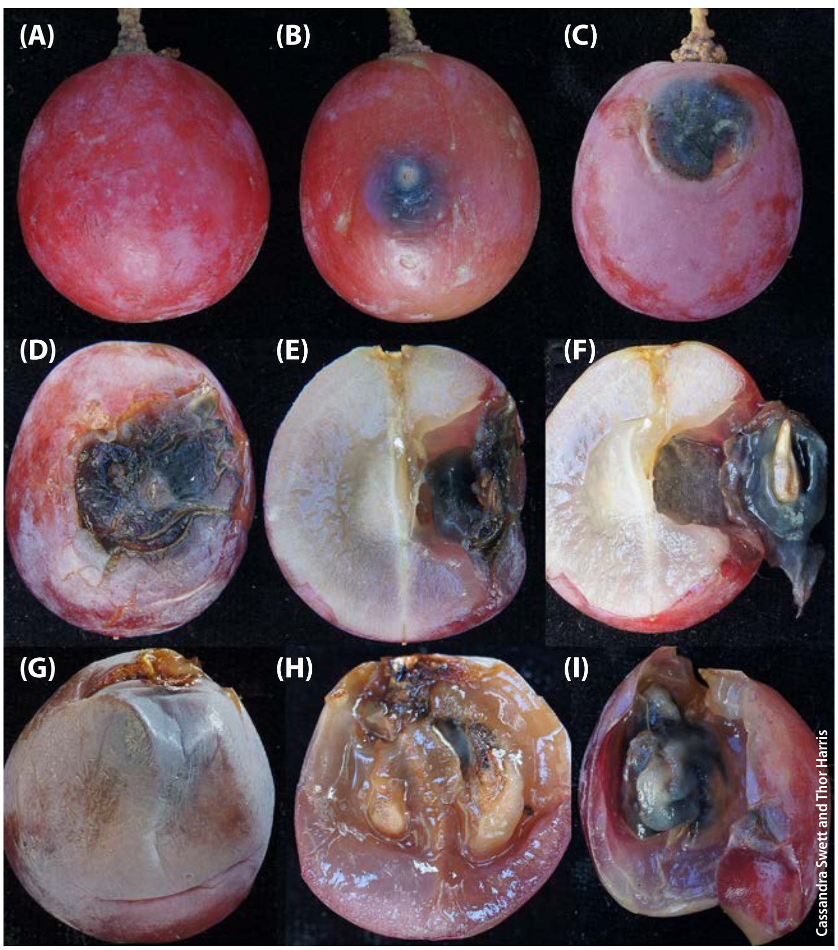

FIG. 1. Brown spot postharvest on grape. (A) healthy berry, (B) early brown spot, (C) brown spot with cavity and fungal sporulation, (D) advanced brown spot, (E) fungal growth inside the berry, (F) fungus replacing the placenta and encasing the seed, (G) infected berry with no external spot, (H) spores lining the interior of the mycelial mat, (I) berry placenta replaced by fungal growth. Source: Swett et al. 2016.

Brown spot has been attributed to several species of the *Cladosporium herbarum* species complex (*C. ramotenellum, C. tenellum, C. limoniforme*) and *C. cladosporioides* (Crous et al. 2007; Swett et al. 2016). As described by Swett et al. (fig. 1), typically a fluffy, light green to white mycelial mat will form where infection has taken place on the berry epidermis. A mycelial callus can form under the epidermis as a result of an internal infection, creating a scab and a brown spot on the underside of the epidermis. As the infection progresses, the scab will encompass the seed of the grape, forming a fungal fruiting body that eventually replaces the grape seed placenta, and prolific sporulation will occur on the seed (Swett et al. 2016; fig. 1).

In the last 20 years, a total utilization technique for fumigant applications of SO_2 during cold storage has been established for table grapes; it increases efficiency, reduces environmental pollution and protects operators (Crisosto and Mitchell 2002; Luvisi et al. 1992; Palou et al. 2002). An important step of the technique is to apply the first SO_2 treatment (~ 100 to 150 ppm-h) during the initial forced-air cooling of the grapes after harvest, which is then followed by weekly applications during cold storage with homogenous air distribution (Luvisi et al. 1992). The total utilization technique system uses ~ 10 times less SO_2 than the previous standard fumigation system, but it requires uniform room air distribution for the treatment to be effective (Crisosto and Mitchell 2002).

The total utilization technique was based on laboratory studies that revealed that at least 100 ppm-h SO_2 was necessary to kill *B. cinerea* conidia and inactivate exposed mycelia at 0°C (Smilanick and Henson 1992). Even less than 100 ppm-h was effective at warm temperatures to cause the death of conidia and mycelium of *B. cinerea* on grape (Crisosto and Mitchell 2002; Luvisi et al. 1992). These latter studies confirmed that SO_2 applied at 200 ppm-30 min, 400 ppm-15 min, 50 ppm-2 h or 25 ppm-4 h was as effective as the 100 ppm-h treatment (Crisosto et al. 2002; Palou et al. 2001, 2002). The sensitivity of *B. cinerea* conidia to SO_2 increases two- to four-fold for every 10°C increment between 0 and 32°C, because of the effect of temperature on SO_2 absorption on the fruit, fungi and surrounding packaging (Smilanick and Henson 1992).

SO_2 has mainly been used to control gray mold disease of table grapes, but the low application rates applied as part of the total utilization technique have not prevented the emergence and spread of brown spot during cold storage (Fernández-Trujillo et al. 2012). The objectives of our two-part study were (1) to evaluate, in vitro, the effect of temperature and SO_2 concentration over time applications on fungal colony growth of three *Cladosporium* species (*C. ramotenellum*, *C. cladosporioides* and *C. limoniforme*), and (2) to determine the efficacy of different SO_2 concentrations over time in inhibiting the growth of *Cladosporium* species on artificially inoculated Redglobe berries.

Origin of fungal isolates

Cladosporium species (*C. ramotenellum*, *C. cladosporioides* and *C. limoniforme*) were isolated from brown spot–symptomatic berries grown in Delano, California, from 2013 to 2015. Species isolates were obtained from symptomatic tissue placed on 150 by 15 mm (millimeter) petri plates with 3% rose bengal potato dextrose agar (Difco Laboratories, Detroit, Mich.) amended with 500 ppm tetracycline and 300 ppm streptomycin.

Cladosporium colonies were hyphal tipped after 7 days to produce pure cultures for species identification. PCR (polymerase chain reaction) amplification of the actin gene using primers ACT-512 and ACT-783 and DNA sequencing confirmed the identity of species (Swett et al. 2016). Species isolates were maintained in Dr. W. Douglas Gubler's laboratory, Department of Plant Pathology, UC Davis, as of June 2016. Pathogenicity was demonstrated when species isolates were inoculated and re-isolated from lesions on Crimson Seedless berries following standard protocols (Swett et al. 2016).

Source, preparation of grapes

Redglobe berries were obtained from a commercial vineyard in Delano. Asymptomatic, nonwounded berries were removed from clusters with the pedicel still intact by clipping with sterile scissors. Berries were then vigorously washed in a 0.5% potassium chloride and 0.1% Tween 20 solution to remove surface debris. Berries were surface disinfected first in a 70% ethanol solution for 30 seconds, then in a 10% bleach solution for 5 minutes, and dried in a sterile laminar flow hood (Dugan et al. 2002).

Dry berries (*n* = 9 per fungal species tested) were aseptically distributed in triplicate on sterilized polyethylene chambers (215 by 300 by 105 mm) on sterilized polyethylene grids (210 by 297 mm) at 2°C with high relative humidity (RH 93%). RH was obtained with paper towels moistened with sterile deionized water and placed below a plastic grid. RH was measured with a humidity sensor (HOBO, Onset Computer Co., Bourne, Mass.).

Mycelial growth study

To determine the effect of temperature and SO_2 on fungal growth, potato dextrose agar (PDA) plates were inoculated with one of three species: *C. ramotenellum, C. cladosporioides* or *C. limoniforme*. Inoculum was grown on 2% PDA at 23°C for 5 to 7 days. Plugs of colonized PDA obtained with a sterile 4-mm cork borer were placed on a 2% PDA plate, spore side down. The baseline for all measurements was 4 mm.

Inoculated plates were incubated in a polyethylene chamber at 23°C for 13 hours. The petri plates were moved to a fumigation chamber and exposed to the three SO_2 treatments while still lidded. SO_2 concentrations were measured using passive colorimetric dosimeter tubes (Gastec Corp., Ayase-Shi, Japan) and a portable SO_2 detector that continuously measured SO_2 concentration inside the fumigation chambers (Palou et al. 2002). Dosimeter tubes were taped to chamber walls opposite the SO_2 flow as well as inside of a petri plate. Untreated controls were inoculated as previously described, received no SO_2 exposure but were treated and incubated identically. For each species, three petri plates were inoculated and treated in triplicate and were incubated at 2°C and −2°C for up to 32 days after treatment.

Radial measurements of fungal colonies were taken to assess the effect of SO_2 concentration over time on mycelial growth. Colony measurements were taken from the reverse side of the lidded petri plate. Using a polyethylene ruler, two perpendicular diameter measurements were made and averaged to determine overall colony size. The diameter of the mycelium plug inoculum (4 mm) was included as the minimal measurement for all treatments. Measurements were taken every 6 to 8 days during incubation at 2°C and −2°C.

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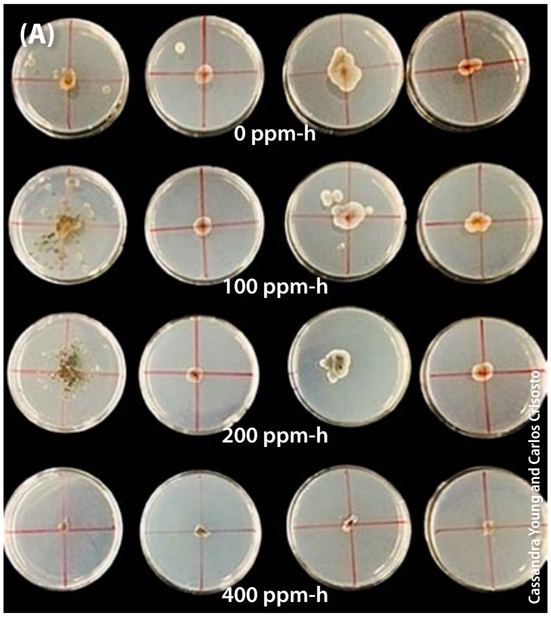
Petri plates inoculated with one of three species — *C. ramotenellum*, *C. cladosporioides* or *C. limoniforme* — in a fumigation chamber and exposed to the three SO_2 treatments while still lidded. SO_2 concentrations were measured using passive colorimetric dosimeter tubes and a portable SO_2 detector.

Inoculated berry study

Inoculated berries were not wounded prior to inoculation. Inoculum was prepared with 14-day-old cultures grown on PDA. Spores were suspended in 0.5% potassium chloride and 0.1% Tween 20 in sterile distilled water. Spore density was determined using a hemocytometer, and the suspension was adjusted to 1×10^7 spores/mL by the addition of sterile deionized water.

The shoulder of each berry was inoculated by placing 10 μL of spore suspension within a 4-mm Vaseline ring, to prevent the inoculum from moving. Berries were positioned with the inoculated shoulder facing up. Untreated controls consisting of berries inoculated with sterile deionized water were included for each temperature and SO_2 treatment. Berry lesions on unwounded berries were measured after 28 days of storage at 2°C.



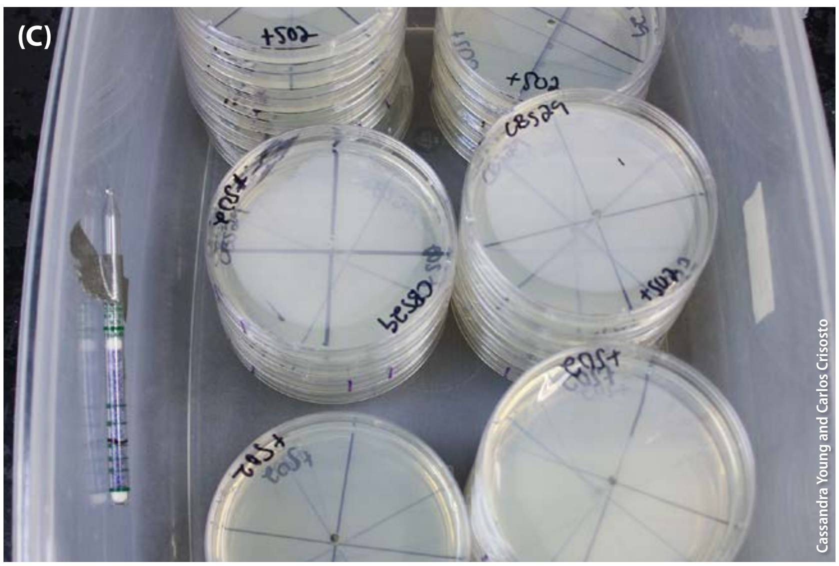


FIG. 2. (A) Mycelial growth of *C. cladosporioides*, *C. limoniforme* and *C. ramotenellum* in lidded petri plates treated with SO_2 of 0, 100, 200 or 400 ppm-h. (B) Passive colorimetric dosimeter tubes were used to measure SO_2 concentrations. (C) One was placed inside each fumigation chamber, opposite the SO_2 input valve.

Concentration-time SO_2 treatments

Twenty-four hours after berries were inoculated with one of the three *Cladosporium* species, they were exposed to three concentration-over-time treatments of gaseous SO_2: 100 ppm-h (100 µL/L per h), 200 ppm-h (100 µL/L per 0.5 h) or 400 ppm-h (100 µL/L per 0.25 h) (Palou et al. 2001). SO_2 concentrations were measured as previously mentioned. Dosimeter tubes were taped to chamber walls opposite the SO_2 flow.

For both studies, fumigation chambers were Sterilite containers (Sterilite, Townsend, Mass.) modified to allow for a rubber tube to flow SO_2 into the chamber. Chambers were placed inside a biological safety cabinet during treatment. Chamber lids were opened once a treatment was concluded and the inoculated berries on a grid/mycelial plugs on petri plates were placed into polyethylene chamber to be stored in cold storage.

Statistical analysis

Radial growth of *Cladosporium* colonies was analyzed using a linear mixed model approach for all three species using the R package lme4 (Bates et al. 2014). The mixed model used a Gaussian error distribution and consisted of SO_2 treatments, temperature and species as fixed effects and replicate as a random effect. We calculated the estimated marginal means and computed all pairwise comparisons using Tukey's honestly significant difference (HSD) test.

For the berry study, we analyzed the proportion of infected berries with a linear mixed model approach using a Gaussian error distribution for all species, with SO_2 treatments and species as fixed effects and replicate as a random effect and computed all pairwise comparisons using Tukey's HSD test.

Fungal growth significantly reduced

Radial colony growth of the three *Cladosporium* species on petri plates with PDA was significantly reduced by the 400 ppm-h SO_2 treatment, as seen in figures 2 and 3. The 400 ppm-h concentration was most effective against *C. cladosporioides* when petri plates were incubated at −2°C, which resulted in no radial growth. The 400 ppm-h was also effective in slowing *C. cladosporioides* colony growth at 2°C; radial growth grew only from 4 to 9 mm on average.

Radial colony growth of *C. limoniforme* and *C. ramotenellum* was also slowed down at 400 ppm-h, growing from 4 to 5 mm and 4 to 6 mm, respectively, at −2°C. However, the same treatment was less effective at 2°C, where, on average, fungal radial growth reached 10 mm for *C. limoniforme* and 12 mm for *C. ramotenellum* after 30 days. At the lower SO_2 ppm-h (200 ppm-h, 100 ppm-h), there was no significant difference in radial colony growth between any of the treated species and the untreated controls by 30 days at 2°C.

All species after 10 days at −2°C had reduced colony growth for all concentrations compared with those incubated at 2°C. The colony growth of *C. cladosporioides* at −2°C was slower than that of the other species; and it was also slower than the colony growth of *C. cladosporioides* incubated at 2°C, illustrating the effect of temperature on rate of growth.

200 ppm-h treatment eliminated disease

In the berry study, all *Cladosporium* species caused disease in untreated control berries: *C. cladosporioides* caused disease in 65% of berries, *C. limoniforme* in 55% berries and *C. ramotenellum* in 75% of berries (fig. 4). By contrast, SO_2 treatments significantly reduced disease incidence by *Cladosporium* species on inoculated Redglobe berries.

The 100 ppm-h treatment reduced disease incidence to less than 25% of berries for all species. The 200 ppm-h treatment was the most effective, in that it eliminated disease for all three *Cladosporium* species tested. In the 400 ppm-h treatment, there was less than 5% disease incidence in berries inoculated with *C. ramotenellum* and no infection occurred in berries inoculated with *C. cladosporioides* or *C. limoniforme*. Nevertheless, there was no statistically significant difference in the proportion of infected berries between the 100, 200 and 400 ppm-h SO_2 treatments of the three *Cladosporium* species tested (fig. 4).

Potential of SO_2 as a control for brown spot

Our results demonstrate that a single application before cold storage of at least 200 ppm-h SO_2 at cold storage temperatures may be an effective tool for reducing brown spot disease incidence on grape berries, although the ability of mycelium of *Cladosporium* species to grow on PDA growth medium in petri plates with an SO_2 application was somewhat variable. We have demonstrated SO_2 of 200 ppm-h and 400 ppm-h essentially prevent disease development in Redglobe berries from the three *Cladosporium* species tested. *C. cladosporioides* exhibited tolerance at 100 ppm-h, whereas 100 ppm-h was effective against *C. ramotenellum* and *C. limoniforme*. While mycelial growth on PDA was reduced with a treatment of 400 ppm-h SO_2, mycelial growth was not completely eliminated. Additionally, *C. ramotenellum* grows faster than the other species on a petri plate with PDA, regardless of temperature or SO_2 treatment. Unsurprisingly, in the berry study, inoculation of *C. ramotenellum* resulted in the highest disease incidence in the untreated control berries. Our study also confirmed the critical importance of maintaining table grapes below 0°C and above their freezing point to maximize their storage life potential (Crisosto and Mitchell 2002).

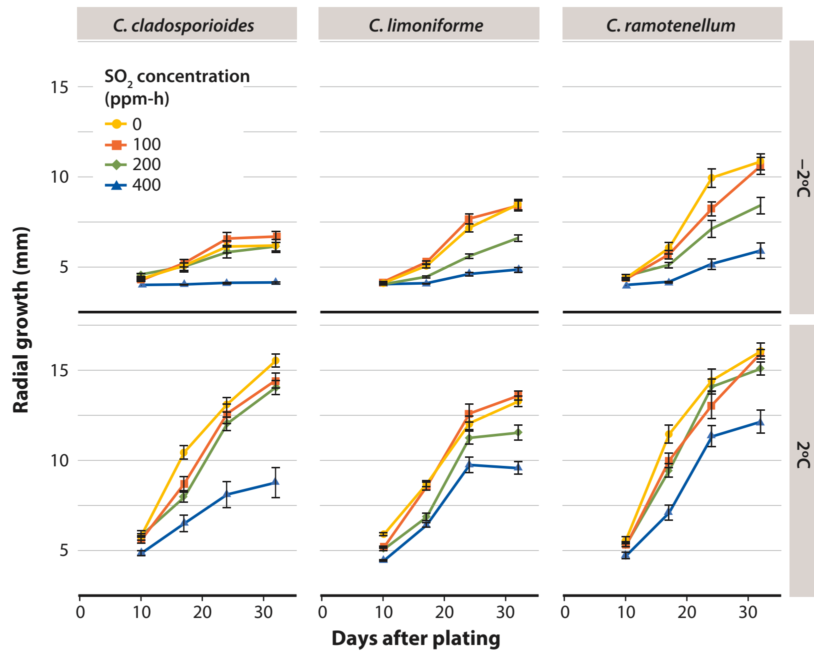


FIG. 3. Influence of 0, 100, 200 and 400 ppm-h SO_2 on radial growth of three *Cladosporium* species plated on PDA growth medium using a 4-mm mycelial plug inoculum. Lidded petri plates were incubated in cold storage at −2°C and 2°C for up to 32 days. Mean ± standard error.

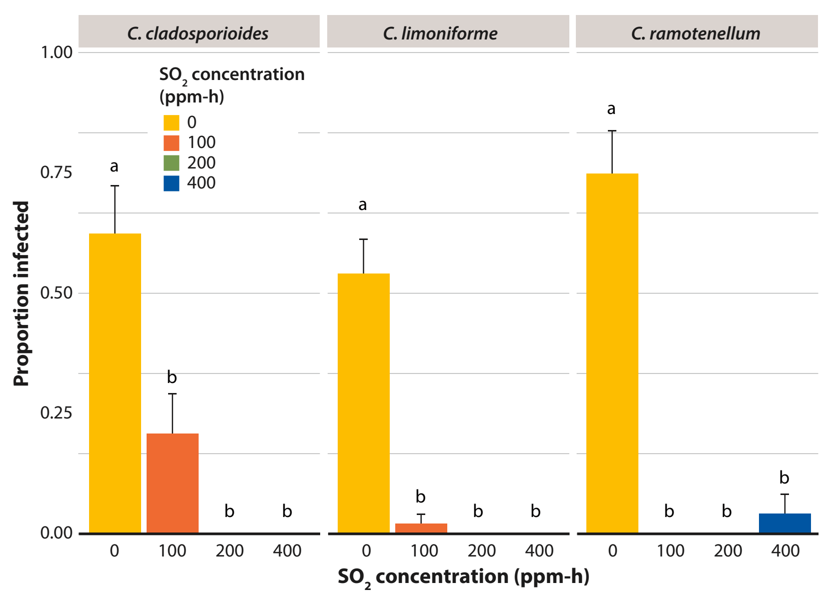


FIG. 4. Influence of SO_2 at three concentrations on the proportion of infected Redglobe berries after inoculation with three species of *Cladosporium*. After inoculation, berries were placed in cold storage at 2°C, RH 93%. Lesions on berries were measured at 28 days. Mean ± standard error. Letters represent significant difference at α = 0.05, according to Tukey's honestly significant difference (HSD) test.

These results are promising for the control of brown spot during long-term storage and export of Redglobe table grapes. Although not much is known about the natural berry infection by *Cladosporium*, we do know that infection can occur on the surface through the epidermis and may also be a latent infection where infection starts from within the berry. Berries used in our experiments were surface sterilized before inoculation so we could be sure that infection occurred through the epidermis with our inoculum; thus, we can conclude the SO_2 application prevented disease from of the *Cladosporium* surface inoculum. However, SO_2 may not be adequate to prevent infection resulting from latent infection, causing internal rot of the berry and inoculum production, but may inhibit the resulting spread if applied after the emergence of fungal growth (Harvey 1955; Lee et al. 2015; Swett et al. 2016).

This work demonstrates a potential management strategy of brown spot post-harvest. In practice, multiple factors can influence the amount of gaseous SO_2 that comes into contact with the berry surface, including air flow in storage, sorption of packing materials and the amount of condensation on berries, which can absorb gasses. Additionally, a single application of SO_2 is typically not as effective as multiple SO_2 applications, but multiple applications may not be feasible during transport (Crisosto et al. 2002). Total utilization technique focused on gray mold control applies SO_2 at 100 to 150 ppm-h, which may be too low to be effective against brown spot, especially under cold storage conditions. Future studies should be done to improve sampling and the detection of brown spot in the field prior to harvest as well as during postharvest, so this research can be applied to known compromised lots in transport and better determine the efficacy of this practice under commercial conditions. CA

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RESEARCH ARTICLE

Monterey pine forest made a remarkable recovery from pitch canker

For 3 years pitch canker progressed rapidly through native stands on the Monterey Peninsula, then changed little over 14 years, before steadily declining.

by Thomas R. Gordon, Gregory J. Reynolds, Sharon C. Kirkpatrick, Andrew J. Storer, David L. Wood, Daniel M. Fernandez and Brice A. McPherson

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Abstract

Monterey pine (*Pinus radiata*) is a species of limited distribution, with three native populations in California. In 1986, a disease known as pitch canker, caused by the fungus *Fusarium circinatum*, was identified as the cause of extensive mortality in planted Monterey pines in Santa Cruz County. Monitoring studies on the Monterey Peninsula documented rapid progression of the disease in the native forest during the 1990s, with most trees sustaining some level of infection. However, between 1999 and 2013, the severity of pitch canker stabilized, with many previously diseased trees then free of symptoms, and plots monitored between 2011 and 2015 documented a steady decline in the occurrence of new infections. Consequently, whereas pitch canker was once a conspicuous visual blight in the forest, by the end of the observation period, symptomatic trees had become a rarity. The arrested development of pitch canker is suggestive of a reduction in the frequency and duration of fog near the coast, which provides conditions necessary for the pathogen to establish infections.

Monterey pine (*Pinus radiata* D. Don) is native to California, where the distribution is limited to three populations on the Central Coast: Cambria in San Luis Obispo County, Monterey in Monterey County and Año Nuevo in Santa Cruz and San Mateo counties (Rogers 2002). As the dominant tree species throughout most of its native range, Monterey pine is of great ecological value, and a defining scenic feature in recreational areas such as Point Lobos State Natural Reserve and San Simeon State Park. Native populations are also an important genetic resource because Monterey pine is one of the most widely planted species in plantation forestry. Monterey pine plantations, which occupy over 10 million acres worldwide (Rogers 2004), make a particularly significant contribution to the economies of New Zealand, Chile and Australia.

Examining Monterey pines for evidence of wounds caused by twig beetles, a vector of the pitch canker pathogen. Researchers found the disease to be more severe near the coast than farther inland, suggesting the frequency and duration of fog may influence development of pitch canker.

Thomas Gordon

Resinous lesion on a Monterey pine branch infected by the pitch canker pathogen, *Fusarium circinatum*. Removal of bark reveals discolored tissue killed by growth of the pathogen.

Native Monterey pine with typical early symptoms of pitch canker. Yellow-brown needles result from an infection that has girdled a branch proximal to the dying needles.

Monterey pine with multiples sites of pitch canker infection, resulting in brown needles and naked tips where branches have been girdled.

The local and global importance of Monterey pine incentivizes maintaining the integrity of native populations, all of which are threatened by urbanization, and the associated need for fire suppression. In the absence of fire, growth of understory vegetation limits opportunities for pine seedlings to establish. Another threat to native populations is an exotic disease known as pitch canker, caused by the fungus *Fusarium circinatum* Nirenberg & O'Donnell.

Pitch canker was first described by Hepting and Roth (1946) in North Carolina, where the disease was discovered in a mixed-species plantation. Virginia pine (*Pinus virginiana*), shortleaf pine (*P. echinata*) and pitch pine (*P. rigida*) were all observed to be susceptible to pitch canker. Over the next several decades, pitch canker became a widespread problem in plantations and seed orchards in the southeastern United States (Dwinell et al. 1985). In 1986, pitch canker was identified as the cause of extensive mortality in Monterey pine in coastal California (McCain et al. 1987). Genetic evidence indicates the pathogen was moved to California from the infestation in the southeastern United States (Wikler and Gordon 2000), most likely on contaminated seed (Gordon et al. 2001).

Infections by the pitch canker fungus cause resinous lesions that girdle the affected branch, resulting

Monterey pine killed by the pitch canker pathogen, *Fusarium circinatum*. Tree death is associated with multiple infections on the trunk.

in death of tissues distal to the infection. Infections on the trunk can cause decline and death of the entire tree. Trees weakened by pitch canker are attractive to native insects such as engraver beetles (*Ips* spp.), which increase the risk of mortality (Erbilgin et al. 2008).

In California, severe impacts of pitch canker on Monterey pine were observed in off-site (i.e., outside the native range) plantings bordering State Highway 1 in Santa Cruz County as early as 1986 (McCain et al. 1987). This was consistent with the history of pitch canker in the southeastern United States, where the disease was problematic in managed stands and not in native forests. However, by 1994, pitch canker was confirmed in all three native populations of Monterey pine in California. Bishop pine (*P. muricata*) and knobcone pine *(P. attenuata*), two other closed-cone pine species native to California, have also been damaged by pitch canker (Gordon et al. 2001).

The goal of our research was to understand the factors that influence severity of pitch canker in the native Monterey pine forest. To this end, we recorded the incidence and severity of pitch canker over time, assessed the frequency of disease resistance among standing trees in the forest and quantified the abundance of insects that can serve as vectors of the pitch canker pathogen.

Monterey Peninsula research plots

Plots were established in the native forest on the Monterey Peninsula in 1996 (hereafter referred to as 1996 plots) and monitored for incidence and severity of disease through 2013. Forty plots were located west of Highway 1 in Monterey County, where the largest contiguous stands of native Monterey pine are found. Thirty-nine of the 40 plots were composed solely of Monterey pine. One plot had only bishop pines, and data from that plot were excluded from the analyses presented here. Of the remaining 39 plots, 18 were within 0.9 miles (1.5 kilometers) of the coast (= coastal plots) and 21 were located farther inland (= inland plots).

Each plot included 15 trees of at least 49 inches (125 centimeters) in height. Trees were rated for incidence and severity of pitch canker as described by Wikler et al. (2003). Each tree was categorized as having 0, 1 to 10, or > 10 symptomatic shoot tips. Trees were also placed in categories based on the number of cankers on the trunk of the tree: 0, 1 to 3, or > 3. Data on tip and trunk symptoms were combined to give each tree a disease severity rating, such that 1 to 10 tips counted as 1 point, over 10 tip infections counted as 2 points, 1 to 3 stem cankers counted as 1 point, and over 3 trunk cankers counted as 2 points. Thus, the minimum tree disease severity rating was 0, and the maximum was 4.

In 2011, six additional plots were established to monitor development of pitch canker in a cohort of younger trees (= 2011 plots). Each of the 2011 plots included 50 or 51 trees, with a DBH (diameter at breast height) ranging from 0.4 to 4.3 inches (1 to 11 centimeters). Following an initial assessment in September 2011, plots were evaluated three times per year in 2012 and 2013 (January, May and September), with additional assessments in January and July 2014, and January 2015. On each assessment date, the number of new pitch canker infections on each tree was recorded. New infections were distinguished from pre-existing infections based on symptoms, as described by McNee et al. (2002).

Previous work showed standing trees in the Monterey pine forest to vary in susceptibility to pitch canker, based on the length of lesions that developed at the site of inoculation (Storer et al. 1999). Research has also documented that infections by the pitch canker pathogen can enhance resistance to subsequent infection attempts, a phenomenon referred to as induced resistance (Bonello et al. 2001). To determine how this may have affected the abundance of resistant trees on the Monterey Peninsula, a selection of Monterey pines was inoculated in 2011 and the resulting lesions measured, as described by Gordon et al. (1998).

Each tree was inoculated on three branches by creating a wound approximately 0.06 inch (1.6 millimeters) in diameter that penetrated the bark in the internodal area between terminal and penultimate branch whorls and depositing therein an aqueous suspension of approximately 250 spores of *F. circinatum*. Inoculum was prepared as described by Schmale and Gordon (2003). A total of 133 trees were located in six plots (separate from plots established for monitoring in the same year) in native stands on the Monterey Peninsula, with a minimum of 20 trees at each site.

To assess the abundance of twig beetles (*Pityophthorus* spp.), which can serve as vectors for the pitch canker pathogen (Erbilgin et al. 2009; Sakamoto et al. 2007), funnel traps were deployed as described by Storer et al. (2004). Traps were baited with pityol, which is attractive specifically to *P. setosus,* one of the most common twig beetle species in the Monterey pine forest (Dallara et al. 2000). Traps were placed at six locations and sampled periodically from September 2011 through May 2013. At each sampling date, the number of twig beetles recovered was recorded, along with the percentage of insects carrying spores of the pitch canker pathogen, as described by Storer et al. (2004).


Greg Reynolds

A funnel trap baited with the pheromone pityol was used to trap twig beetles. The pitch canker pathogen was recovered from insects on eight of 14 sampling dates, at levels that ranged from 0.1% to 4%.

Disease severity leveled off

In the 3 years following establishment of plots on the Monterey Peninsula (1996 to 1999), the incidence and severity of pitch canker increased dramatically (Wikler et al. 2003). Furthermore, in a previous study of pitch canker in planted Monterey pines, only 2.2% of trees in heavily diseased plots remained free of infection, indicating that nearly all trees were susceptible to the disease (Storer et al. 2002). Consequently, it seemed likely that damage from pitch canker would continue to increase, with a potentially irreversible, negative

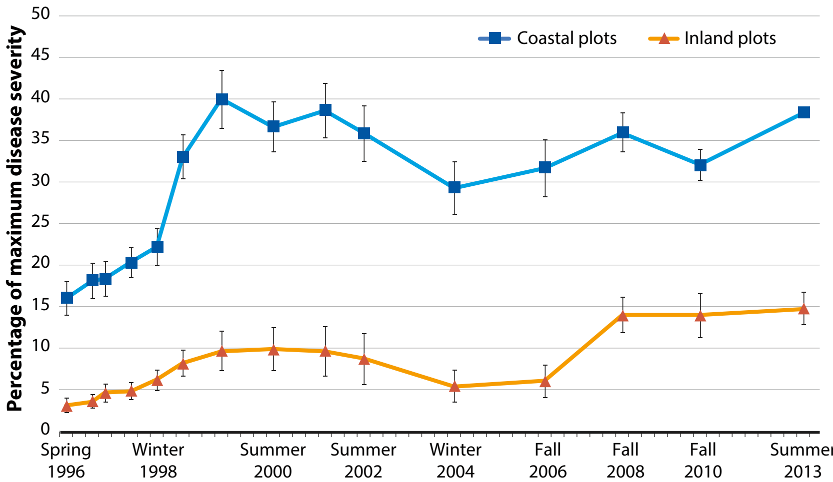

FIG. 1. The mean percentage of maximum severity of pitch canker in coastal (n = 18) and inland (n = 21) plots of Monterey pine on the Monterey Peninsula established in spring 1996 and evaluated at intervals until summer 2013.

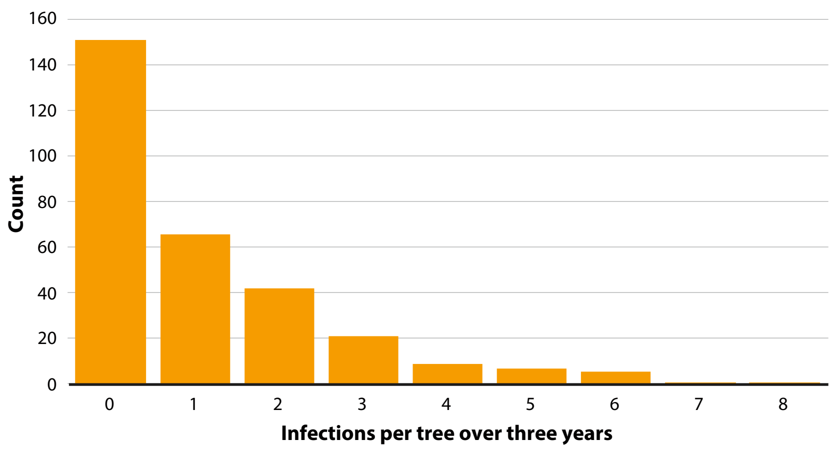

FIG. 2. The number of Monterey pines sustaining between zero and eight infections by the pitch canker pathogen in the Monterey pine forest from September 2011 through January 2015.

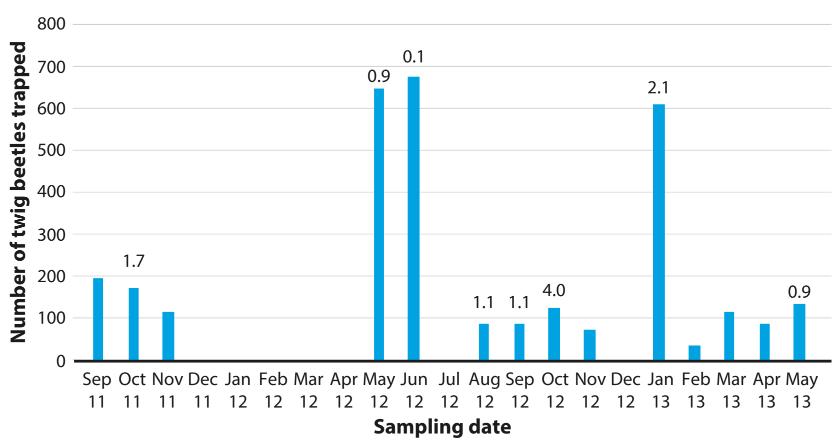

FIG. 3. The number of twig beetles recovered from traps baited with the pheromone pityol on the dates (month/year) indicated. The height of each bar represents the total for traps placed at six locations in the Monterey pine forest. The number above the bar is the percentage of beetles from which *Fusarium circinatum* was isolated. The absence of a number indicates that the pathogen was not recovered from any twig beetles on that date.

impact on the forest. Contrary to this expectation, disease severity in the 1996 plots leveled off and changed very little over the next 14 years (fig. 1).

In part, stabilization of the disease may be due to induced resistance, acting to reduce susceptibility of trees that sustained prior infections. Induced resistance may also help to explain a very low frequency of infection of trees in the 2011 plots. Assessments of 304 trees revealed a total of 27 and 63 new infections at 4 and 8 months after plots were established, respectively. Thereafter, the number of infections declined steadily, with a total of 14 recorded on the final assessment date in 2015. Over the 3 years that plots were monitored, 50% of trees (151/304) sustained no infections, and 22% (66/304) had only one (fig. 2).

If induced resistance was an important contributor to the reduction in the incidence and severity of pitch canker, most trees in the forest should be resistant to the disease. The results of the inoculation trial revealed a wide range of responses to inoculation, with mean lesion lengths (n = 3) ranging from 0.1 to 3.3 inches (2.5 to 85 millimeters). Lesions ≤ 0.6 inch (15 millimeters) in length are unlikely to girdle branches and hence no visible symptoms will develop. Therefore, lesion lengths below this threshold are indicative of resistance to pitch canker (Gordon et al. 1998). On this basis, 41.3% (55/133) of trees inoculated in 2011 were resistant, compared to 38.8% of Monterey pines inoculated with *F. circinatum* in 2002 (Gordon et al. 2011). This comparison suggests there was relatively little change in resistance of Monterey pines to pitch canker in the native forest on the Monterey Peninsula.

F. circinatum is a wound-infecting pathogen, and, in California, wounds created by twig beetles (*Pityophthorus* spp.) can serve as infection courts (Sakamoto et al. 2007; Storer et al. 2004). The number of twig beetles recovered from traps in the Monterey pine forest between September 2011 and May 2013 ranged from 37 to 677. There was no apparent trend across this time interval (fig. 3). The pitch canker pathogen was recovered from insects on eight of 14 sampling dates, at levels that ranged from 0.1% to 4%.

Two of the sites included in the present study were also sampled in 1999. In that year, recovery of *F. circinatum* from trapped twig beetles, across three sampling dates at both locations, ranged from 0.9% to 17% (Storer et al. 2004). Thus although twig beetles remained abundant in the forest, fewer of them were carrying the pathogen. Whether this was a consequence of fewer trees with active infections, and hence fewer spores being produced, or it was among the causal factors reducing the incidence of pitch canker cannot be determined.

Environmental effects on disease

Another factor that could influence development of pitch canker is the frequency with which environmental conditions are conducive to infections. One indication of an environmental effect on the infection process was greater disease severity in coastal plots than in inland plots on the Monterey Peninsula. This differential in disease severity changed very little over a span of 17 years (fig. 1) and may be due, in part, to greater frequency and duration of fog in the coastal plots. Consistent with this interpretation are data showing a higher rate of infection in trees maintained at 100% relative humidity than in trees exposed to a lower relative humidity (Sakamoto et al. 2007).

This is relevant to the arrested development of pitch canker on the Monterey Peninsula if the frequency and duration of fog events decreased along the Central Coast, which would have made moisture required by the pathogen less available, thereby reducing the risk of infection. Indeed, in the typical summer fog seasons of 2014 and 2015, particularly during the normally foggy month of August, data collected by D. Fernandez (unpublished data) indicated significantly lower fog levels than in the preceding 4 years. His two data sites were near sea level and within 20 kilometers of our Monterey pine study sites on the Monterey Peninsula.

Over a period of 16 years, a remarkable recovery from pitch canker was evident in the Monterey pine forest on the Monterey Peninsula. At the start of this interval, the disease was a highly visible blight on the landscape, and by the end, few symptomatic trees could be found in most parts of the forest. Although induced resistance can help to explain the recovery of previously symptomatic trees, most standing trees in 2011 appeared to be susceptible to the disease, and insect vectors carrying spores of the pathogen could still be recovered in the forest. However, infections require relatively warm conditions when moisture is present

One indication of an environmental effect on the infection process was greater disease severity in coastal plots than in inland plots on the Monterey Peninsula.

(Inman et al. 2008). On the Monterey Peninsula, this requirement was met through high humidity and deposition associated with summer fog. It may be that a reduction in frequency with which moisture was made available through fog played a key role in the diminished impact of pitch canker.

Observations suggest that a dramatic decline in disease severity has also occurred among planted pines in Monterey and Santa Cruz counties. Less information is available on development of pitch canker in other locations, but fewer and shorter intervals of fog may well have an effect similar to what we documented on the Monterey Peninsula.

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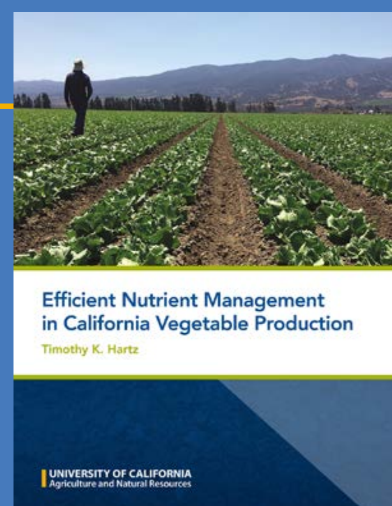

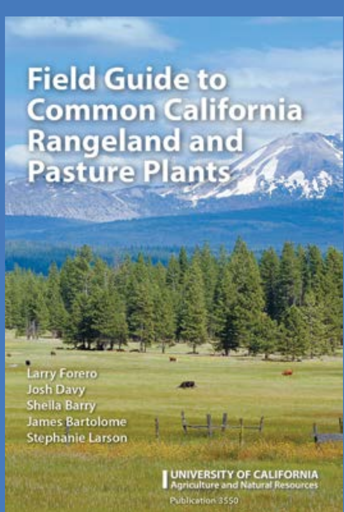

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