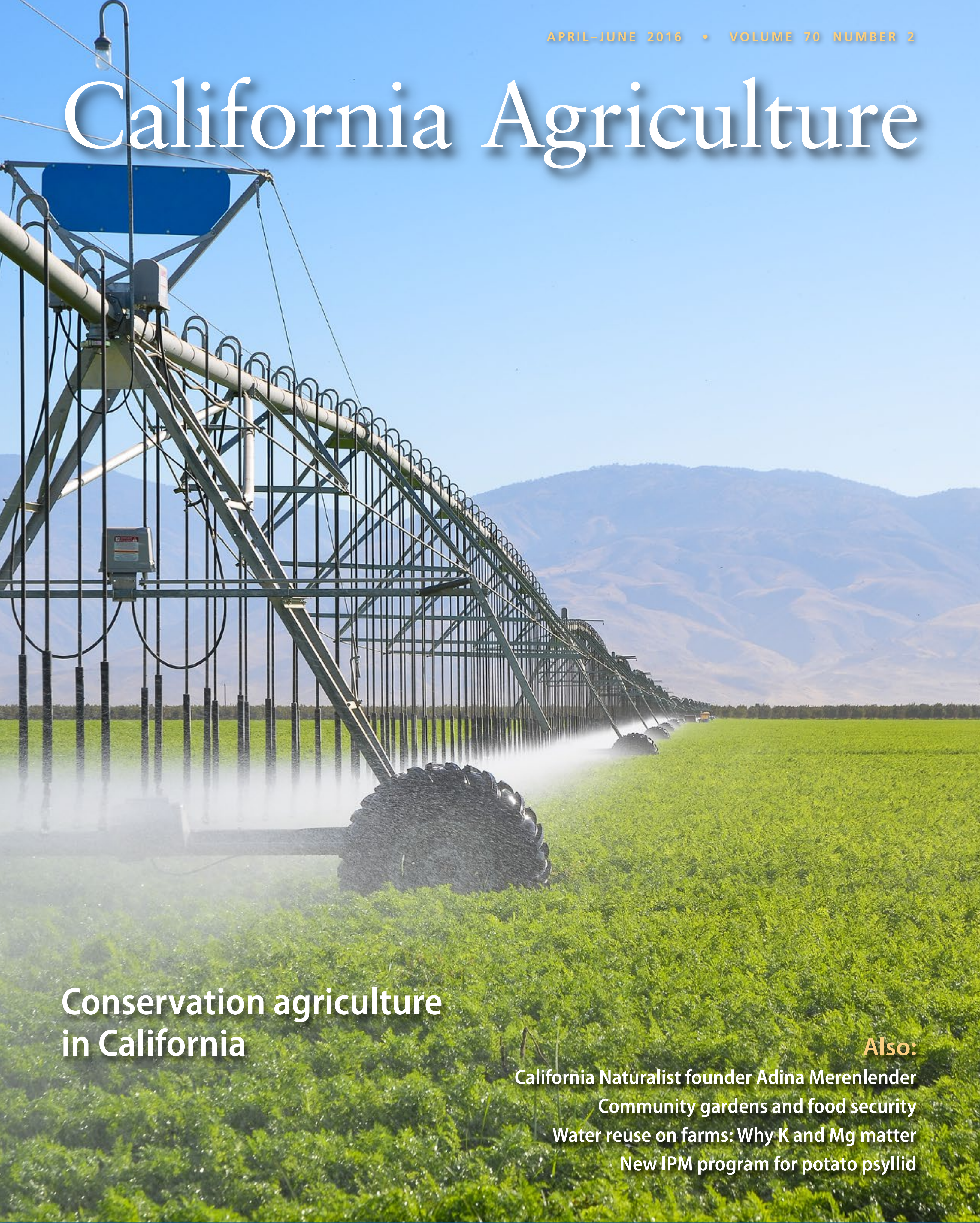
APRIL–JUNE 2016 • VOLUME 70 NUMBER 2

California Agriculture



Conservation agriculture in California

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California Naturalist founder Adina Merenlender

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University *of* California
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COVER: Recent UC research demonstrates the potential of overhead irrigation as an alternative to furrow and drip irrigation on Central Valley crops such as wheat, corn and cotton (page 62). Benefits of overhead irrigation include less soil disturbance, which complements conservation agriculture practices, and lower labor requirements. Shown here is an overhead system irrigating a carrot field in Arvin - Lamont, Kern County. *Photo by Jeffrey Mitchell*.

Conservation agriculture in California

Jeffrey Mitchell

Editorial

Public funding for agricultural research benefits us all

by Glenda Humiston, Vice President, UC Agriculture and Natural Resources

In February, President Obama proposed a budget for fiscal year 2017 that would double funding, to $700 million, for the Agriculture and Food Research Initiative (AFRI), the nation's premier competitive grant program for research in the agricultural sciences.

I applaud this proposal. In recent decades, federal support for agricultural research has waned, even as key international competitors like Brazil and China have increased their investments in this area dramatically.

Agricultural research helps farmers compete in the global market and meet food demand, and it is critical to the continued growth of U.S. agricultural productivity. It also addresses a host of other issues: climate change, safe drinking water, childhood obesity, the ecosystem services provided by farmland, the invasive species that damage crops and spread diseases, and many more.

Glenda Humiston

Public support for research in these areas is essential and irreplaceable, and the availability of competitive grant funding helps to attract top young scientific talent to study the full range of agricultural problems.

Private sector funding for agricultural research also contributes to innovation and progress — and now exceeds USDA research spending. But business concerns tend to focus those research dollars on a few large crops, mainly corn and soybeans, and on applications likely to yield a near-term profit.

That leaves a great deal of important work reliant on public support — particularly in California, with our extraordinarily diverse agricultural sector.

Agricultural research is also an excellent investment for our economy. One in 12 jobs in America is linked to agriculture. Nationally, every additional dollar invested in USDA research returns a benefit of roughly $20. In California, the gains are even greater, with an estimated benefit of $33 per additional public dollar invested in agricultural research here.

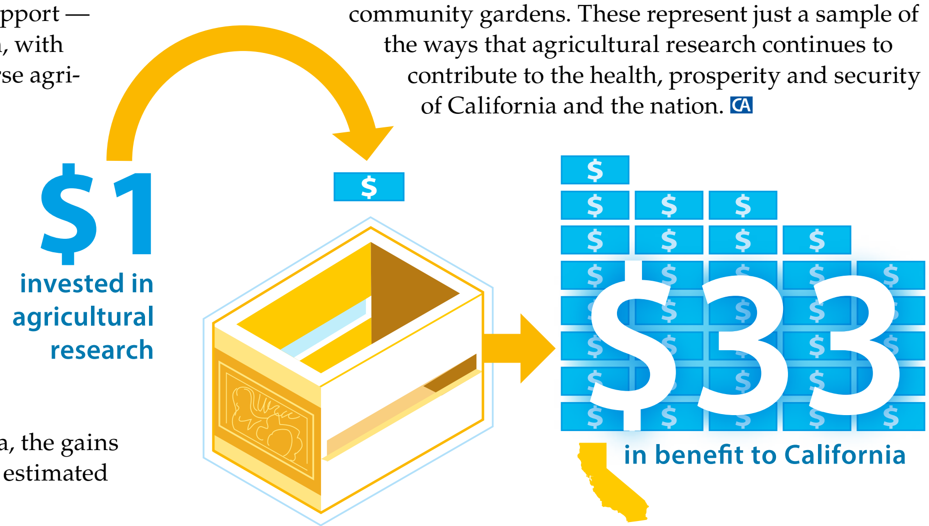
There are countless concrete examples of how agriculture in California is benefiting from publicly supported research today.

UC ANR Cooperative Extension research and outreach has been instrumental in the development of drip irrigation, which is now used on approximately 40% of irrigated cropland in California. A recent study valued the benefit attributable to this research at between $78 million and $283 million per year.

Publicly supported research is critical to the ongoing management of invasive pests and diseases. One major current focus in California is huanglongbing (HLB) disease. Spread by the Asian citrus psyllid, HLB has damaged 100,000 acres of Florida citrus since 2007. In California, it has been found in residential citrus trees but not yet in commercial orchards. In February, USDA awarded $20.1 million for research nationwide to fight the disease, including nearly $4 million to UC Riverside, where researchers are working to develop early detection methods and HLB-resistant rootstocks to help protect California's $2.1 billion citrus industry.

With California's aquifers stressed after years of drought and subject to new rules for sustainable management, UC ANR researchers are testing the use of farm fields and orchards as percolation basins. It's a new approach to recharge depleted groundwater basins by capturing flows from rivers in winter, when water is often abundant.

This issue of *California Agriculture* illustrates the range of issues that researchers are tackling — from sustainable water reuse for irrigation to managing pests with fewer pesticides to promoting nutrition and community gardens. These represent just a sample of the ways that agricultural research continues to contribute to the health, prosperity and security of California and the nation. CA



Conservation agriculture: Systems thinking for sustainable farming

by Jeffrey Mitchell, Ron Harben, Garrison Sposito, Anil Shrestha, Daniel Munk, Gene Miyao, Randy Southard, Howard Ferris, William R. Horwath, Eric Kueneman, Judee Fisher, Monte Bottens, Phil Hogan, Robert Roy, Jim Komar, Dwayne Beck, Don Reicosky, Michelle Leinfelder-Miles, Brenna Aegerter, Johan Six, Tom Barcellos, Dino Giacomazzi, Alan Sano, Jesse Sanchez, Mike Crowell, John Diener, Darrell Cordova, Trevor Cordova *and* Jerry Rossiter

California is an unquestioned global leader in the productivity of its farms and the diversity and quality of its crops. However, there are significant threats to the sustainability of the state's agricultural systems. The scarcity of water has received great attention in recent years, but that is just one of many concerns. Fossil fuel use, carbon emissions, nitrate pollution of groundwater, labor cost and availability, air pollution and loss of soil fertility all present challenges to the long-term viability of farming in California.

Conservation agriculture can help to address all of these issues. Fundamentally, conservation agriculture is about "kindly use" of the land, to quote farmer-essayist Wendell Berry. It is based on three principles: reducing soil disturbance (tilling less, or not at all), retaining crop residues on the soil surface year-round and fostering crop and soil biodiversity. By designing farming systems around these principles, our work has shown that farmers can save water, store more carbon in the soil, burn less fossil fuel, cut labor costs, lower dust emissions and increase profits.

Despite conservation agriculture's promise, however, its adoption has been slow in California. In the Midwest and Great Plains regions, conservation agriculture is practiced on more than 30% of cropland, compared with less than 5% of annual cropland in California. As founders and members of the Conservation Agriculture Sustainability Innovation center (CASI), we are partnering with California farmers and equipment makers to develop conservation agriculture practices and technologies that are effective and appropriate for the state's production systems, and to build networks to help their adoption.

The magnitude of the benefits possible with conservation agriculture is striking. A few examples:

- **Water:** No-till, surface mulching practices and increases in soil organic matter can reduce soil water evaporation by 4 to 5 inches annually (Klocke et al. 2009; Mitchell, Singh et al. 2012; van Donk et al. 2010) and increase soil water storage capacity by the equivalent of roughly 2 inches (Franzluebbers 2010; Hudson 1994). If applied on a significant amount of California's roughly 8.5 million acres of irrigated lands, these measures could reduce statewide irrigation demand by millions of acre-feet.
- **Cost:** By limiting tractor passes and other operations, reduced-tillage practices cut production costs by $100 to $150 per acre across a range of crops grown in California (Mitchell, Carter et al. 2012; Mitchell, Klonsky et al. 2012).

In 2010, CASI held a public education event on cover crops for farmers and private sector, UC and NRCS participants at the UC ANR West Side Research and Extension Center in Five Points.

Ron Harben

- **Carbon:** In a long-term tomato-cotton rotation study in the San Joaquin Valley, after 15 years of reduced tillage in combination with cover cropping, soil carbon content doubled in the top 6 inches of the soil profile (Mitchell et al. in review). Implemented broadly, these practices could be a major new tool in California's efforts to reduce net greenhouse gas emissions.
- **Particulate matter:** Air pollution is a major concern in the San Joaquin Valley and other agricultural regions. Compared with standard tillage, conservation tillage can reduce by 85% the emissions of fine dust particles (PM10 — particulate matter less than 10 microns in diameter), as demonstrated in a study of a dairy forage system (Madden et al. 2008).

Yet there are good reasons why conservation agriculture has, to date, not been adopted widely in California.

First, shifting to a conservation agriculture approach requires investments in technology (primarily irrigation and planting equipment), changes in how a farm is managed, and a transition period of several years for soil health and its benefits to develop — each of which introduces risks for farmers. Knowledge gained through the shared experiences of farmers and agricultural specialists helps to reduce those risks and ease the process of adoption. In California, while there are a number of notable conservation agriculture pioneers, the network of farmers who can share their experiences is still relatively small.

Second, conservation agriculture practices were largely developed and refined on corn, soybean, wheat and cotton farms in the Midwest and Great Plains; a key driver was the opportunity to reduce soil erosion from sloping fields. For those systems, conservation agriculture equipment and guidance are abundant. California — with its Mediterranean climate, largely flat farming landscapes, and diverse mix of crops and soil types — has very different farming systems, meaning that conservation agriculture equipment and techniques need to be adapted to work here, or in some cases developed from scratch. That adaptation and innovation requires research and development.

To address these two related challenges — adoption and innovation — CASI was founded in 1998, beginning as a workgroup within UC Agriculture and Natural Resources and growing to include more than 2,200 partners, including hundreds of farmers, private firms, and researchers and other staff from the UC and California State University (CSU) systems, the U.S. Department of Agriculture — both the Natural Resources Conservation Service (NRCS) and the Agriculture Research Service — and environmental groups.

As a result of the activities of these individuals and groups, conservation agriculture practices are well established for a number of California crops, and the necessary equipment is available. These crops include corn, sorghum, wheat, triticale, forages, cotton, beans and processing tomatoes.

For these crop systems, our focus at CASI is on outreach. We are working to expand partnerships with the private sector to train trainers and get innovation into the hands of farmers. Support from these partners — in particular California Ag Solutions, Wilcox Agriproducts, Reinke Manufacturing Co., Senninger Irrigation, Valmont Industries, Lindsay Corp. and Orthman Manufacturing — has been invaluable.

In addition, we are developing regional centers for demonstration and innovation. In these partnerships — between local farmers, UC and CSU researchers, resource conservation districts and NRCS — farmers work with researchers to establish comparison plots to evaluate conservation agriculture practices. These demonstration sites, currently in place in Fresno, Kern, Mendocino, Sacramento and Stanislaus counties, provide valuable research results, while also establishing sites where farmers can learn from CASI experts and from each other.

Our long-term goal is for CASI to become a true farmer-led organization, following the example of successful conservation agriculture partnerships elsewhere, such as No Till on the Plains and the Pacific Northwest Direct Seed Association.

In addition to outreach, there's a continuing need for research and innovation, both to improve equipment and management practices and to understand and optimize system-level processes such as crop sequences.

Benefits of conservation agriculture systems

Research conducted by CASI has demonstrated a number of economic and environmental benefits that are achieved when conservation agriculture practices are used, including

- Tillage costs typically reduced by $40 to $150 per acre
- Lower fuel use
- Reduced farm energy use
- Reduced dust emissions by 50% to 80%
- Increased soil carbon levels
- Lower soil water evaporation
- More diverse and abundant soil biology
- Increased carbon capture in the production system
- Increased soil aggregation
- Increased irrigation application efficiency and uniformity
- Biologically fixed nitrogen added to the soil, and
- Less surface water runoff

CASI farmers and members visited South Dakota, Nebraska and Colorado in 2006 to learn about conservation agriculture systems. Here, participants tour the Dakota Lakes Research Farm, a research and extension center of South Dakota State University, in Pierre.

There is a need for more cost-benefit data on conservation agriculture practices across a range of California crop systems. Research on ways to increase the amount of water in the soil that is transpired by crops rather than lost to evaporation could lead to water-saving farming methods. Experiments could help to determine how best to combine multiple conservation practices — for instance, reduced tillage, surface residue preservation and precision irrigation (see research article on pages 62–70 of this issue).

We are also working to expand the scope of conservation agriculture into cropping systems for which it was previously unthinkable. Lettuce is a good example. While it is daunting to consider how conservation agriculture practices might be applied to such a high-precision, high-value, rapid-turnover crop, there are large potential payoffs in improved soil health, reduced fuel, water and fertilizer inputs, reduced dust emissions and more. With all this in mind, in January we held a planning meeting with several farmers to discuss developing conservation agriculture for lettuce systems.

Examples from around the nation and the world help to expand our notions of what can be achieved: 60% of Brazil's tomatoes, for instance, are farmed without tillage. Many of the crops grown in California are successfully produced elsewhere using no- or greatly reduced tillage techniques. Virtually all of the wheat in Western Australia, much of the small grain in Canada and the Great Plains, and a sizable proportion of cotton, corn and bean production in the Midwest and Southeastern United States is produced using no-till and strip-till practices. It may be beneficial to bring techniques and concepts used in those systems to California. CASI's connections with farmers in these diverse regions help us to learn about such global innovations and how they may be successfully scaled up here.

We are heartened by the growing official recognition of conservation agriculture. In his 2016-2017 state budget, Gov. Jerry Brown has called for $20 million to support the California Healthy Soils Initiative. The NRCS soil health campaign, launched in 2012, is supporting education and outreach efforts nationwide, while a just-concluded meeting of the Board on Earth Sciences and Resources of the National Research Council focused on new research policy and federal funding initiatives to improve soil carbon sequestration in the face of climate change. At UC Davis we have proposed the creation of a Systems Agronomy Institute that would position the university as a national leader in conservation agriculture innovation and learning, supporting the state and federal soil health initiatives with research and outreach.

Moving forward, CASI will continue to harness the skills and resources of researchers, farmers and private sector and government partners. Our broad and growing network is committed to continuing the expansion of conservation agriculture practices in California for the sustainability of our farms and the benefit of the state's environment and economy. CA

Conservation agriculture practices are well established in California for several crops. Shown here is a winter small grain silage harvest (foreground) ahead of strip-tillage and corn seeding (background) by Mike Faria at Vetter Ranch in Tipton.

Outlook

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Letters

January–March 2016

Re: Management of blue gum eucalyptus in California by Kristina Wolf and Joseph DiTomaso (vol. 70, no. 1, January–March 2016)

The article discussed, at length, the various aspects of the management and environmental impact of the introduced blue gum tree in California, and also included an extensive list of references. However, the article completely ignored the introduction and impact of bark boring insects (*Phoracantha* sp.) on the survival of blue gum plantings in California. It also ignored an article on the subject in *California Agriculture* (Beetle from Australia threatens eucalyptus) by Scriven, Reeves and Luck in the July-August 1986 issue (volume 40, number 7).

The *Phoracantha* bark beetle species continue to have an impact on eucalyptus species including blue gum, especially in Southern California. The extended drought has also enhanced the successful attack of the beetles on stressed trees.

The ignoring of the impact of insects on the planting of *Eucalyptus* in California seems to be a significant omission in the article.

Glenn Scriven, UC Riverside (retired)
Homeland, California

Authors Kristina Wolf and Joseph DiTomaso respond:

Thank you for noting the impact of the eucalyptus longhorn borer (Phoracantha semipunctata) *on eucalyptus species in Southern California. Our review on* E. globulus *(blue gum) in California focuses specifically on the traits of this tree species that might make it invasive in certain regional or climatic contexts. Therefore, we did not assess the impacts of this particular pest on eucalyptus populations in California. As there is little information documenting invasive populations of blue gum in Southern California, the possibility of this beetle species having any potentially negative impact on already noninvasive populations was not reviewed for the purposes of our article. Hanks et al. (1991) found that this beetle cannot colonize the bark of live, vigorous eucalyptus trees (although drought-stressed trees of this species may be more susceptible; see Hanks et al. 1995), and it is thus unlikely to have major impacts in terms of biological control of blue gum in areas where it has demonstrated invasive characteristics (i.e., coastal regions where summer fog provides moisture for trees in California's otherwise long dry season). In our extensive reviews of the literature and outreach efforts to land managers across California, we also did not encounter any reports of measureable impacts on blue gum due to this insect, and as such, it does not seem to be relevant to the control of blue gum in areas where it is a concern in California.*

Sources:

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WHAT DO YOU THINK?

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Adina Merenlender: Building a new mode of extension for biodiversity conservation

When UC ANR conservation biologist Adina Merenlender launched the California Naturalist program in 2012, she was looking to do more than just educate people. She wanted to build a community — inspired to be stewards of the natural world and to push for the resources and policies needed to defend the state's threatened biodiversity.

Adina Merenlender, founder and director of the UC ANR California Naturalist program, is a UC ANR Cooperative Extension specialist in conservation biology based at the Hopland Research and Extension Center and an adjunct professor in the Department of Environmental Science, Policy and Management at UC Berkeley.

"Success to me," Merenlender said on an afternoon walk through the oak woodlands of the Hopland Research and Extension Center (REC), "is when the public connects directly with what UC has to offer and will go to bat for UC gardens, reserves and presses, and call for more faculty to study and teach natural history."

Today, the program is blossoming. More than 1,500 participants have completed a California Naturalist course. The program now has a full-time academic coordinator, Greg Ira, and has received grant funding from the National Science Foundation and the California Wildlife Conservation Board, and in 2015 was honored as the program of the year by the national Alliance of Natural Resource Outreach and Service Programs. The second statewide California Naturalist conference is scheduled for September 9–11 at the Pali Mountain Center in the San Bernardino Mountains.

Through partnerships with more than 30 science and environmental education organizations around the state, the California Naturalist program provides 40-hour certification courses focused on natural history as well as stewardship and communication. The training encourages California Naturalists to volunteer around the state with natural resource agencies and nonprofit organizations, and participants are encouraged to engage in research, environmental monitoring, restoration work and education and outreach.

The California Naturalist program encourages participants to engage in research, environmental monitoring and restoration work. Here, California Naturalists explore trace fossils with geologist Ed Clifton at Point Lobos State Natural Reserve in Monterey County.

"The desire to learn about natural history is insatiable," Merenlender said. "We're giving motivated people a way to help out."

The mix of science and action that characterizes the California Naturalist program mirrors the 20-year UC ANR career of Merenlender, a Cooperative Extension (UCCE) specialist based at Hopland REC and an adjunct professor of environmental science, policy and management at UC Berkeley.

The threat that development poses to intact natural landscapes has driven Merenlender's work since her early years with UC ANR. In the late 1990s, Merenlender and her collaborators used satellite land-cover data to track and project the rapid expansion of vineyards in Sonoma County (Merenlender 2000). In calling out this agricultural growth as a threat to habitat and biodiversity, the work put Merenlender at odds with the powerful wine industry.

Merenlender stood by the work and her role as conservation biologist trying to change the world — and still does.

"I try to make my work constructive and to offer solutions," she said. "But you do have to daylight the issues."

Mediterranean stream restoration

Merenlender then led us down to a seasonal creek at Hopland REC that illustrates a related strand of her research — the restoration of streams in Mediterranean climate systems.

As part of a long-term study, one section of a creek degraded by early clearing and dredging was fenced in the 1980s to exclude deer and other large herbivores, while an adjacent section was left open.

Standing on the sun-bleached cobbles of the unfenced reach, Merenlender points out the dense vegetation that now covers the fenced area — much as it likely did before the area was settled.

In studying streams like this one, Merenlender and graduate student Jeff Opperman made two findings that have shaped the way stream restoration is conducted in much of California.

First, they determined that woody debris — the key to the pools and varied stream channels that characterize good habitat for native salmonids — is of a different nature in Mediterranean-climate oak woodland systems than in wetter coastal forests. In oak woodland areas like Hopland REC, the woody debris in creeks is generally alive — low branches of oaks, bays, and thickets of willows — while in coastal conifer forests, it is primarily dead wood — fallen trunks and branches.

Their second finding, illustrated by the fence enclosure, was that deer can inhibit the recovery of such ecosystems by eating woody plants before they have a chance to mature to the point where they can provide shade and the important woody debris.

Together, these results shifted the approach to stream restoration in Mediterranean ecosystems: Instead of introducing large woody debris, as is done in coastal evergreen forests, the focus is on creating conditions that allow stream vegetation to regenerate, providing important shade, and helping to restore stream morphology for improved salmon habitat.

Research by Merenlender and her collaborators has helped to transform the practice of stream restoration in Mediterranean climates.

Rethinking agricultural ponds

Merenlender's work on vineyard expansion and stream restoration then came together in a body of research, conducted with several graduate students and other collaborators, that shifted the politics of grapes, fish and water in wine country.

It began with several studies of the role of water quantity in salmonid recovery in Mediterranean-climate watersheds (Christian-Smith and Merenlender 2010) and the impacts of upstream water use — from vineyards as well as rural residential pumping — on summer stream flows and juvenile salmon survivorship (Grantham et al 2012).

At the same time that her lab reported the collective impact on salmon survivorship of diverting water from streams to irrigate vineyards during the dry season, Merenlender's team provided models that demonstrated agricultural ponds placed correctly don't necessarily impact winter salmon runs as previously thought and should be used where possible to offset

Long-term study sites on Parson's Creek at Hopland REC show the effect of deer herbivory on the recovery of natural cover in a degraded riparian zone. A site not protected from deer, *left*, has virtually no woody vegetation. By contrast, a site fenced in the 1980s, *right*, is now densely vegetated, providing shade and helping to form pools, both of which benefit fish.

summer pumping and thus — in many, though not all, cases — provide a benefit to fish (Deitch et al 2013).

This finding helped to shift the thinking about farm ponds in the environmental community and among state water regulators, with the practical result that the review process, which was essentially stopped around 1993 due to concern for salmon and litigation by environmental groups, was resumed, allowing farmers to move forward with the permitting process for a new pond.

That work also changed Merenlender's reputation in the wine grape industry. Once seen as an antagonist for trying to stave off habitat conversion, she was invited to speak at grower meetings on water management solutions.

"You have to stick with it long enough that your enemies become your friends," she said.

Half for us, half for them

But Merenlender still has concerns about the wine grape industry — and about the state of biodiversity conservation more broadly. While wine industry players large and small have embraced the idea of sustainability in their operations, many don't consider the conversion of natural landscapes into vineyards to be a problem, she said. Likewise, for all of California's environmental leadership in areas like reducing greenhouse gas emissions and managing air pollution, the state hasn't made a serious effort to stop the chief cause of biodiversity loss: the development of natural lands for residential and agricultural use.

"When we're talking about habitat, in a state with the most endangered species, we need to be thinking about what E.O. Wilson said: 'Half for us, half for them,'" she said, quoting the renowned Harvard biologist considered the father of the academic study of biodiversity. "If we're serious about biodiversity, we're going to have to set meaningful targets for conserving California's native ecosystems and manage these ecosystems."

Building support and enthusiasm for that type of conservation is one of Merenlender's hopes for the California Naturalist program. In the coming years, she foresees a day when the California Naturalists will play a role, perhaps through "day-at-the-Capitol" visits to Sacramento. She's also hoping that UC natural resource academics will connect directly with the California Naturalists about their research and information to help stave off a sixth mass extinction — capitalizing on the power of this new community.

"Working with our partnering organizations around the state, we are creating a whole new mode of natural resource extension," she said.

With leadership from Associate Director Sabrina Drill, California Naturalist is dedicated to broadening the California Naturalist community to include more diversity in age, race and income.

One difficulty in raising money for the California Naturalist program is that institutional donors who fund environmental education tend to support only primary and secondary school programs; there's very little support for adult programs. Merenlender thinks that programs targeting young adults is essential.

"That's when you set your compass," she said.

Merenlender grew up in Los Angeles, and didn't have much interaction with the natural world in childhood beyond watching *Wild Kingdom* on Sunday evenings. She was more than halfway through her undergraduate years at UC San Diego when she got involved in her first conservation biology project, a study of African rhinoceroses.

Today, her research is focused on how conservation efforts can best support biodiversity, for instance by planning for habitat connectivity and the effects of the changing climate. She advises a number of land trusts and public land agencies on systematic conservation planning, and co-authored the first comprehensive book on wildlife corridor planning (Hilty et al 2012).

The threat of extinction is on Merenlender's mind even here in the 5,300 acres of quiet, protected hills and valleys that make up Hopland REC.

Tracyina rostrata, a small flowering annual, is now found only at Hopland REC. The center's staff monitor the known populations of the plant regularly, and its numbers appear to be shrinking.

"We used to have four sites," Merenlender said. "Now it seems to be down to one site. Gulp." CA

—Jim Downing

***Above*, California Naturalists learn about the plants and animals of the American River Parkway at the Effie Yeaw Nature Center near Sacramento.**

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Understanding organic potato fertilization dynamics at Intermountain REC

Strong consumer demand and high prices are encouraging an increasing number of potato growers to consider organic production. Growing organic potatoes introduces new complexities for nutrient and pest management — complexities that Intermountain Research and Extension Center (IREC) Director Rob Wilson and Daniel Geisseler, a UC ANR Cooperative Extension specialist based at UC Davis, are unraveling in an ongoing experiment.

IREC, in the Siskiyou County town of Tulelake, serves the Klamath Basin farming region, an area of roughly 200,000 acres of irrigated land on the California-Oregon border that is one of the leading potato-growing regions for both states. At an elevation of roughly 4,000 feet and with a high desert climate, farming conditions in the basin are quite different from the Central Valley and other low-elevation agricultural regions of California.

Potatoes have a relatively high demand for nitrogen, and organic growers have two general ways to provide it: organic amendments like manure, compost and blood meal; or nitrogen-fixing cover crops, such as varieties of vetch or field peas.

Wilson and Geisseler are teasing out the costs and benefits of the various options and developing nutrient-monitoring plans to guide growers' management decisions. While the work is tailored to the needs of potato growers in the Klamath Basin, it will also help to expand the understanding of nutrient dynamics in organic farming systems more broadly.

In organic farming systems, meeting a crop's nitrogen need is complicated because the available sources, whether cover crops or amendments, provide nitrogen in a form — organic nitrogen — that is not directly available to plants. By contrast, the fertilizers used on conventional farms generally provide nitrogen in plant-available forms — ammonia and nitrate — known as mineral forms of nitrogen.

Soil microbes convert organic nitrogen to ammonia and then to nitrate. Mineralization takes time, and it happens at a different rate depending on the source — the nitrogen in chicken manure is mineralized more quickly than that in steer manure, for instance. The rate is also influenced by environmental variables such as soil type and temperature. The mineralization timetable is important because potatoes need a significant amount of nitrogen in the early stages of their life cycle, before the potato tubers start to grow in earnest.

One objective of the research project is to evaluate how the nitrogen mineralization process proceeds for cover crop residues. Around 90% of the nitrogen in a nitrogen-fixing cover crop is contained in the aboveground plant tissue. To convert that nitrogen into a

Researchers at IREC are evaluating different organic amendment and cover crop treatments for organic potato production.

Rob Wilson

useful fertilizer, the crop must be chopped and tilled into the soil, where soil microbes can mineralize it.

"By determining how much nitrogen is mineralized, we can help growers have a better understanding of the value of the amendments and the different cover crops," said Wilson.

Cost is another comparison point. Per pound of nitrogen provided to the crop, the direct costs of growing a cover crop are generally lower than the cost of organic amendments — and there doesn't appear to be a yield penalty. In the first year of tests, potato yields from fields "fertilized" by cover crops — woolypod vetch and hairy vetch — were greater than those from comparison plots treated with organic amendments or with urea, a conventional nitrogen fertilizer.

Woollypod vetch (*Vicia villosa* ssp. *dasycarpa*).

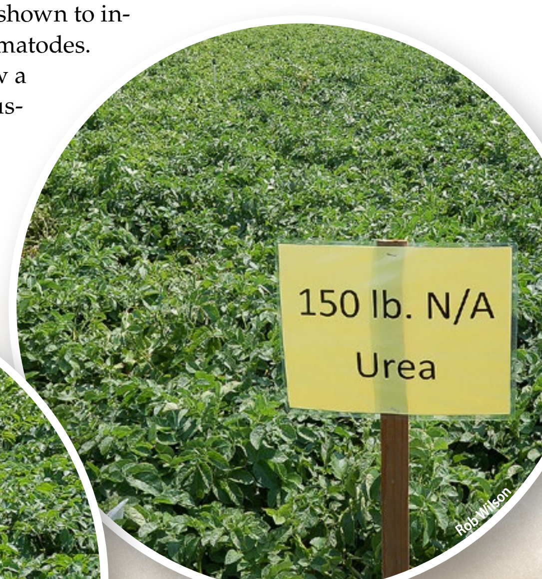
The cost comparison is complicated, however, by considerations such as the availability of irrigation water to grow a cover crop, and the fact that growing a cover crop the year before planting potatoes may displace a cash crop. To better assess the range of costs associated with growing a cover crop, Wilson and Geisseler will try growing several varieties at different times of the year and with and without irrigation.

To make the organic nitrogen in the cover crop available to the next crop planted in the field, the cover crop is chopped, *above*, and then tilled into the soil, where the nitrogen is mineralized by microbes.

In the coming year, Wilson and Geisseler will be evaluating 11 different organic amendment treatments and 17 cover crop treatments, experimenting with adding amendments and planting cover crops to find the best treatments for Tulelake potato production.

A future direction for the work will be to evaluate the pest management benefits and pitfalls of cover crops in an organic potato system. Mustard cover crops, for instance, can act as biofumigants, though they do not provide a nitrogen benefit. Some legumes, on the other hand, have been shown to increase certain fungal diseases and nematodes. Wilson said it may be possible to grow a combination of crops — a blend of mustard and a nitrogen-fixing legume, for instance — to get the benefits of both. CA

— *Jim Downing*



In the first year of tests, vetch and field pea cover crops added sufficient nitrogen through the potato growing season to produce similar yields compared to potatoes fertilized with amendments or with urea.

Precision overhead irrigation is suitable for several Central Valley crops

by Jeffrey P. Mitchell, Anil Shrestha, Joy Hollingsworth, Daniel Munk, Kurt J. Hembree *and* Tom A. Turini

Overhead systems are the dominant irrigation technology in many parts of the world, but they are not widely used in California even though they have higher water application efficiency than furrow irrigation systems and lower labor requirements than drip systems. With water and labor perennial concerns in California, the suitability of overhead systems merits consideration. From 2008 through 2013, in studies near Five Points, California, we evaluated overhead irrigation for wheat, corn, cotton, tomato, onion and broccoli as an alternative to furrow and drip irrigation. With the exception of tomato, equal or increased yields were achieved with overhead irrigation. Many variables are involved in the choice of an irrigation system, but our results suggest that, with more research to support best management practices, overhead irrigation may be useful to a wider set of California farmers than currently use it.

A 1976 *Scientific American* article called center-pivot irrigation "perhaps the most significant mechanical innovation in agriculture since the replacement of draft animals by the tractor" (Splinter 1976). Patented in 1952 by Frank Zybach, a farmer in eastern Colorado, center-pivot systems are automated, precision irrigation water application machines typically made up of seven or eight connected pipes with drop hoses and sprinkler nozzles that rotate in a line around a pivot point. Linear move systems are similar but apply irrigation water in a straight line across a field. Together, center-pivot and linear move systems are known as overhead, or mechanized, irrigation systems and are the most prevalent form of irrigation system in the United States (NASS 2013). They account for the irrigation of 50.4% of total U.S. irrigated acreage.

In Nebraska, the state with the highest crop acreage under irrigation, 70,000 overhead systems are used on more than 7.2 million acres — 87% of the state's total irrigated land — and the remaining gravity irrigation systems are being rapidly replaced by overhead systems because of overhead systems' superior application precision and yield benefits (Pfeifer and Line 2009). In California, by contrast, roughly 350 overhead systems irrigate about 150,000 acres, just 2% of the state's total irrigated acreage.

Technology adoption

Several factors may have contributed to the slow rate of adoption of overhead irrigation in California.

First, difficulties encountered by early adopters of the technology led to overhead systems gaining an undeserved reputation for being unable to keep up with California's high crop evapotranspiration demands, losing unacceptably large amounts of water to evaporation, and being prone to getting stuck in muddy fields. While successful installations of center-pivot systems in recent years show that the technology can in fact work well in California, these negative perceptions persist.

Incomplete coverage by center-pivot systems is another issue. With a standard center-pivot system, roughly 20%, or 33 acres, of a typical 160-acre (quarter section) field is unirrigated. "Swing-out"

Online: http://dx.doi.org/10.3733/ca.v070n02p62

In California, overhead systems are used on just 2% of the state's total irrigated acreage. Here, a center-pivot system irrigates small grain winter forage and summer silage corn production in Denair.

Jeffrey Mitchell

extension arms — designed to irrigate the corners of a square field — and the practice of "close-packing" irrigation circles in a hexagonal array can help to address this issue, but both have drawbacks. Swing-out systems are expensive, adding $25,000 to $45,000 to the cost of center-pivot system depending on options. As a result, they tend to be used mainly on high-value crops such as potatoes. The hexagonal-array approach was introduced in the 1960s but hasn't been widely adopted because land tends to be divided up into regular square and rectangular parcels (Ganzel 2006).

The work of UC ANR Cooperative Extension (UCCE) on drip irrigation since it was introduced in 1969 brings the state an estimated $78 to $283 million annually in water savings and yield increases (Taylor et al. 2014). There has been far less research on overhead irrigation systems in California, despite their earlier introduction in the state. In the 69-year history of this journal, for instance, only three articles address overhead irrigation (Hanson and Orloff 1996; Hanson et al. 1986; Smith et al. 1991).

The dramatic expansion of drip irrigation in California over the past 30 years may provide a parallel to what is currently happening with overhead irrigation. There was an initial reluctance toward believing that drip technology would ever have a role in crop fields that had for 50 years been surface irrigated. However, drip caught on through the bold and pioneering early work of applied researchers Don May, of UCCE Fresno County, and Claude Phene, of the USDA Agricultural Research Service's San Joaquin Valley Agricultural Water Management Laboratory, in Parlier. They identified optimal water management practices for high-yielding, drip-irrigated processing tomatoes, and growers became receptive to the technology. Now drip is used on 90% or more of San Joaquin Valley tomato acreage (Mitchell et al. 2014). Similarly, as research results demonstrate the benefits of overhead irrigation, the technology may spread.

The possibilities of overhead irrigation systems being useful choices for some crops in California agriculture deserve exploration. Overhead irrigation systems have been adopted in many regions of the world since the 1950s because they can irrigate large tracts of land automatically, lightly and frequently; can inject fertilizers and herbicides directly into the water supply line; and can accommodate rolling terrain and coarse or sandy soils (Splinter 1976). Overhead irrigation also has a distinct advantage over other irrigation methods in its labor requirements. Overhead systems require less maintenance than drip systems in terms of avoiding clogging of emitters and repairing leaks. In addition, overhead irrigation may also aid salinity management by uniformly leaching salts from a crop's root zone (John Diener, farmer, Five Points, personal communication).

A wheat crop is irrigated in Five Points with a low-elevation spray application system, which has applicators positioned 12 to 18 inches above the ground.

Researchers used bubbler nozzles, *above*, on the tomato crop from transplant establishment through the early vegetative growth phase to minimize soil evaporation.

On October 2, 2010, about 30 university and private sector partners (including author Mitchell) established the California Overhead Irrigation Alliance (COIA) to develop and provide research-based information on overhead irrigation systems. Since its inception, COIA has conducted a variety of studies, provided several public field days and farm tours related to overhead irrigation, and has been involved with a number of overhead irrigation demonstrations for various crops grown in the Central Valley. COIA did not fund the work reported in this paper.

Selecting an irrigation system

Selecting and purchasing an irrigation system is expensive and complex (Amosson et al. 2011). The decision involves a number of factors, including available financing, crop rotation, energy prices, energy sources, application efficiency, operating pressure and the depth from which water must be pumped. A recently published study provides a number of relevant considerations to assist growers in making decisions about irrigation systems by detailing the costs and benefits of five types of commonly used irrigation systems. These include furrow, or surface, irrigation; subsurface drip irrigation (SDI); and three types of center-pivot systems: mid-elevation spray application (MESA) systems that have water sprayer heads positioned about midway between the mainline and ground surface; low-elevation spray application (LESA) systems that have water applicators positioned about 12 to 18 inches above ground level; and low energy precision application (LEPA) that apply water with drop socks or bubblers near the ground surface (Amosson et al. 2011).

An irrigation system's operating pressure, first of all, affects the cost of pumping water. Higher pressure makes irrigation more expensive (table 1). Furrow systems typically require the lowest operating pressure. LESA, LEPA and SDI have similar operating pressures. The percentage of irrigation water used by the crop relative to the total amount of water applied, the application efficiency, also varies between irrigation systems, with furrow systems typically having lower efficiencies (table 1). Higher application efficiency reduces the amount of water used, which in turn affects operating costs (Amosson et al. 2011).

The investment costs for irrigation systems also vary considerably, from about $210 per acre for furrow and $556 per acre for a quarter-section center-pivot system, to $1,200 per acre for an SDI installation in 2011 dollar values (Amosson et al. 2011). The cost advantage for a center-pivot system over an SDI system, however, may diminish as field size is reduced below a quarter section of land (O'Brien et al. 1998). In addition, system cost comparisons are sensitive to the assumed life span of the system. Center pivots tend to last longer than SDI systems, meaning that the capital costs can be spread over a longer period (O'Brien et al. 1998).

Technical support services to support conversion to overhead systems are increasingly available in California, with all four major companies having a significant presence in the state (Rick Hanshew, Reinke Mfg.; Dan Schueler, Senninger Co.; Chuck Powell, Lindsay Zimmatic Co.; Jerry Rossiter, T & L Irrigation Co.; John Bliss and Pat Murray, Valmont Industries; Craig Stafford, Nelson Irrigation, personal communication).

The potential advantages of overhead systems, however, need to be balanced with the higher rates of water application and soil water evaporation compared with SDI. Also, overhead water application rates must be carefully matched with a soil's intrinsic water intake rate, to avoid runoff and lower application uniformities. In sum, farmers must keep many factors in mind and carefully weigh trade-offs.

TABLE 1. Typical characteristics of five irrigation distribution systems

	Operating pressure*	Application efficiency†	Efficiency index‡	Gross investment
	psi	*%*		*$/ac*
Furrow	10	60	1.47	208.56
Mid-elevation spray application (MESA)	25	78	1.13	
Low-elevation spray application (LESA)	15	88	1.00	556.00
Low-energy precision application (LEPA)	15	95	0.93	
Subsurface drip irrigation (SDI)	15	97	0.92	1,200.00

Source: Adapted from Amosson et al. 2011 with permission.

* psi = pounds of pressure per square inch of water.

† Application efficiency = percentage of irrigation water used by a crop relative to the amount applied.

‡ Efficiency index = amount of water (inches per acre) that each system would have to additionally apply to be as effective as the LESA system.

Irrigation systems study

Since 2008, at the UC West Side Research and Extension Center, in Five Points, we have been conducting a variety of large-scale comparisons of overhead irrigation for crops common to the Central Valley. The purpose of these evaluations has been (1) to determine whether yields can be achieved with overhead irrigation that are comparable to yields achieved with furrow and drip irrigation for wheat, corn, cotton, tomato, onion and broccoli; (2) to develop best management practices for overhead irrigation that can be used to increase the performance of this technology in California; and (3) to synthesize recent farmer experiences with overhead irrigation for a variety of crops in California.

The crops studied are currently irrigated using a variety of systems. Corn and wheat are customarily furrow irrigated. Cotton is generally furrow irrigated as well, but in recent years is increasingly irrigated with either surface or SDI. Onions and broccoli are typically irrigated by sprinklers, but also in some cases, by surface or SDI. Tomatoes, as mentioned above, are predominantly irrigated by SDI. Performance data for some of the crops in our study have been recently published elsewhere (Hollingsworth et al. 2014; Mitchell et al. 2014; Mitchell, Carter et al. 2015); here, we summarize our evaluations of overhead irrigation.

Field plots. Field studies were conducted from 2008 through 2013 in two adjacent 3.24-hectare (8-acre) fields at UC West Side Research and Extension Center, in Five Points (N 36°20′14″, W 120°6′58″). The soil type was a Panoche clay loam (fine-loamy, mixed, superactive, thermic Typic Haplocambids) with a 0% to 2% slope.

The experimental design for wheat and corn was a split plot with three replications. Irrigation system (furrow or overhead in 2008–2009 and 2009–2010, and SDI or overhead in 2012–2013) was the main plot and tillage (standard or no-till) was the subplot. Overhead irrigation complements no-till and other conservation agriculture practices by minimizing soil disturbance. In each year, all plots of wheat and corn were established using the overhead system.

For cotton, onions, tomatoes and broccoli, the experimental design was a randomized complete block with four replications where treatment comparisons included two irrigation systems (overhead and surface drip for onions, overhead and SDI for the other crops). All crops were initially established using the overhead system. The tomatoes were transplanted using a three-row finger transplanter (Mitchell et al. 2014).

Crop varieties. Varieties of crops included the Dekalb corn hybrid DKC67-88 (Monsanto Co., St. Louis, Missouri), the general-purpose hard red spring forage wheat variety WB Patron (Monsanto Co., St. Louis, Missouri) and the broccoli hybrid Green Magic (Park Seed, Hodges, South Carolina).

Overhead irrigation system. The overhead irrigation was a Valley lateral move system (Valmont Industries, Valley, Nebraska), with eight 150-foot-wide (46.1-meter) spans. The area under each span was considered a treatment plot. Thus, each treatment plot was 150 feet wide by 300 feet long. The system was fitted with spinner-type nozzles that spin 360 degrees (outer nozzles had a 180-degree center-facing range to prevent overlap with adjacent plots). Nozzles were spaced 5 feet (1.52 meters) apart and 3 feet (0.91 meter) off the ground.

SDI system. In alternate spans, the nozzles were turned off and ⅞-inch-(2.25-centimeter-) diameter Netafim Streamline 875 0135F drip tape (Netafim USA, Fresno, California) was installed 12 inches (30 centimeters) deep in the soil and 30 inches (76 centimeters) apart. In each row, the emitters were spaced every 13.8 inches (35 centimeters). The drip tape was maintained in the plots for the entire course of the study.

Fertilizers. Cultural practices that are common in this region were used for all crops. Fertilizer nitrogen (N) was applied in all plots at 150 pounds per acre for wheat and 200 pounds per acre for corn exclusively via fertigation for the overhead systems and a combination of ground-applied and water run for the furrow irrigation systems. Fertigation applications of UAN32 totalling 269 pounds per acre for onion, 185 pounds per acre for cotton, 180 pounds per acre for tomato and 245 pounds per acre for broccoli were made to both the overhead and SDI systems.

Growth analysis, harvest. In these studies, we used the functional approach to crop growth analysis (Hunt 1982): We evaluated the change in crop biomass by sampling whole plants at weekly intervals to gain a more detailed season-long assessment of crop growth in the experimental treatments — taking, drying and weighing destructive biomass harvests of the wheat, corn, onion and tomato, and measuring the canopy coverage with a digital IR camera (Dycam ADC Camera, Woodland Hills, California) of tomato and broccoli (Mitchell et al. 2014). Crops were harvested using commercial mechanical harvesters or a farmer-supplied hand-harvest crew (broccoli), and yields were determined using gondola trailers and electronic scales mounted on trailers for all crops except broccoli. For broccoli, harvest bin trailers were weighed using drive-on commercial scales at a nearby farm.

Seeding issues, weeds. There were no observed insect or disease pest issues or other cultural anomalies that warranted unusual interventions. In the 2008 no-till wheat plots, however, we did notice lower plant populations in the bottoms of residue-laden furrows due to difficulties the no-till grain drill had in seeding and in placing seed in good contact with soil. Also, heavy weed pressure was observed in all the plots and required frequent hand-weeding in the two onion studies.

Yields. Yields were determined by machine harvesting and weighing the aboveground wheat biomass in 2008 to 2010 and the grain in 2012, and by combine harvesting and weighing the corn. Data were analyzed using SAS v. 9.2 (SAS Institute, Cary, North Carolina). Testing for normality and homogeneity of variance checked assumptions of ANOVA.

Water applications. Irrigation events were scheduled and applied based on accumulated daily evapotranspiration (ET_o) data from the CIMIS (California Irrigation Management Information System) station 100 yards from the study site and crop coefficient (K_c) values based on percentage canopy cover estimates (Grattan et al. 1998; Hanson and May 2006). We assumed the same K_c values for each irrigation system. Additional work is needed, however, to determine how crop ET and K_c values differ with different irrigation systems. Total water applications were verified through in-line flowmeters and were kept as similar as possible for each irrigation system.

Cost estimates. Economic budget data were obtained from published UCCE production cost studies (Stoddard et al. 2006; Takele et al. 2013; Tourte and Smith 2010; Wilson et al. 2011) and also from surveys of five Central Valley farmers. Costs associated with installing and removing sprinkler pipe for crop germination and establishment and for installing and removing thin-walled (6 to 8 mil) surface drip tape were estimated. These costs would be required when rotating from a subsurface-irrigated crop such as tomato to a common Central Valley rotation crop such as onion or garlic, for which surface or near-surface (2 to 3 inches below the soil surface) tape is used.

Application uniformity. The Christiansen coefficient of uniformity (CU) was determined using the equation below for the overhead irrigation system using catch cans (Mitchell, Shrestha et al. 2015):

$$CU = 100\ [1 - (A/B)]$$

where *CU* is the Christiansen coefficient, *A* is the sum of the absolute value of the deviation of the average catch can value from each individual catch can data point and *B* is the sum of the catch can observations. The CU is the easiest and most widely used method for determining application uniformity of overhead systems (Harrison and Perry 2013).

Uniformity of the furrow and SDI systems was not determined in these studies and was not used in the scheduling of irrigations for any of the systems. Because of the short irrigation runs of the experimental fields (300 feet), we may reasonably assume that the efficiencies of the furrow and drip systems were in the high range of reported values (60% to 85% for furrow, and 97% for SDI) (Amosson et al. 2011; Hanson et al. 1997; Hanson et al. 1999).

Irrigation systems performance

With the exception of tomato, equal or increased yields were achieved with overhead irrigation relative to a variety of comparisons with furrow and drip (SDI except for onion plots, which were irrigated with surface drip) for wheat, corn, cotton, onion and broccoli. Similar water amounts were applied in the overhead system and the drip systems. More water was applied to the furrow systems than the overhead system due to the lower application efficiencies of the furrow system and to the inherent difficulty of achieving uniform water infiltration across a field with furrow irrigation, particularly following intensive intercrop tillage, which is routinely done to prepare beds for subsequent cropping.

Wheat. Similar amounts of water were applied in both the overhead and SDI systems for the 2012–2013 wheat grain crop. However, because of difficulties applying the initial furrow irrigations for germination of the shorter-season green chop wheat crops (wheat crop biomass harvested green or fresh for use as animal feed) in 2008–2009 and 2009–2010, about 8 inches more water were applied in the furrow systems than in the overhead systems (table 2); such initial furrow applications are common to "push" water across recently tilled fields.

The CU of the overhead system was determined to be 93.3%, a very high level of water application evenness (Mitchell, Shrestha et al. 2015). Our overhead system was a linear move system, which has a higher inherent application efficiency than a pivot system, but the relatively high uniformity may also have resulted from improvements made in recent years with water application packages (nozzles and pressure regulators) (Dan Schueler, Senninger Co., personal communication).

Comparing green chop forage wheat production under furrow and overhead irrigation in 2008–2009 and 2009–2010, we found no effect of tillage in either year, and no irrigation system effect in the second year, but yields in the overhead system plots were lower than in the SDI plots in the first year (fig. 1). We speculate that the overhead system yields may have been lower in the first year because of the very high number of overhead irrigations applied (30, compared with 18 in the second year), which likely resulted in a higher proportion of applied water being lost as evaporation and less water stored in the soil compared with the second year (Mitchell et al. 2014; Thompson et al. 1997); also ET_o was higher in the first year (table 2).

Evaporation from soil tends to proceed in two relatively distinct stages between soil wetting events. In the first stage, which is generally called energy-limited, or atmosphere-limited, evaporation is governed mainly by atmospheric conditions and the energy available to vaporize water in the near-surface soil atmosphere (Salvucci 1997). The second stage, generally termed soil-limited evaporation, is characterized by decreasing evaporation rates and is limited by water availability and diffusion in the soil. More first-stage evaporation occurred with the overhead system than the furrow system because of the much more frequent soil wetting with the overhead system; the furrow system had more second-stage evaporation.

Aboveground forage biomass accumulation measured during the second season by sampling 1-square-meter plots within each replication showed no consistent trends for either the tillage or irrigation systems (fig. 2). A goal of the functional approach to crop growth and development sampling is to take frequent data using small sample sizes to gain insights into growth trends that may not be detected using less frequent sampling. However, frequent sampling has limitations of its own; specifically, it is labor-intensive, which in practice can limit the number of replications and thus reduce statistical power.

No yield differences were seen in the 2012–2013 wheat grain crop with similar water application amounts under overhead (5,759 pounds per acre) and SDI (5,317 pounds per acre) systems.

Corn. Irrigations for both the furrow and overhead systems were applied to meet estimated crop ET in each of the three years. As with the wheat crop, increased initial furrow irrigations were needed to establish the corn in the furrow plots, and thus more water was applied in the furrow system than the overhead system (table 3). The overall irrigation

TABLE 2. Comparisons of overhead, furrow (2008–2009, 2009–2010) and SDI (2012–2013) irrigation of wheat, 2008–2013, Five Points

	2008–2009	2009–2010	2012–2013
Furrow			
Applied water (inches)	19.1	20	
Number of irrigations	4	4	
Yield*	19,787 a†	17,414	
SDI			
Applied water (inches)			21.7
Number of irrigations			26
Yield*			5,317
Overhead			
Applied water (inches)	11.8	10.6	20.8
Number of irrigations	30	18	25
Yield*	15,020 b	17,787 NS‡	5,759 NS
ET_o (inches)	13.6	9.9	24.6
Precipitation (inches)	8.1	5.5	3.2
Planting date	Dec 11, 2008	Dec 9, 2009	Dec 12, 2012
Harvest date	Apr 23, 2009	Apr 9, 2010	May 25, 2013

* lbs per acre for 2008–2009 and 2009–2010 aboveground silage and grain seed yield in 2012–2013.

† Means within a row, for yield, followed by different letters are significantly different according to Fisher's least significant difference test at a significance level of 0.05.

‡ NS = non significant at $P = 0.05$.

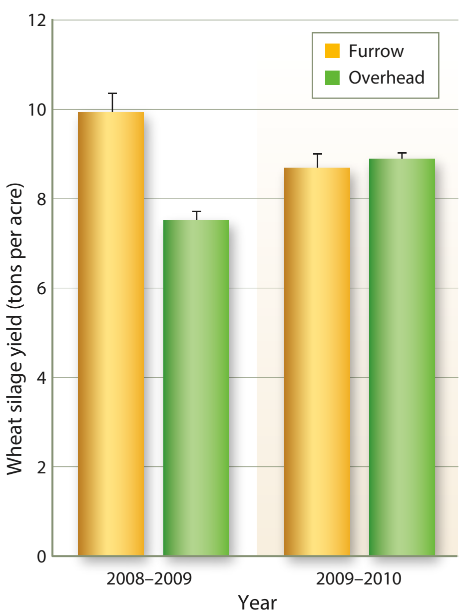


Fig. 1. Wheat silage biomass yield for furrow and overhead irrigation plots, Five Points, 2008–2009 and 2009–2010.

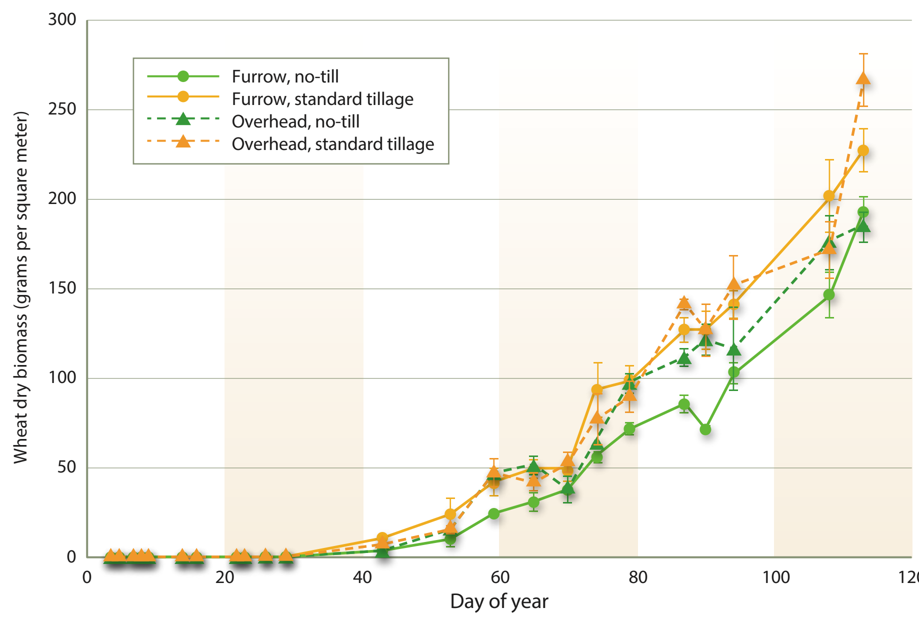


Fig. 2. Wheat silage biomass growth and development for furrow and overhead and standard till and no-till systems in Five Points, 2009–2010.

amounts were similar to amounts applied in the dairy corn silage fields with furrow systems in the San Joaquin Valley, and the roughly weekly frequency of furrow irrigations matched commercial practices also. A higher frequency of irrigations with smaller application volumes was used for the overhead system.

Over the three years, there were no differences in corn yield due to irrigation system; however, the no-till systems had about 10% higher ($P = 0.001$) grain yields than the standard plots (fig. 3). This may have resulted from early-season reductions in soil water evaporation in the no-till systems compared to the standard plots due to residues covering the soil surface and there having been no soil-drying tillage disturbance prior to seeding (Klocke et al. 2009; van Donk et al. 2010). As long as adequate crop stands, for yield potential, are achieved at seeding in no-till systems, our previous research at Five Points has shown that no-till and residues can reduce soil water evaporation losses by about 13% compared with bare soil systems, which is the equivalent of about 4 inches of water during a summer crop season (Mitchell et al. 2012). This potential advantage of no-till systems may have been seen in our studies. The no-till comparisons were included in these studies because they are part of our ongoing research efforts to evaluate the performance of systems that couple precision irrigation with low-disturbance tillage.

TABLE 3. Comparisons of overhead and furrow irrigation of corn, 2008–2010, Five Points

	2008	2009	2010
Furrow			
Applied water (inches)	26.1	32.8	32.2
Number of irrigations	12	11	12
Yield (lbs per acre)	8,201	7,077	7,421
Overhead			
Applied water (inches)	24.3	31.6	30.3
Number of irrigations	31	56	40
Yield (lbs per acre)	8,378	6,259	7,191
Planting date	May 8, 2008	May 6, 2009	May 14, 2010
Harvest date	Sep 29, 2008	Oct 12, 2009	Oct 15, 2010
ET_o (inches)	39.2	41.0	40.2

Broccoli. Growth and development of broccoli as determined by a Tetracam ADC wavelength band–separating digital camera (Tetracam, Chatsworth, California) were similar under the overhead and SDI systems (fig. 4) with similar amounts of applied water (table 4). These similar growth patterns resulted in statistically similar broccoli yields (13,263 pounds per acre for overhead, and 11,225 pounds per acre for SDI). The applied irrigation water amounts and the yields were on a par with those at commercial farms in this region of the San Joaquin Valley.

Onion, cotton, tomato. In the same fields that were used for the crops discussed above, we also evaluated the performance of the overhead system compared with surface drip in onion crops and SDI in cotton and processing tomato crops. Similar amounts of water were applied to each of these crops in the overhead and drip systems. In 2011 and 2012, we found no differences due to irrigation system in crop growth, development and yield, or quality for cotton (Hollingsworth et al. 2014). For onion, yields were not affected by irrigation in 2011 (39.4 t/ac for drip and 37.8 t/ac for overhead), but yields were higher in the overhead system in 2013 (28.3 t/ac for drip and 35.1 t/ac for overhead) (Mitchell et al. 2014).

In evaluations of overhead and SDI systems with tomato crops in 2010 and 2012 (table 5), yields were 48% higher with the SDI system than the overhead system (Mitchell et al. 2014) (fig. 5). This occurred despite our efforts to vary the overhead irrigation application methods (sprinkler versus bubbler nozzles) and the locations

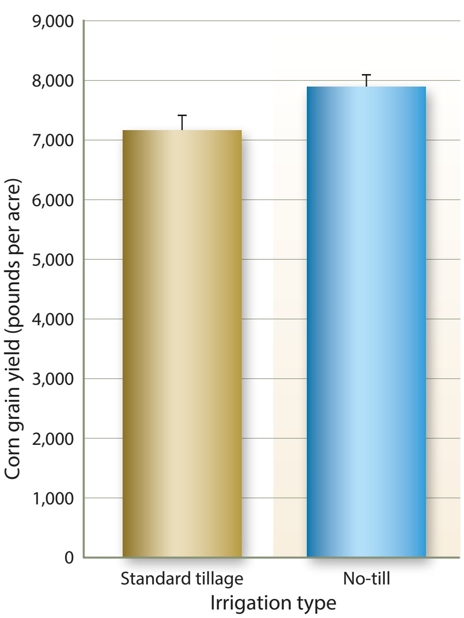


Fig. 3. Corn grain yields for standard tillage and no-tillage systems, Five Points, 2008–2010.

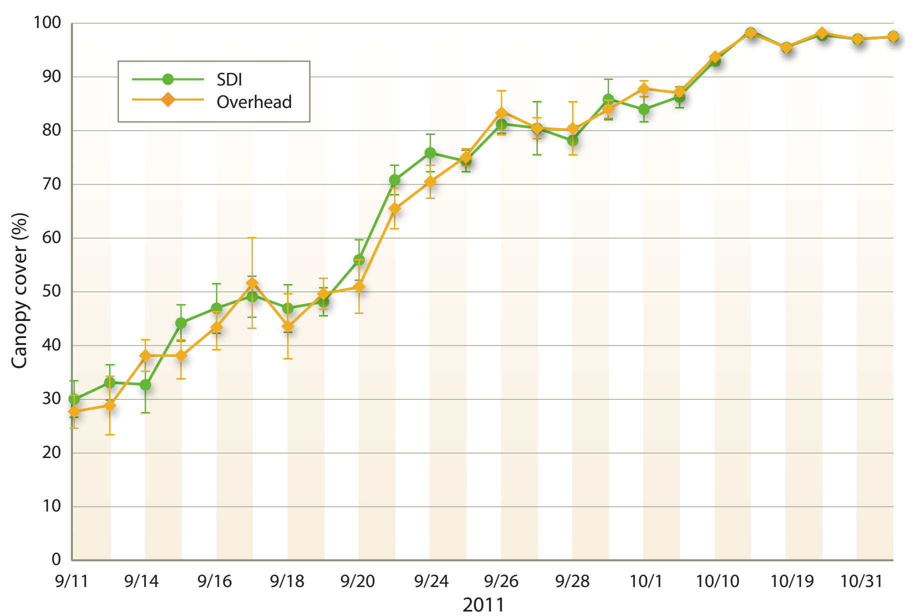


Fig. 4. Broccoli canopy cover (%) under SDI and overhead irrigation, Five Points, 2011.

TABLE 4. Comparisons of overhead and SDI irrigation of broccoli, 2011, Five Points	
	2011
SDI	
Applied water (inches)	16.9
Number of irrigations	35
Yield (lbs per acre)	11,225
Overhead	
Applied water (inches)	15.9
Number of irrigations	33
Yield (lbs per acre)	13,263
Et_o (inches)	14.9
Precipitation (inches)	0.9
Planting date	Aug 17, 2011
Harvest date	Nov 16, 2011

TABLE 5. Applied water, number of irrigation events, precipitation and seasonal reference evapotranspiration (ET_o) for comparisons of overhead and SDI (2010 and 2012) irrigation of tomato, Five Points		
	2010	**2012**
SDI		
Applied water (inches)	23.8	33.4
Number of irrigations	48	43
Yield (tons per acre)	42.2 a*	66.5 a
Overhead		
Applied water (inches)	22.7	33.9
Number of irrigations	47	43
Yield (tons per acre)	23.9 b	41.1 b
ET_o (inches)	25.5	26.9
Planting date	April 30, 2010	April 25, 2012
Harvest date	August 29, 2010	April 27, 2012

* Means within a row, for yield, followed by different letters are significantly different according to Fisher's least significant difference test at a significance level of 0.05.

of application devices (directly over plants or over the furrow) to avoid fruit wetting and risks of late-season disease (fig. 6).

The overhead system was used to establish the tomato seedlings in both plots, and then only in the overhead system plots. Bubbler nozzles, which dribble water in a narrow stream, were used in the overhead system plots from transplant establishment through the early vegetative growth phase to apply water directly to the plants and minimize soil water evaporation (fig. 6). The overhead system was then fitted with rotator-type nozzles (Nelson Irrigation, Walla Walla, Washington) with 360-degree random rainfall spray patterns to increase the wetted volume across the beds. At the edges of the split plots, 180-degree center-facing nozzles were used to prevent overspray with the SDI system. Once fruit began to size and mature, the 360-degree nozzles were replaced with bubbler nozzles repositioned in the furrow areas and used until irrigation cutoff before harvest to avoid the potential of rotting fruit due to direct spray (fig. 6).

The significantly lower overhead yields resulted presumably from several factors, the first of which is the higher soil water evaporation losses of the overhead system compared with the SDI system. Overhead irrigation efficiency declines when applied water evaporates from the wetted canopy and from the soil surface before it is used by the crop (Thompson et al. 1997; Tolk et al. 1995). However, total evaporation losses are lowered because crop transpiration is suppressed due to canopy-intercepted water and microclimate modification (Stambouli et al. 2013; Tolk et al. 1995). Field water balance measurements have shown that net evaporation losses from overhead systems range from 5.1% to 7.1% of applied water for corn (Tolk et al. 1995) and about 9.8% during the day and 5.4% at night for alfalfa (Stambouli et al. 2013).

In our studies, we tried to minimize evaporation losses by using LEPA nozzles early and late season. There were, however, periods during the season in both years when higher levels of evaporation occurred in the overhead system plots than in the SDI system plots, particularly because of the relatively high number of overhead irrigations that were applied.

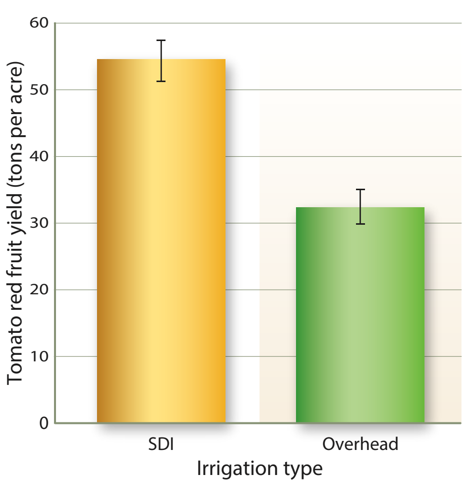


Fig. 5. Average tomato red fruit yields for SDI and overhead systems, Five Points, for 2010 and 2012. 1 ton per acre = 2.2417 Mg·ha^{-1}.

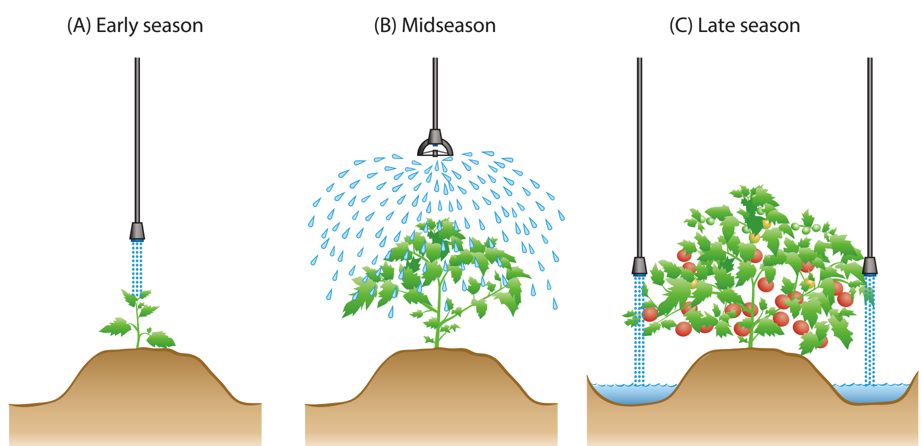


Fig. 6. Overhead irrigation application methods and locations of application devices for (A) early season, (B) midseason and (C) late-season tomato production, Five Points, 2010 and 2012.

Higher K_c values and evaporation are expected with higher irrigation frequencies (see sidebar), particularly early in the crop season when more bare soil is exposed (Ventura et al. 2001).

A second factor that may have contributed to the lower yields in the overhead system plots is that no pre-irrigation (root zone soil water replenishment) was done before either of the cropping seasons. Such pre-season, profile-recharging irrigations are commonly used at local commercial farms (Scott Schmidt, farmer, Five Points, personal communication). Having the soil profile full at the beginning of the tomato season might have buffered against the midseason growth reduction and eventual yield losses that were observed in the overhead system plots. We attempted to account for the lack of pre-irrigation by increasing the amount of total water applied to both systems. In the case of the overhead system plots, however, the timing or location of this applied water did not result in increased tomato growth and yield.

A final contributing factor to the lower yields of the overhead system tomato plots was the way in-season liquid fertilizer was applied. With the SDI system, fertilizers were applied directly to the root zone, where acquisition and uptake occur; with the overhead system, fertilizers were applied throughout the entire planting bed area, including the furrow (fig. 6) (Mitchell et al. 2014). The more diffuse application in the overhead system plots may have been a major contributing factor to both the restricted growth and the lower yields there. It could be addressed by a variety of banded or other more precise application methods. Monitoring plant nutrient status may also be a means for improving the performance of the overhead system.

Economics, innovation, research

Results from our five years of field evaluations generally support the widely recognized value of overhead irrigation technology and indicate that it provides a precision irrigation option that could be of use to a wider segment of California farmers, particularly farmers of most of the crops we studied. Surveys of the numbers of overhead systems that have been recently purchased in California suggest that use of overhead systems is increasing for these crops, and for carrots, where overhead irrigation is now commonly used (Dan Schueler, Senninger Co., personal communication). Overhead irrigation is also now being used commercially in California with alfalfa, sugar beet and potato crops (J. Diener and D. Schueler, personal communication).

Economic considerations are generally the primary factor in the adoption of one irrigation system over another. The yield reductions in the tomato plots that were overhead irrigated would not presently encourage tomato growers to switch from SDI to overhead systems. However, if further research showed that yields with overhead systems could match or nearly match those from SDI, there might be an economic incentive to shift to overhead systems. For example, production costs associated with transitioning from a tomato crop to a sprinkler- or surface drip–irrigated rotation crop such as onion or garlic, which is common in the Central Valley, could be \$130 to \$430 per acre lower if the crops were overhead irrigated rather than SDI irrigated.

A few commercial efforts in the Central Valley to use overhead irrigation for tomato production in the 1990s and another more recent attempt in 2009 resulted in unsatisfactory productivity. Additional innovation is needed to improve overhead irrigation of tomatoes, which have a prominent role in many Central Valley annual crop rotations. We are currently working with a team of Central Valley tomato farmers and processors, irrigation company experts and research colleagues to improve overhead irrigation for this crop. A recent effort to use overhead irrigation for processing tomatoes near Walnut Grove, in 2015, was effective in achieving profitable yields (Michael Boparai, personal communication).

Much is known about overhead irrigation management in other U.S. states that could improve the adoption of this technology for diverse crop systems in California. Matching water application rates with infiltration characteristics of the soil is important, to avoid using frequent, light irrigations, as we did, that have greater evaporation losses. Practices that increase infiltration are encouraged; these include gypsum applications, and increasing soil water holding capacity through conservation agriculture (Dumanski et al. 2006; Mitchell, Carter et al. 2015), for example, by reducing soil disturbance (no-till), preserving surface residue and emphasizing biological diversity above- and belowground. Gypsum applications, however, are not likely to have an impact on sandy, or coarse-textured soils, or under soil conditions that do not have Na-related infiltration problems (K. Bali, personal communication).

Irrigation innovation is an important way for agriculture to become more efficient and sustainable. We believe that

Irrigation frequency and water use efficiency

Increasing the volume of applied water at each irrigation event and thereby reducing the number of irrigations during a season reduces evaporation losses and is a means for improving the water use efficiency of the overhead system in soils with sufficient water holding capacity.

The following example illustrates this point. When overhead irrigation occurs over a crop canopy, an inevitable percentage of the applied water captured by the canopy and stored in the uppermost soil surface level is subject to evaporation loss and does not become part of the crop's direct transpiration stream (Philip 1966). The amount of "interception storage" (Fred Lamm, personal communication), which represents a loss of water, varies by crop and canopy architecture; it is about 0.10 of an inch for corn (Thompson et al. 1997). If a 0.5-inch sprinkler irrigation is applied, this 0.10 inch loss is a 20% loss of the total applied water. If a 1.0-inch irrigation, however, is applied, the loss to evaporation is only 10%.

In a practical sense, best management practice for overhead systems involves applying the largest sprinkler irrigation possible to match the soil's basic infiltration rate and avoid runoff. This will minimize evaporative losses and the risk of growth and yield reductions. It is important to recognize, however, that not only is the soil's infiltration rate important, but so is the ability of the soil to retain applied water. Future research that includes fine-scale measurements of soil water content would help clarify these mechanisms. CA

We believe that overhead irrigation technology has not gained greater traction in California not because it does not work, but rather because of a lack of concerted attention to the management details that are needed to refine and perfect its adaptability for California cropping systems.

overhead irrigation technology has not gained greater traction in California not because it does not work, but rather because of a lack of concerted attention to the management details that are needed to refine and perfect its adaptability for California cropping systems. More research is needed, as was done for drip. There is a clear need for research on developing appropriate crop coefficients for overhead systems and for conducting comprehensive economic life-cycle analyses of the various irrigation systems. Research is also needed on overhead irrigation timing and how to better match water application rates to soil intake characteristics, particularly on fine-textured soils.

Lastly, research into understanding how irrigation system decisions change and new systems are adopted is also important because it will provide information on how to achieve the necessary transformational changes that are challenging agricultural production systems (Awada et al. 2014; Lindwall and Sonntag 2010). Tradition and familiarity with existing common irrigation systems such as surface and SDI are barriers to the adoption of overhead irrigation in California at this time. Given the importance of water shortages and the crop-per-drop considerations that California growers increasingly are facing, more research in this area, and the areas mentioned earlier, would be very important. CA

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Accounting for potassium and magnesium in irrigation water quality assessment

by J.D. Oster, Garrison Sposito *and* Chris J. Smith

Irrigation with treated wastewater is expected to increase significantly in California during the coming decade as a way to reduce the impact of drought and mitigate water transfer issues. To ensure that such wastewater reuse does not result in unacceptable impacts on soil permeability, water quality guidelines must effectively address sodicity hazard. However, current guidelines are based on the sodium adsorption ratio (SAR) and thus assume that potassium (K) and magnesium (Mg), which often are at elevated concentrations in recycled wastewaters, pose no hazard, despite many past studies to the contrary. Recent research has established that the negative effects of high K and Mg concentrations on soil permeability are substantial and that they can be accounted for by a new irrigation water quality parameter, the cation ratio of structural stability (CROSS), a generalization of SAR. We show that CROSS, when suitably optimized, correlates strongly with a standard measure of soil permeability reduction for an agricultural soil leached with winery wastewater, and that it can be incorporated directly into existing irrigation water quality guidelines by replacing SAR.

Recycled wastewaters generated by municipalities and farms in California are being reused increasingly for irrigation, both to expand available water resources and to avoid discharge to surface waters, with the current statewide goal being to reuse 2.5 million acre-feet of wastewater by 2030 (Weber et al. 2014). However, the high salinity and sodium (Na) concentrations characteristic of recycled wastewaters pose a significant challenge to their sustainable reuse for crop production (Assouline et al. 2015; Laurenson et al. 2012; Platts and Grismer 2014a, 2014b). Adding to this challenge, several recent studies (Arienzo et al. 2012; Buelow et al. 2015; Marchuk et al. 2013; Rengasamy and Marchuk 2011; Smith et al. 2015) have documented deleterious effects on soil hydraulic properties caused by high concentrations of potassium (K) and magnesium (Mg), which are typical of recycled wastewaters (Buelow et al. 2015; Laurenson et al. 2012; Weber et al. 2014). The potential consequences include negative impacts on infiltration, water availability and plant growth. Buelow et al. (2015), who investigated California soils, in particular have called for further research to understand the high-risk scenarios that may arise when irrigating with potassium-rich wastewaters. We note in passing that recycled wastewaters are not the only concern of the kind discussed here. High concentrations of Mg occur naturally in groundwater in and near the Coast Range in California because of their serpentine geology (Ben Faber and Mark Battany, UC ANR Cooperative Extension, personal communication, 2015).

All of the studies cited indicated that the negative impacts of K and Mg on the saturated soil hydraulic conductivity

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High concentrations of potassium and magnesium are typically found in recycled wastewaters and can have negative impacts on infiltration, water availability and plant growth.

Will Suckow

place them between the extremes of Na as the worst soil dispersant and calcium (Ca) as the best soil flocculant: Na > K > Mg > Ca. In general, flocculation has a positive impact on soil permeability while dispersion has a negative impact. Although this ordering of negative impacts on soil hydraulic properties among the four cations was documented quantitatively 60 years ago (Quirk and Schofield 1955) and has often been discussed in reviews (Keren 1984; Levy 2012), it has not yet been incorporated into standard irrigation water quality criteria. As noted by Rengasamy and Marchuk (2011) and Buelow et al. (2015), the need to do this has become urgent because of increasing need to reuse wastewaters for irrigation, which is expected to grow exponentially in California during the next few decades (Weber et al. 2014).

In respect to the impacts of Na on soil permeability, the sodium adsorption ratio (SAR) has long been the standard diagnostic parameter for sodicity hazard (U.S. Salinity Laboratory Staff 1954):

$$SAR = Na/[(Ca + Mg)/2)]^{0.5} \qquad (1)$$

where each chemical element symbol indicates a concentration in millimoles of charge per liter ($mmol_c/L$). SAR can be related through rigorous thermodynamic arguments to the exchangeable sodium percentage (Oster and Sposito 1980), a key soil property impacting permeability (Bresler et al. 1982; Keren 1984; Levy 2012; Shainberg and Letey 1984). Similarly, a potassium adsorption ratio (PAR) has been defined with K concentration replacing that of Na (U.S. Salinity Laboratory Staff 1954); but, as noted above, there are as yet no guidelines based on PAR in standard reference publications related to irrigation water quality assessment (Ayers and Westcot 1985; Rhoades et al. 1992; Tanji and Kielen 2002; Tyagi and Minhas 1998; Wallender and Tanji 2012). (See sidebar, "Development of water quality guidelines for irrigated agriculture in California.")

CROSS, a new irrigation water quality parameter

Building on earlier conceptual work by Rengasamy and Sumner (1998), Rengasamy and Marchuk (2011) have proposed a generalization of SAR which quantifies both the differing effects of Na and K as dispersing cations diminishing

Development of water quality guidelines for irrigated agriculture in California

The quality of water for irrigated agriculture is based on the effect the water can have on crop growth and on soil permeability. The salt concentration in irrigation water is the primary factor that affects crop growth: water quality decreases as the salt concentration increases. Water quality impacts on soil permeability are more complicated. Two opposing factors need to be considered: salt concentration, as estimated conventionally by electrical conductivity (EC), and sodicity hazard, as reflected in the sodium adsorption ratio (SAR), which is calculated according to Equation (1) using the concentrations of Na, Ca and Mg in the irrigation water. The effects of EC and SAR on soil permeability are opposite to one another: permeability increases with increasing EC, whereas permeability decreases with increasing SAR. Consequently, soil permeability is maintained by an optimal combination of high EC and low SAR. The irrigation water quality guidelines based on this optimization that are used to assess possible negative impacts on soil permeability (table 1) are those proposed by Ayers and Westcot (1985).

TABLE 1. Interpretive guidelines for assessing the combined effect of SAR and EC in irrigation water on soil infiltration problems

SAR	Degree of impact of SAR according to EC		
	None	Slight to moderate	Severe
($mmol_c/L)^{0.5}$		*dS/m*	
0–3	> 0.7	0.7–0.2	< 0.2
3–6	> 1.2	1.2–0.3	< 0.3
6–12	> 1.9	1.9–0.5	< 0.5
12–20	> 2.9	2.9–1.3	< 1.3
20–40	> 5.0	5.0–2.9	< 2.9

Source: Ayers and Westcot 1985.

These well-known guidelines omit K from consideration. One reason for this omission is that Na concentrations in irrigated soils are usually much higher than those of K, but the more important reason is that the iconic USDA Handbook 60 (U.S. Salinity Laboratory Staff 1954) concludes that "exchangeable K has only a slight or no adverse effect upon the physical properties of soils." This conclusion was influenced by "measurements made recently at the Laboratory on samples of seven soils adjusted to various levels of exchangeable sodium and exchangeable potassium (Fig. 1)." The cited Fig. 1 displays the ratio of air permeability to water permeability as a function of both exchangeable sodium percentage (ESP) and exchangeable potassium percentage (EPP). This ratio increases exponentially with ESP, whereas for EPP there is no increase for three of the seven soils examined, while the increase is small for the other four. In parallel with this perspective concerning K, Mg was considered to have positive effects equal to those of Ca on soil permeability, leading Handbook 60 to group the two bivalent cations together in promoting and maintaining good soil structure. Bresler et al. (1982) have noted, however, that this customary grouping in fact may not reflect the true status of Mg, which, like K, is typically masked by the two- to fivefold greater concentration of Ca over Mg in irrigation waters.

Interestingly, at about the same time that Handbook 60 was discounting K when assessing the impacts of irrigation water quality on soil permeability, it was becoming known that the negative impact on soil permeability of K was in fact not negligible and that the positive impacts of Ca and Mg on permeability were not equal. Quirk and Schofield (1955), inspired by research on the effects of salt concentration on the permeability of agricultural soils in California (Fireman and Bodman 1939), reported what appears to be the first systematic investigation to quantify the separate effects of Na, K, Mg and Ca on the saturated soil hydraulic conductivity. They equilibrated soil pads with concentrated Cl solutions of Na, K, Ca or Mg, then leached the pads with a series of more dilute Cl solutions of the same cation. Their results showed decreases in the hydraulic conductivity over a 5-hour period of leaching which clearly depended on the type of cation. The magnitude of these decreases followed the order: Na > K > Mg > Ca.

soil permeability and the differing effects of Mg and Ca as flocculating cations enhancing soil permeability. This new parameter, the cation ratio of structural stability (CROSS), incorporates the inverse of the critical flocculation (or coagulation) concentration (Rengasamy and Sumner 1998; Sposito 2008) for a cation as a measure of its "relative flocculating power," which is taken as a chemical basis for distinguishing cations that promote soil particle aggregation from those that promote soil particle dispersion. Rengasamy and Sumner (1998) reported critical flocculation concentrations (CFCs) for Na-, K-, Mg- and Ca-saturated clays extracted from four soils, which they then used to calculate the average relative flocculating power of each cation by dividing its average CFC for the four soils into the average CFC for Na-clay, taken as a reference. Compared to Na, the average relative flocculating power of K, Mg and Ca for the four soils was found to be 1.8 ± 0.3, 27 ± 5 and 45 ± 8, respectively. Thus a measure of the *dispersing* power of K relative to Na would be 1.0/1.8 = 0.56 and a measure of the *flocculating* power of Mg relative to Ca would be 27/45 = 0.60. Rengasamy and Marchuk (2011) then proposed the following generalization of SAR:

$$CROSS_f = \frac{(Na + 0.56\ K)}{[(Ca + 0.60\ Mg)/2]^{0.5}} \qquad (2)$$

where we have added a subscript *f* to indicate that the two numerical coefficients in CROSS are based on the relative flocculating power of K and Mg. Rengasamy and Marchuk (2011) tested $CROSS_f$ as a diagnostic water quality parameter by comparing it to SAR in obtaining high correlation with the percent dispersible clay in four Australian soils. Although SAR did correlate significantly with percent dispersible clay, the correlation with $CROSS_f$ was greatly superior. Similarly, Marchuk and Rengasamy (2012) reported a highly significant linear correlation between $CROSS_f$ and the salt concentration (expressed conventionally as electrical conductivity) required to flocculate three Australian soils. They concluded that, by including the dispersive effects of K in addition to Na and differentiating the flocculating effects of Mg from Ca, $CROSS_f$ performed better than SAR in predicting soil clay dispersion and flocculation.

Optimizing CROSS

Additional insight into the significance of CROSS can be had by generalizing Equation (2):

$$\begin{aligned} CROSS &= (Na + a\,K)/[(Ca + b\,Mg)/2]^{0.5} \qquad (3) \\ &= SAR^* + a\,PAR^* \end{aligned}$$

where *a* and *b* are numerical coefficients to be determined by a suitable method and

$$SAR^* = Na/[(Ca + b\,Mg)/2]^{0.5} \qquad (4)$$

$$PAR^* = K/[(Ca + b\,Mg)/2]^{0.5} \qquad (5)$$

are generalizations of SAR and PAR, respectively. According to the ordering of negative cation impacts on soil permeability as determined by Quirk and Schofield (1955), Na > K > Mg > Ca. (See sidebar, "Why do cations with the same valence have different effects on soil permeability?") Therefore, the coefficients *a* and *b* in Equation (3) are both expected to have values < 1, as they do in Equation (2). Equation (3) suggests further that CROSS can be interpreted as the weighted sum of a generalized SAR and PAR, with the weighting factor *a* < 1 interpreted as a measure of the lesser negative impact of PAR* on soil permeability relative to SAR*. The coefficient *b* < 1 can be interpreted as a multiplier of the actual concentration of Mg to produce an "effective concentration" of Mg. This smaller effective concentration reflects the lower flocculating power of Mg relative to Ca. Evidently the concentration of Mg in an irrigation water would have to be 1/*b* times larger than that of Ca so as to have the same positive impact as Ca on soil permeability. Since *b* < 1, SAR < SAR* and PAR < PAR*, which implies that CROSS ≥ SAR for any water composition. Therefore, the use of CROSS as a diagnostic tool to evaluate irrigation water quality according to standard criteria (Ayers and Westcot 1985) will result in a more conservative assessment of potential soil management problems. (See sidebar, "Using CROSS to assess irrigation water quality.")

In their seminal study of cation effects on soil permeability, Quirk and Schofield (1955) defined the cation concentration low enough to result in a 10% to 15% reduction in the saturated hydraulic conductivity, after leaching with water of known composition for a prescribed time-period, as the

Why do cations with the same valence have different effects on soil permeability?

The phenomenon underlying the validity of either SAR or CROSS is soil particle flocculation caused by cation adsorption (Sposito 2008). Diffuse double layer theory (Rengasamy and Sumner 1998; Sposito 2008), which often is used to model cation adsorption leading to flocculation, hypothesizes that only cation valence matters in flocculation. Hence all cations of a given valence should adsorb to soil particles and flocculate them in the same way, although monovalent cations should be less effective than bivalent cations. This is the basis for the definition and chemical validity of SAR (Oster and Sposito 1980).

However, as noted by Rengasamy and Sumner (1998), if cations with the same valence adsorb with differing strength to soil particles, this will affect flocculation. Recently, Marchuk and Rengasamy (2011) defined a molecular-scale geochemical parameter for estimating the relative strength of cation adsorption, *the ionicity index*. This parameter reflects specific cation effects in adsorption by quantifying the relative tendency of a cation to adsorb *weakly* to soil particles; higher ionicity index implies weaker adsorption. (The opposite of ionicity is covalency, which results in strong adsorption to soil particles.) They showed that the ordering of the ionicity index among the four common cations in irrigation waters is Na (0.891) > K (0.863) > Mg (0.735) > Ca (0.670), thus increasing from weakest to strongest adsorption, and that this index is highly correlated with the dispersion (as conventionally measured by turbidity) of both reference clay and soil clay suspensions. The ionicity index goes beyond diffuse double layer theory by saying that both valence and the relative strength of cation adsorption to soil particles influences the flocculating power of a cation. Following this line of reasoning, we suggest that the differences among Na, K, Mg and Ca reflected by the numerical coefficients in CROSS are related to the ionicity index of the cations. CA *threshold concentration* (TEC). The TEC is a widely adopted, convenient measure of the impact of cations on soil permeability (Buelow et al. 2015; Quirk 2001; Shainberg and Letey 1984). Accordingly, we tested Equation (3) as a diagnostic water quality parameter by examining how well it correlates with TEC values we calculated (table 4) using laboratory data reported by Jayawardane et al. (2011) and Arienzo et al. (2012) for a Sodosol from the Riverina region of Australia which had been irrigated with winery wastewater (Smith et al. 2015). Like many irrigated California soils, this soil is high (> 50%) in smectite clay minerals and has alkaline pH (> 8), with a surface horizon of clay loam texture overlying a subsurface horizon of medium clay texture.

A linear correlation between $CROSS_f$ in Equation (2) and the TEC values in table

Using CROSS to assess irrigation water quality

Currently, CROSS is the only tested irrigation water quality parameter that accounts for the effects of all four major cations on soil physical properties. It is based on the premise that the effects of K and Mg on the permeability of soils, at threshold levels of EC, are due to the dispersion of soil aggregates and consequent blockage of soil pores. The same relationships hold for the effects of Na and Ca. Consequently incorporating K and Mg does not pose new deleterious mechanisms for consideration, and the use of CROSS as a diagnostic tool should be similar to the use of SAR. Published research dating back at least 60 years documents the negative impacts of K and Mg on physical properties of soils and clays from Australia, Kazakhstan, South Africa, Niger, the United States and the United Kingdom (Aylmore and Sills 1982; Dontsova and Norton 2002; Horn 1983; Levy and van der Watt 1990; Quirk and Schofield 1955; Reeve et al. 1954; Rengasamy and Sumner 1998; Vyshpolsky et al. 2010; Zhang and Norton 2002). In most cases, the soils studied contained substantial amounts of illite and smectite, typical clay minerals in irrigated soils in California (Buelow et al. 2015).

The interpretative guidelines for irrigation water quality involving SAR and CROSS should therefore be similar. Also, the same procedures to adjust the Ca concentration for effects of bicarbonate on calcite precipitation leading to SAR_{adj} (Ayers and Westcot 1985; Lesch and Suarez 2009) can be used to calculate an adjusted value of CROSS. Values of $CROSS_{opt}$ calculated with Equation (6) for 10 waters applied in California — five municipal wastewaters, two river waters, and three canal waters — are given in table 2. As noted in connection with Equation (3), CROSS > SAR in all cases. For two of the wastewaters, and one river water, the predicted impact of the water on soil permeability increased from *none* to *slight to moderate* using $CROSS_{opt}$ instead of SAR (table 3). This more conservative assessment is an expected effect of including all four major cations with their differing impacts on soil permeability when evaluating irrigation water quality. CA

TABLE 2. Water quality assessment of irrigation waters and wastewaters used for irrigation in California

Water source	Ca	Ca adj*	Mg	Na	K	EC	SAR (Using Ca)	$CROSS_{opt}$ (Using Ca)	SAR (Using Ca adj)	$CROSS_{opt}$ (Using Ca adj)
	$mmol_c/L$					dS/m	$(mmol_c/L)^{0.5}$			
Sacramento River	0.6	1.1	0.6	0.5	0.30	0.18	0.6	1.1	0.5	0.8
Gage Canal	2.9	2.0	0.7	1.5	0.00	0.50	1.1	1.2	1.3	1.5
California Aqueduct	1.7	2.0	1.2	3.4	0.10	0.68	2.8	3.6	2.7	3.4
Delta-Mendota Canal	2.8	4.0	0.8	3.5	0.00	0.69	2.6	2.9	2.3	2.5
Colorado River	4.6	2.6	2.9	9.5	0.10	1.48	4.9	6.1	5.7	8.0
Fresno wastewater	1.3	1.0	1.1	3.4	0.40	0.69	3.1	4.2	3.3	4.8
Santa Rosa wastewater	2.0	1.6	1.6	3.9	0.30	0.70	2.9	3.9	3.1	4.3
Bakersfield wastewater	2.3	1.6	0.4	4.7	0.70	0.88	4.0	4.6	4.7	5.5
South Bay wastewater	2.6	2.0	2.5	6.4	0.40	1.21	4.0	5.5	4.3	6.2
Palo Alto wastewater	2.3	3.0	2.8	8.5	0.00	1.35	5.3	7.6	5.0	6.7

* Ca adj calculated using Table 11 in Ayers and Westcot (1985), which contains Ca adj values calculated as proposed by Suarez (1981).

TABLE 3. Irrigation water quality assessment (degree of impact on soil permeability) based on the guidelines in table 1 and the data in table 2

Water source	Water quality assessment: Ca — SAR	Ca — CROSS	Ca adj — SAR	Ca adj — CROSS
Sacramento River	Severe	Severe	Severe	Severe
Gage Canal	SM*	SM	SM	SM
California Aqueduct	SM	SM	SM	SM
Delta-Mendota Canal	SM	SM	SM	SM
Colorado River	None	SM	None	SM
Fresno wastewater	SM	SM	SM	SM
Santa Rosa wastewater	SM	SM	SM	SM
Bakersfield wastewater	SM	SM	SM	SM
South Bay wastewater	None	None	None	SM
Palo Alto wastewater	None	SM	None	SM

* SM = slight to moderate.

4 is shown in figure 1A. This correlation is good enough to confirm the hypothesis that negative soil permeability effects of K and Mg are important. Figure 1B shows the much-improved linear correlation between the generalized CROSS in Equation (3) and TEC that we obtained using an optimization technique to provide best-fit values of the coefficients *a* and *b* (Duan et al. 1993; Rosenbrock 1960). The optimized CROSS is:

$$CROSS_{opt} = SAR^* + 0.335\ (\pm\ 0.038)\ PAR^* \quad (6)$$

$$= \frac{(Na + 0.335\ (\pm\ 0.038)\ K)}{(Ca + 0.0758\ (\pm\ 0.012)\ Mg)/2)^{0.5}}$$

where "opt" designates optimization. Comparison of figure 1A with figure 1B shows that use of Equation (6) instead of Equation (2) improves the correlation of CROSS with TEC dramatically.

The optimized values of the coefficients *a* and *b* in Equation (6) can be interpreted chemically as follows. The electrolyte concentration required to cause flocculation of soil clays is usually considerably greater than that which results in the dispersion of soil clays (Quirk 2001). In light of this fact, the TEC values for Na and K reported by Quirk and Schofield (1955), which relate to soil clay dispersion, might be better suited to estimate the *a* coefficient in CROSS than the CFC values Rengasamy and Marchuk (2011) used. Under this hypothesis, the value for *a* should equal the ratio of TEC for K (67 $mmol_c/L$) to that for Na (250 $mmol_c/L$) as determined by Quirk and Schofield (1955), which is 0.27. The optimized value of *a* in

TABLE 4. Sodium (SAR) and potassium adsorption ratio (PAR), threshold concentration (TEC) and cation concentrations in applied water leading to a 15% reduction in the saturated hydraulic conductivity of surface and subsurface layers in a calcareous soil from the Riverina region of Australia

Soil layer	SAR or PAR*	TEC	K	Na	Mg	Ca
		mmol$_c$/L				
Surface	SAR40 Ca	66.0	0.00	61.30	0.00	4.70
Surface	PAR40 Ca	15.5	15.21	0.00	0.00	0.29
Surface	SAR20 Ca	30.2	0.00	26.70	0.00	3.50
Surface	PAR20 Ca	9.6	9.18	0.00	0.00	0.42
Surface	SAR5 Ca	2.0	0.00	1.76	0.00	0.24
Surface	PAR5 Ca	2.0	1.76	0.00	0.00	0.24
Subsurface	SAR40 Ca	134.0	0.00	116.90	0.00	17.10
Subsurface	PAR40 Ca	32.9	31.65	0.00	0.00	1.25
Subsurface	SAR20 Ca	16.7	0.00	15.50	0.00	1.20
Subsurface	PAR20 Ca	26.9	24.92	0.00	0.00	1.98
Subsurface	SAR5 Ca	1.5	0.00	1.35	0.00	0.15
Subsurface	PAR5 Ca	1.5	1.35	0.00	0.00	0.15
Surface	SAR40 Ca+ Mg	191.0	0.00	159.30	15.85	15.85
Surface	PAR40 Ca+ Mg	22.6	22.00	0.00	0.30	0.30
Surface	SAR20 Ca+Mg	66.9	0.00	52.95	6.98	6.98
Surface	PAR20 Ca+Mg	10.7	10.18	0.00	0.26	0.26
Surface	SAR5 Ca+ Mg	1.5	0.00	1.35	0.07	0.07
Surface	PAR5 Ca+ Mg	2.0	1.76	0.00	0.12	0.12
Subsurface	SAR40 Ca+ Mg	224.8	0.00	183.00	20.90	20.90
Subsurface	PAR40 Ca+ Mg	71.9	66.40	0.00	2.75	2.75
Subsurface	SAR20 Ca+ Mg	33.3	0.00	29.10	2.10	2.10
Subsurface	PAR20 Ca+ Mg	7.1	6.87	0.00	0.12	0.12
Subsurface	SAR5 Ca+ Mg	1.0	0.00	0.93	0.03	0.03
Subsurface	PAR5 Ca+ Mg	1.0	0.93	0.00	0.03	0.03
Surface	SAR40 Mg	517.0	0.00	357.00	160.00	0.00
Surface	PAR40 Mg	140.0	121.50	0.00	18.50	0.00
Surface	SAR20 Mg	283.0	0.00	158.00	125.00	0.00
Surface	PAR20 Mg	99.5	73.00	0.00	26.50	0.00
Surface	SAR5 Mg	23.2	0.00	12.00	11.20	0.00
Surface	PAR5 Mg	18.9	10.30	0.00	8.60	0.00
Subsurface	SAR40 Mg	501.0	0.00	349.00	152.00	0.00
Subsurface	PAR40 Mg	136.0	118.50	0.00	17.50	0.00
Subsurface	SAR20 Mg	156.0	0.00	103.00	53.00	0.00
Subsurface	PAR20 Mg	60.7	49.00	0.00	11.70	0.00
Subsurface	SAR5 Mg	8.7	0.00	5.90	2.80	0.00
Subsurface	PAR5 Mg	15.1	8.85	0.00	6.25	0.00

Source: Arienzo et al. 2012.

*The number is the corresponding SAR, or PAR, for the cation concentrations within the same row.

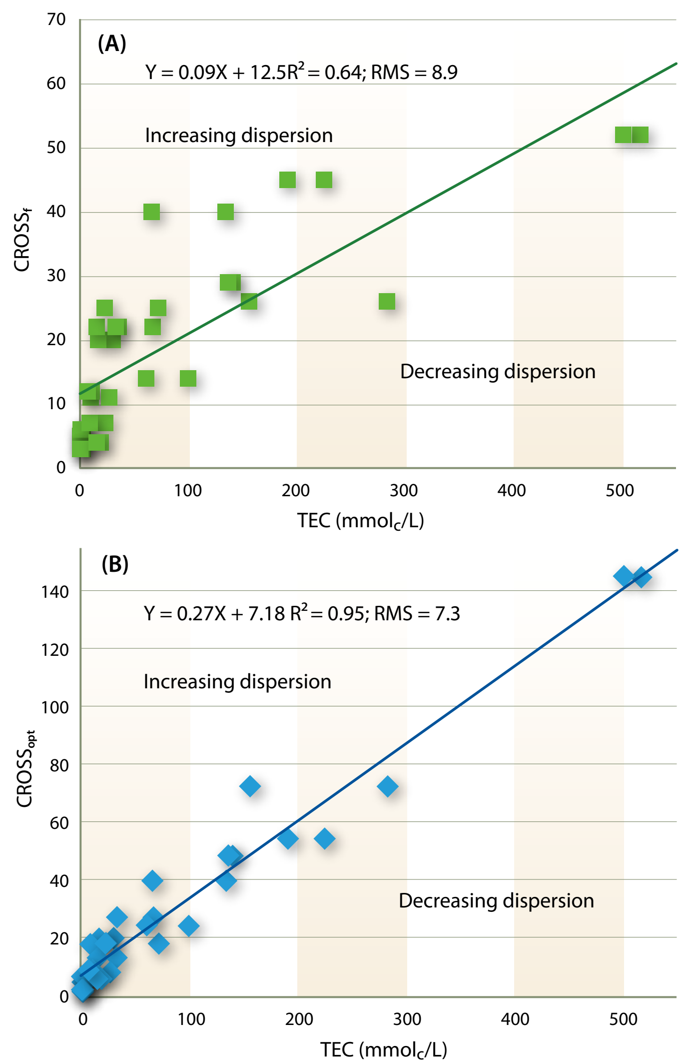

Fig. 1. Correlations between the cation ratio of structural stability (CROSS), with the coefficients for K and Mg based on their (A) relative flocculating power ($CROSS_f$) or (B) statistically optimized ($CROSS_{opt}$), and the threshold concentration (TEC, $mmol_c/L$) in applied water leading to a 15% reduction in the relative saturated hydraulic conductivity of a calcareous soil from the Riverina region of Australia (Arienzo et al. 2012). RMS represents the root-mean-square.

Equation (6), which indicates the dispersive power of K to be about one-third that of Na, is consistent with this estimate.

Our optimized *b* coefficient, however, is not approximately equal to *a*, as it is in Equation (2). Following the discussion given above, its very small value implies that the concentration of Mg needs to be about an order of magnitude larger than that of Ca in order to have the same positive effect as Ca in promoting soil flocculation. This large difference can, in fact, be deduced from directly examining the data in table 4. For example, the TEC values associated with SAR40 Ca and SAR40 Mg are 66.0 and 517.0 $mmol_c/L$, respectively. Here the coefficient *a* plays no role; the coefficient *b* (and, therefore, Mg) is solely responsible for the second, much larger value of TEC. According to Equation (6), $CROSS_{opt}$ for TEC = 517 $mmol_c/L$ is equal to 147. In this case $CROSS_{opt}$ is equal to SAR*. Since SAR = 40, SAR* is 3.67 times larger than SAR, implying $b = 0.0743$, which agrees with the optimized value.

Conclusions

Sixty years of research on soil permeability as affected by irrigation water quality have established that the decreasing order of negative impacts of the four major cations follows the sequence: Na > K > Mg > Ca. Current irrigation water quality guidelines (Ayers and Westcot 1985) omit K entirely and consider Mg to have no negative impacts on soil hydraulic properties. The new irrigation water quality parameter, CROSS (Rengasamy and Marchuk 2011), a generalization of SAR, accounts for the negative impacts of K and Mg on soil permeability. We found an excellent correlation between a suitably optimized CROSS and TEC, a standard measure of the reduction in soil permeability under leaching, for a Sodosol irrigated with winery wastewater having significant concentrations of K and Mg (fig. 1B). Thus we propose the substitution of CROSS for SAR in irrigation water quality guidelines as a generalization of sodicity hazard to include the relative deleterious impact on soil hydraulic properties of the four common cations. CA

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Community and home gardens increase vegetable intake and food security of residents in San Jose, California

by Susan Algert, Lucy Diekmann, Marian Renvall *and* Leslie Gray

As of 2013, 42 million American households were involved in growing their own food either at home or in a community garden plot. The purpose of this pilot study was to document the extent to which gardeners, particularly less affluent ones, increase their vegetable intake when eating from either home or community garden spaces. Eighty-five community gardeners and 50 home gardeners from San Jose, California, completed a survey providing information on demographic background, self-rated health, vegetable intake and the benefits of gardening. The gardeners surveyed were generally low income and came from a variety of ethnic and educational backgrounds. Participants in this study reported doubling their vegetable intake to a level that met the number of daily servings recommended by the U.S. Dietary Guidelines. Growing food in community and home gardens can contribute to food security by helping provide access to fresh vegetables and increasing consumption of vegetables by gardeners and their families.

Gardeners today represent a broad cross section of the U.S. population. The most often cited reasons for gardening include cost savings and a desire to improve the taste, nutrition and quality of the fruits and vegetables consumed (National Gardening Association 2014). A high vegetable intake is associated with a healthy diet that is lower in calories and higher in fiber. Yet national health surveys indicate that all Americans are eating fewer vegetables than are recommended for optimal health (Haack and Byker 2014; USDA DHHS 2010), and vegetable consumption is particularly low among low-income populations (Hiza et al. 2013; Kirkpatrick et al. 2012).

Increasing access to and consumption of fresh vegetables is an important public health goal. Gardening can contribute to food security at all income levels by providing access to fresh, culturally acceptable produce and encouraging a more nutritious diet. Food security is defined as “access by all people at all times to enough food for an active and healthy life” (Coleman-Jensen et al. 2012) and is a concept that encompasses food’s quantity, quality and cultural acceptability. Cultural acceptability acknowledges that customary, preferred and prohibited foods differ between groups.

Community gardens have been shown to increase gardeners’ intake of fresh vegetables in the United States (Algert et al. 2014), potentially providing access to people who are unable to garden where they live. However, many community gardens have long wait lists and are limited in scope and scale (Public Health Law and

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The La Mesa Verde program in San Jose helps low-income families to establish their own vegetable gardens. A pilot study found that gardening in either a community or backyard space made a significant contribution to gardeners’ daily vegetable intake.

La Mesa Verde, Sacred Heart Community Service

Community gardens have been shown to increase gardeners' intake of fresh vegetables.

Susan Algert

Policy 2010). Research on the ability of home gardens to increase intake of fresh vegetables is sparse (Taylor and Lovell 2014), partially due to home gardens' informal and private nature.

As an extensive and popular land use, home food gardens make up a much larger portion of the total area of urban land in food production than public sites of urban agriculture (Carney et al. 2012; Kortright and Wakefield 2010; Taylor and Lovell 2012). For the many people who do not have access to a community garden, gardening at home can be a strategy for improving access to fresh produce. Home gardens may also enhance food security in communities where fresh fruits and vegetables are not available either because of their cost or a lack of retail outlets.

Increasingly, cities, nonprofits and individuals are interested in gardening as a way to improve access to healthy food. A number of programs in California, including La Mesa Verde (LMV) in San Jose, are assisting low-income families with establishing their own vegetable gardens. As of 2013, Supplemental Nutrition Assistance Program (SNAP) benefits can also be used to purchase seeds and plants so that low-income households can grow their own produce (Center for the Study of the Presidency and Congress 2012). Thus, both home and community gardens are potentially effective interventions to improve nutrition and food security in low-income groups, making it important to document the extent to which gardeners, particularly less affluent ones, increase their vegetable intake when eating from their gardens.

In this study, we compare home gardeners in LMV, a program that explicitly targets low-income households, with community gardeners in San Jose, California, and examine whether these two groups increased their vegetable intake while gardening. We also assessed how gardening impacts other elements of food access, such as cost savings, culturally acceptable foods and informal distribution networks. While the community gardeners in our study are on the whole more affluent than LMV gardeners, both groups are ethnically diverse and widely dispersed in neighborhoods throughout the city of San Jose with various levels of food access.

Survey of gardeners in San Jose

Our study was conducted in partnership with the San Jose Parks, Recreation and Neighborhood Services Department, which runs the city's Community Garden Program, and LMV, a project initiated by Sacred Heart Community Service in 2009. The UC Davis Institutional Review Board approved the study procedures and participants provided informed consent.

San Jose's Community Garden Program has provided gardeners with spaces to grow food, socialize and learn about gardening since 1977. Currently, the city operates 18 community gardens that serve more than 900 gardeners and occupy more than 35 acres in total (City of San Jose 2015). Long wait lists for many of the city's gardens show that demand for garden plots greatly exceeds the supply (Public Health Law and Policy 2010).

The goals of LMV include organic food production, cost savings, greater food security, social cohesion and promotion of a healthy lifestyle. In collaboration with Sacred Heart Community Service, UC Master Gardener volunteers provide raised beds, soil, seeds and plants free of charge to families participating in the LMV program. In addition, the volunteers teach introductory organic gardening workshops on topics such as soil science, vegetable cultivation and garden ecology for participating families and make periodic visits to participants' gardens. Participating gardeners are responsible for purchasing fertilizer or soil amendments on their own and paying for water if it is not covered in their rent.

We surveyed 85 community gardeners from four separate community gardens from April through September 2012. We administered the survey (ucanr.edu/u.cfm?id=139) in English or Spanish at the garden sites during times gardeners were working on their plots. Gardeners completed the survey in writing. Prior to the study, the survey was validated on 20 individuals from a single community garden during March 2012.

In addition, we administered the same survey between September 2013 and April 2014 to 50 SNAP-eligible home gardeners participating in the LMV program. Interpreters helped translate the survey into Spanish or Chinese, and it was given to gardeners during community workshops. In total, just under 100 families were enrolled in the LMV program at the time of the survey. Open-ended

La Mesa Verde, Sacred Heart Community Service

The LMV program offers cooking classes to help participants learn how to prepare and cook a meal using produce grown in their gardens.

interviews were also conducted with families in LMV to examine program benefits and barriers such as having the resources to maintain soil fertility over time.

The survey obtained background information on the gardeners such as vegetable intake when eating from the garden, cost savings, body mass index (BMI), self-reported health, socio-demographic characteristics and benefits of gardening. BMI was assessed using self-reported weight in kilograms divided by self-reported height in meters squared, and self-reported health was obtained using a question from the Behavior Risk Factor Surveillance System (CDC 2015).

In addition, the survey included two closed-ended questions about (1) distribution of excess produce from the garden to others and (2) benefits of gardening, including meeting with friends and family, fresh air, exercise, stress release and the exchange of ideas with program leaders and other gardeners. Gardeners were also asked to write down their favorite things about gardening and to list the crops grown in their garden, starting with the ones they grow the most.

We assessed vegetable intake with a question from the Expanded Food and Nutrition Education Program (EFNEP) food behavior checklist and used color visuals instead of text to improve readability (Townsend et al. 2012). Participants reported their usual vegetable intake in cups per day. Participants were then asked "Are you eating vegetables from your garden right now?" The third question in this series used color images in place of text to ask gardeners to report how many additional cups of vegetables they consumed when they were eating from the garden. Study participants may have over reported the quantity of vegetables they consumed on a daily basis and when eating from the garden. Bias of over reporting and having no control group are weaknesses of this pilot project.

Descriptive data was summarized as mean and standard deviations, and compared using student *t*-tests for continuous data between the two groups and chi-square analysis for categorical variables.

Profile of gardeners

The group of home gardeners was younger ($p < 0.001$), lower income ($p < 0.001$), less likely to have completed college ($p < 0.001$) and more ethnically diverse than the group of community gardeners. The average annual income of both the home gardeners ($26,832) and the community gardeners ($57,600) was well below the median annual income ($95,300) in Santa Clara County, where 57% of households earn more than $75,000 each year (Avalos 2014). Educational attainment was also lower among the home gardeners, only 20% of whom had graduated from college compared to 56% of community gardeners. The home gardeners were primarily American Indian, Hispanic, mixed race and white, while 53% of the community gardeners were white (table 1). Most of the American Indian LMV participants were recruited from the Indian Health Center of Santa Clara Valley.

The two study groups also differed in their years of experience as gardeners. Fifty-eight percent of LMV gardeners reported having less than 2 years of experience, whereas only 33% of community gardeners had gardened for 2 years or less (not significant). The home gardeners in this survey were relatively inexperienced because one of the goals of LMV is to train novice gardeners. Seventy percent of LMV participants lived in a house compared to 66% of community gardeners.

Self-reported health status was similar between the two groups, with 45% of LMV participants reporting excellent or very good health ($n = 22$), 35% reporting good health ($n = 17$) and 20% reporting fair or poor health ($n = 10$). Thirty-five percent of community gardeners rated their health excellent or very good ($n = 23$), 48% rated their health good ($n = 32$) and 17% rated their health fair or poor ($n = 11$). There was no difference in BMI between the two groups of gardeners (table 1), most of whom were overweight.

When eating from their gardens, both groups met the U.S. Dietary Guidelines for recommended daily servings of vegetables for adults to promote optimal health.

Effect on vegetable intake

In spite of their demographic differences, the two groups increased their vegetable consumption to a similar

TABLE 1. Comparison of home and community gardeners in San Jose, 2012–2014

	Home garden	Community garden	Significance
Number of participants	50	85	
Gender, female	42/50 (84%)	42/83 (50%)	NS
Age, years	49 ± 13	58 ± 12	0.001
Body mass index	28.5 ± 6.0	26.3 ± 5.3	0.058
Monthly income, dollars	2,236 ± 1,637 $n = 37$	4,800 ± 3,570 $n = 51$	0.001
Race, number of respondents	25	79	
Hispanic	5 (20%)	7 (9%)	
American Indian	7 (28%)	14 (18%)	
Black	1 (4%)	4 (5%)	
Pacific Islander	1 (4%)	4 (5%)	
White	6 (24%)	42 (53%)	
Other, mixed	5 (20%)	8 (10%)	
Residence, house	35/50 (70%)	56/85 (66%)	
Education, number of respondents	47	82	0.001
Less than high school	10 (21%)	8 (10%)	
High school graduate	6 (12.5%)	5 (6%)	
Some college	21 (44%)	24 (30%)	
College graduate, or post graduate	10 (20%)	45 (54%)	

extent when eating from their gardens (1.9 ± 0.9 additional cups per person per day for home gardeners versus 2.0 ± 0.8 additional cups per person per day for community gardeners). Prior to harvesting vegetables from the garden, average intake of vegetables was 2.0 cups per day. Average intake doubled to 4.0 cups per day when the majority were eating from the garden, which was during the peak of the summer growing season (June to September). At the time of the survey, 79% of home gardeners and 63% of community gardeners reported that they were consuming vegetables from their gardens. When eating from their gardens, both groups met the U.S. Dietary Guidelines that recommend adults consume 2.5 cups of vegetables daily to promote optimal health (USDA DHHS 2010).

In interviews, gardeners elaborated on the ways in which the vegetables they grew fit into their diet. Many LMV members said they joined the home garden program to increase their vegetable intake. One woman reported that as a result of her home garden, she ate more produce during the main production season while canning and freezing the excess production for later. Several LMV members also described how gardening influenced their food choices, leading them to select

La Mesa Verde, Sacred Heart Community Service

By growing and eating culturally favorite fruits and vegetables, gardeners may maintain connections to cultural or family traditions.

healthier foods and reduce fast food consumption. Community gardeners commented on the high quality of their produce, indicating that their vegetables tasted much better than store-bought vegetables.

Cost savings

Average cost savings reported by both groups was similar at $92 per month for home gardeners and $84 per month for community gardeners. One LMV participant reported that without the savings and direct access to healthy produce generated from eating homegrown vegetables, the previous year would have been a significant struggle. Her garden significantly supplemented her diet, providing food to which she would otherwise have had very limited access.

Garden crops

The most common crops grown by community gardeners were tomatoes (regular and cherry), peppers, green beans and cucumbers. Crops given to the LMV families to grow as part of the program included tomatoes (regular and cherry), peppers, beans, basil, zucchini, radishes, cucumbers and eggplants. Culturally favorite foods were also grown in both community and home gardens, including chayote, bitter melon, goji berries, green tomatoes, fava beans, okra, collards and various Asian vegetables, such as bok choy and mustards. By growing and eating these foods, gardeners may maintain connections to family or cultural traditions; they may also gain access to desired foods that are either not available or are perceived to be too expensive or of poor quality at local retail outlets.

Distribution of excess produce

Both groups primarily gave excess produce to friends and family/household members. Community garden members

One summer day's harvest from the demonstration garden located at Sacred Heart Community Service in San Jose. Both home and community gardeners doubled their vegetable intake to an average of 4 cups per day during the peak of the summer growing season.

Susan Algert

gave excess produce to other gardeners, whereas home gardeners were more likely to give excess away at work and to neighbors. Some gardeners reported trading vegetables for other food, often from a neighbor's garden.

When asked why excess production was often shared with neighbors and friends, a community gardener stated that the garden allowed her to grow food for the table and neighbors. One home gardener said that by showing neighbors how fresh and good homegrown vegetables were, she might convince neighbors to garden. The majority of LMV participants who had helped neighbors to start gardens said they did so because they wanted to share their experiences with eating more fruits and vegetables.

Additional benefits

The top three benefits reported by home gardeners in the LMV program were getting out in the fresh air, stress release and instruction in gardening basics. Open-ended interviews and survey responses indicated other benefits as well. For instance, gardening led LMV participants to spend more time with family members: most participants gardened with their spouse, children or members of their extended family. Several home gardeners explained that gardening made them feel part of a community; they described developing a network of fellow gardeners through the workshops and services offered by LMV and connecting with their neighbors by sharing produce, work and knowledge about gardening. When asked how gardens would change the neighborhood, one participant replied that houses with gardens would look less abandoned.

Community gardeners said their top benefits were exercise, meeting with friends and learning from other gardeners. Open-ended survey responses of community gardeners also emphasized the feelings of community and sharing they experienced when working in the garden. Gardeners appreciated spending time with neighbors, friends and family in their gardens; these interactions were a source of happiness, friendship and learning. The community gardeners also saw their gardens as a source of healthy food, reporting that their gardens gave them the opportunity to have food that was fresh, organic and more nutritional than its store-bought counterpart.

Learning about gardening as a family was emphasized by the home gardeners, whereas learning about gardening from garden leaders and friends was stressed by those using community garden plots. Similarly, other studies have shown that community gardens provide a space and activity around which to socialize and develop social networks (Carney et al. 2012; Harris et al. 2014; Pitt 2014; Zick et al. 2013).

Increasing vegetable consumption

The results of this small pilot study indicate that both community and home gardeners substantially increased their vegetable intake when eating from their gardens. Although the gardeners surveyed differed in their income level, educational attainment, ethnic background and level of gardening experience, we found that gardening in either a community or backyard space made a significant contribution to gardeners' daily vegetable intake.

The findings from this research — which, to our knowledge, is the first to obtain data on the number of portions of vegetables consumed by gardeners when they are eating from their gardens — are consistent with other studies of the nutritional impacts of gardening. A recent study analyzing the output of a model raised bed garden designed for a family of four found that it produced 2.45 vegetable servings per person per day, providing essential vitamins and minerals (Fruge et al. 2014). A study of home and community gardeners in Denver, Colorado, found that gardeners ate fruits and vegetables more times per day than non-gardeners (Litt et al. 2011). Other researchers have shown that the most significant impact of home food gardening on food security was its ability to enhance gardeners' access to fresh produce and improve the nutritional value of their diets by increasing the diversity of fresh produce consumed (Kortright and Wakefield 2010).

Gardening has been associated with a healthier diet and lower BMIs (Alaimo et al. 2008; Litt et al. 2011; van den Berg et al. 2010; Wakefield et al. 2007; Zick et al. 2013). Although participants in our study were overweight, the majority reported good to excellent health. In a previous study of LMV, program participants said they had changed their eating habits and were incorporating more fruits and vegetables into their diet while reducing fast food consumption (Gray et al. 2013). A Philadelphia study demonstrated that gardeners consumed more vegetables such as dark leafy greens and fewer sweet foods and drinks than did non-gardeners (Blair et al. 1991). Further research on the nutritional intake of gardeners is needed to demonstrate whether they have a healthier diet overall.

Creating access to food specific to a gardeners' heritage is often the motivation for growing particular crops. In this study, participants reported growing cultural or ethnic foods such as bok choy, gogi berries, chayote and green tomatoes. Similar to other research projects, many families in this study grew foods that had meaning in terms of their identity as individuals and their personal and community history (Fruge et al. 2014; Schupp and Sharp 2012). The agrobiodiversity of the garden contributes to nutrition and food security by increasing the intake of culturally unique vegetables. Gardens also allow family members to pass culturally relevant knowledge to others such as children, grandchildren and neighbors.

The finding that excess food from both the community and home gardens was given to friends and family suggests that the health benefits of gardens extend beyond what the gardeners themselves experience. A greater understanding of reciprocity networks in the garden and their contribution to nutrition and food

At the time of the survey, 79% of home gardeners and 63% of community gardeners reported that they were eating vegetables from their gardens.

security for an extended network of family and friends should be explored further (Schupp and Sharp 2012).

Limitations of our study include the small sample size, the unknown degree of bias due to self-selection and the potential for recall bias in self reporting. Populations were self-selected based on their interest in gardening; we expect the bias would be equal between the two populations of gardeners. Vegetable intake, health status and BMI are self-reported and subject to recall bias. Gardeners may have over reported the amount of vegetables they consume on a daily basis and the amount of vegetables they consume when eating from their gardens. Cultural differences in interpretation of questions makes administering pilot surveys challenging, particularly for non-English-speaking survey participants. For example, the use of translators to administer surveys in Chinese and Spanish may have led to confusion among the gardeners about the interpretation of some questions. Given that this was a pilot study, the results should be considered exploratory and suggest areas for future research.

At present more than a third of all households, or 42 million households, in America are growing food at home or in a community garden. This represents a 17% increase overall from 2008, when 36 million households were food gardening. The largest increase in participation is among younger households, up 63% to 13 million since 2008. Over the same period, participation also increased 25% by households with children (up to 15 million in 2013), 29% by people in urban areas (up to 9 million) and 38% by households with incomes under $35,000 (up to 11 million) (National Gardening Association 2014). As our pilot study indicates, both community and home gardens are an effective public health mechanism to increase local opportunities to consume more fresh produce. Particularly when provided with resources and training as in the LMV program in San Jose, even novice gardeners can learn to grow their own vegetables.

Significant barriers to residential food production must be addressed, however. These include the lack of gardening skills and the need for secure access to suitable land on which to grow food (Baker et al. 2013; Litt et al. 2011). In addition, costs associated with initiating and maintaining community and home gardens can be substantial, particularly for low-income families, and future research should investigate the relative cost-effectiveness of urban gardens and other strategies for increasing residents' access to fresh produce. CA

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Research Article

A qualitative evaluation of UC CalFresh *Plan, Shop, Save, Cook* curriculum reveals additional outcomes

by Andra Nicoli, Chutima Ganthavorn, Concepcion Mendoza, Anna Martin, Marisa Neelon *and* Lucia L. Kaiser

UC ANR Cooperative Extension (UCCE) conducted six focus groups in 2013 with CalFresh-eligible adults to determine how to improve the existing evaluation method for the* Plan, Shop, Save, Cook *nutrition education classes. Focus group participants (n = 54) cited many behavior changes that are captured by the existing method. During the focus groups, changes in cooking practices and types of food purchased emerged as two domains that are not currently captured. A small pilot study conducted on 22 of the 54 focus group participants suggests that using a telephone interview to survey participants is a feasible and practical approach to collect follow-up data on long-term behavior changes. More rigorous follow-up studies may guide the development of policies aimed at increasing diet quality and food security of adult CalFresh participants.

In 2013, 42% of the poorest American households lacked access to enough food, compared to 14.3% of all American households (Coleman-Jensen et al. 2014). People living in poverty have to make hard choices among basic needs and often run out of money for food before the end of the month. To reduce food insecurity and improve nutrition among low-income families, the U.S. Department of Agriculture (USDA) funds the Supplemental Nutrition Assistance Program (SNAP). As the largest food assistance program in the United States, SNAP served 45,766,672 participants at a cost of $69.7 billion in 2015 (USDA 2016). The 2010 Healthy, Hunger-Free Kids Act provided an additional $407 million in 2015 (SNAP-Ed 2015) for SNAP Education (SNAP-Ed). SNAP-Ed teaches SNAP-enrolled or SNAP-eligible audiences how to make healthy food choices with their food assistance benefits and to adopt physically active lifestyles.

California is home to the largest SNAP program, known as CalFresh. CalFresh reaches about 4.16 million Californians in 1.91 million households each month. The majority of CalFresh recipients are Hispanic (56% Hispanic, 21% white, 13% black, 7% other and 3% mixed race), and most (71.9%) are female-headed households (CDSS 2011). More than half (57%) of CalFresh recipients are children under 18 years old. On average, CalFresh recipients receive $130 a month for groceries. Eligibility is based on having an annual income that does not exceed 200% of the federal poverty level. In California, only 6.2% of CalFresh-eligible households have cash income above the poverty level, compared to 16.6% nationally (Strayer et al. 2012). Due to the recent economic downturn, the percentage of Californians receiving CalFresh rose sharply, from 6% in 2008 to 11% in 2013 (Danielson 2014).

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History of UC CalFresh

UC Davis is one of several organizations that subcontract with the California Department of Social Services to deliver the

CalFresh, California's SNAP program, reaches over 4 million people each month.

USDA FNS SNAP

SNAP-Ed program. The program was known as the UC Food Stamp Nutrition Education Program (FSNEP) when it began in 1994 but changed its name to UC CalFresh Nutrition Education Program (UC CalFresh) in 2012. Today, UC ANR Cooperative Extension (UCCE) delivers adult, family-centered and youth UC CalFresh programs in schools and other community settings in 31 counties. In 2013, the program reached 120,449 participants directly through classes and an additional 478,975 CalFresh-eligible Californians through indirect nutrition education in venues such as health fairs, farmers markets and back-to-school nights.

Historically, UCCE nutrition education to low-income audiences has included one lesson on food resource management practices, including budgeting, meal planning and smart shopping (e.g., comparing unit prices, using coupons, etc.), as part of the eight-lesson curriculum *Eating Smart Being Active* (ext.colostate.edu/esba/). When household food insecurity rates escalated during the 2007 recession, UCCE nutrition advisors identified the need for greater emphasis on building food resource management skills in UC CalFresh audiences. In 2011, UCCE nutrition advisors developed a four-lesson series called *Plan, Shop, Save, Cook* (PSSC), which was adapted from a single lesson in *Eating Smart Being Active*. During each one-hour lesson, participants practice skills and discuss ways to help them eat healthier on limited budgets. Activities include planning healthy meals, writing a shopping list, reading food labels, using unit pricing to choose the lowest cost product, watching a cooking demonstration and tasting easy-to-prepare, low-cost, healthy recipes. (For details on the PSSC curriculum, please contact the UC CalFresh state office at uccalfresh_support@ucdavis.edu.)

Statewide evaluation of PSSC

To evaluate PSSC, UCCE nutrition advisors developed a seven-item evaluation tool (ucanr.edu/u.cfm?id=138) to measure the frequency of planning meals, shopping with a list, comparing unit prices, reading food labels, thinking about healthy food choices, eating a variety of foods and, as a measure of food insecurity, running out of food before the end of the month. All items have a 5-option Likert-type response: 1 = never; 2 = seldom; 3 = sometimes; 4 = most of the time; and 5 = always. These items were chosen because previous research has reported significant associations between several of them and diet quality (Hersey et al. 2001). Moreover, they are used nationally to evaluate similar nutrition education classes offered through the Expanded Food and Nutrition Education Program, a program funded by the USDA to reach low-income families with children (EFNEP; Dollahite et al. 2014).

During fiscal year 2012–2013, 22 counties collected complete pre-post surveys from 2,371 participants in the PSSC series. Of these participants, 66% were Latino and 73% were female (table 1). More than half (54%) were currently enrolled in the SNAP program, and the rest were income-eligible but not enrolled. Statewide program evaluation data covering the period from 2011 to 2013 found significant pre-post changes in the frequency of food resource management behaviors (Kaiser et al. 2015). The percentage of PSSC participants who reported performing these behaviors more often after the PSSC series ranged from 38.8% in comparing prices to 54.0% in reading nutrition labels. The group who reported the greatest reduction in the frequency of running out of food before the end of the month were those PSSC participants who currently received SNAP benefits *and* who reported the greatest pre-post change in food management skills.

Need for a qualitative evaluation

Given the federal debate on reducing SNAP funding and increasing emphasis on evidence-based SNAP-Ed, UC CalFresh must demonstrate a positive impact on CalFresh recipients' food management behaviors. The existing seven-item PSSC evaluation tool only measures pre-post changes in seven behaviors over a one-month period. As a result, there may be additional outcomes that are not captured using this evaluation approach. The study's objective was to determine how PSSC evaluation methods might be improved to capture program outcomes more fully. This paper explores the following questions: (1) What behavioral changes do PSSC participants cite, in addition to those currently measured with the existing evaluation tool? and (2) What is the feasibility of tracking behavioral changes beyond a one-month follow-up period?

Focus group structure

To answer these questions, UC CalFresh conducted six focus groups among PSSC participants in the spring and fall of 2013 in San Joaquin, San Mateo and Santa Clara counties. Selection criteria for the counties were as follows: expressing interest in hosting PSSC focus

TABLE 1. Characteristics of the focus group sample and PSSC statewide population, fiscal year 2012–2013

Demographic characteristics		Study sample *n* = 54	Statewide population *n* = 2,371
		% (*n*)	
Age	18–59 years	100 (54)	89.0 (2,110)
Gender	Female	81.5 (44)	73.3 (1,739)
Ethnicity	Hispanic/Latino	79.6 (43)	66.5 (1,576)
Race	Non-Hispanic/Latino white	9.0 (5)	30.8 (551)
	Black	3.7 (2)	7.8 (185)
	Asian/Pacific Islander	5.6 (3)	3.2 (76)
	Am Indian/Alaskan	1.8 (1)	5.1 (121)
	Other	0	8.4 (201)
Food assistance	Enrolled in CalFresh	48.1 (26)	54.3 (1,288)

In *Plan, Shop, Save, Cook* nutrition education classes, participants learn how to compare unit prices and monitor spending while shopping.

UCCE Yolo County

groups, using the PSSC curriculum as designed, having rural and urban sites and being able to convene both English- and Spanish-speaking groups.

The UC CalFresh state office hosted a webinar for county staff with an overview of focus group methodology and specific expectations for a county's role in conducting the focus groups. The state office sent each county a packet with recruitment guidelines, a script and a demographic survey. The UC Davis Institutional Review Board determined the protocol to be exempt from full review.

A UCCE nutrition specialist (fluent in Spanish) and a UC CalFresh state office staff member moderated focus group discussions — one in Spanish and one in English — in each of the three counties. Each county provided a staff member to take notes. All discussions took place immediately after the fourth and last PSSC class. Participants completed a seven-item PSSC evaluation tool before lesson one (pre-test) and at the end of lesson four (post-test), just before starting the focus group discussion. The researchers informed participants that their decision to stay for the discussion was voluntary, and all agreed to participate.

During the focus groups, the moderators asked participants why they decided to attend PSSC classes, what they had learned, how they had applied the information and what areas can be added or improved for future classes. Each focus group lasted about one hour and was audiotaped. Participants received an incentive, typically a cookbook, for their time.

Student assistants transcribed and/or translated the audiotapes. The two moderators examined the final versions for main themes and conferred with co-authors for interpretation. One moderator used NVIVO 10 software (QSR International, Burlington, MA, 1999-2012) with the coding query function to establish thematic areas and cross-tabulate themes with PSSC terms.

Focus group participants

Fifty-four PSSC participants attended the focus groups in San Joaquin, San Mateo and Santa Clara counties. Table 1 compares the demographic data of the focus group sample ($n = 54$) to the statewide PSSC population served in 2012–2013. The study sample and statewide populations were predominantly female (81.5% study population versus 73.3% statewide population), of Hispanic ethnicity (79.6% versus 66.5%) and between 18 and 59 years old (100% versus 89.0%). Two participants from Spanish-speaking groups and two from English-speaking groups did not complete all of the PSSC lessons, each missing one to two lessons.

What participants learned

In explaining why they attended PSSC classes, participants commonly mentioned health-related reasons, although a few also cited a desire to be more organized and save money. Many wanted to learn how to prepare healthier meals to improve existing health conditions or prevent the onset of new problems, particularly diabetes. One Santa Clara County attendee stated that coming to class was important ". . . because in my family, we have diabetes and there are some that are overweight and this is what we want to improve, so we can be healthier." Participants repeatedly talked about wanting to learn healthy ways to lose weight and have a more balanced diet for their families. They also wanted to learn how to shop for healthy foods on a limited budget.

Many mentioned that the classes helped them refine their nutrition knowledge and decision-making skills. Participants most commonly mentioned having a greater awareness of healthy food choices and tools to choose nutritious foods, plan meals and save money. They felt that the ability to read Nutrition Facts labels would help them select healthy foods. They also gained useful information on writing and "sticking to" a

***Plan, Shop, Save, Cook* lessons include a cooking demonstration and feature healthy, low-cost recipes that are easy to prepare.**

grocery list, using coupons and watching portion sizes.

Participants reported that they learned how to compare unit prices and recognize the influence of branding on food prices. One San Mateo County attendee told facilitators that "after taking this nutrition class, I would first look at planning cooking, plan out what I would buy, and see if I could get the best economic buy". When asked what she had learned about shopping, a Spanish-speaking woman stated, "that the (name) brand costs more . . . but it's the same thing [as the generic product]".

Focus group participants also mentioned that they learned about using healthier oils in food preparation, steaming and baking rather than frying, incorporating vegetables and fruit into the daily diet, measuring ingredients and using seasoning to improve food taste without adding salt. Comments on cooking included "I have learned that we shouldn't cook with so much oil . . . what the right portion of oil one should use is . . .", "at the house lettuce and broccoli was almost never eaten . . . and I am adding lettuce and broccoli, celery, cauliflower . . . and (using) other recipes" and "My cooking skill level was the microwave . . . and now I'm gonna probably steam a fish or something . . . ."

The moderators asked participants to think about "what they had in their kitchen today" and whether they had changed the foods they buy after attending the classes. Participants mentioned changes in eating habits, purchasing a greater variety of fruits and vegetables, including more legumes (peas, beans, lentils), buying less soda, consuming more water and switching to healthier types of oils (canola or olive). A few reported purchasing more fish and chicken and less red meat or pork.

Attendees stressed that by learning food resource management skills rather than just buying what looked good, they assessed food choices and "looked at foods differently now". One San Joaquin County participant stated, "I never did plan ahead of time. I always came home and was just asking, 'what am I going to make?' Incorporating all the food groups, whether it is on one plate or throughout the day and then portion control . . . having the plate [MyPlate, a USDA infographic depicting the five food groups] on your fridge really helps."

The focus groups also discussed topics to include in future classes. Attendees suggested including more recipes and food preparation tips, recipes for children, and materials on food safety and vitamin content in foods. Participants also wanted more information on how food affects the body and how to incorporate more exercise into their daily schedule.

At the end of the focus group sessions, attendees were asked to name the most important tip from the PSSC lessons that they would use regularly. Overall, they recalled several tips, including reading nutrition labels, choosing smaller portions, using a calculator while shopping to monitor spending, looking at expiration dates, planning meals and using a grocery list. Some emphasized the importance of eating healthier through changing food selection, purchasing and eating habits. Participants also mentioned incorporating a variety of food groups for "balanced" meals and "watching" sugar, sodium and fat content.

Long-term follow-up

To explore the feasibility of administering a longer-term follow-up to evaluate behavior change, UC CalFresh county staff interviewed participants by phone from one to six months after the focus groups using the same seven-item tool. Complete follow-up data was available for 22 of the 54 focus group participants. Beyond one month after the last classes, 32 participants were no longer at their phone numbers and/or could not be reached by email addresses. Those who were interviewed said they made changes in food consumption and preparation techniques, in addition to improving their food resource management skills. For example, four months after the last PSSC class, a San Mateo County man stated, "I never did any of the above before the workshops. I would just buy food but did not look at labels …. I'm taking it seriously now. I don't feel sluggish anymore — now I have a lot more energy." Preliminary results suggest that further study is warranted to see if participant behavior changes are sustained or improved over time. Ideally, this would be a study with a large sample size and a comparison, or control, group.

Discussion and implications

Results indicate that PSSC participants cite many attitudinal and behavior changes that are consistent with those measured using the existing evaluation tool, such as greater awareness of healthy food choices and reading the Nutrition Facts label (table 2). The statewide evaluation identified reading Nutrition Facts labels as the behavior showing the most improvement (Kaiser et al. 2015).

Two areas were identified that are not captured by the current tool: changes in cooking practices and the types of food purchased. Both of these areas may influence diet quality. To capture these changes, additional questions could be added to the PSSC evaluation tool to ask about use of healthier cooking methods (such as steaming or baking rather than frying) and purchase of healthier options (such as fish, poultry or beans rather than red meat).

The longer-term benefits of food resource management education have been documented in a recent randomized, delayed controlled study conducted in an EFNEP population in New York where the *Eating Smart Being Active* curriculum was delivered (Dollahite et al. 2014). Designing a SNAP-Ed program evaluation that captures additional dietary behaviors with a longer follow-up time can help inform the development of policies aimed at improving diet quality and food security. While research documents the beneficial effect of SNAP on food security (Nord 2012), the program's impact on diet quality is modest at best (Gregory et al. 2013). To address

TABLE 2. Participant quotes related to PSSC Food Behavior Checklist evaluation questions (n = 54)

PSSC items	Participant quotes
Think about healthy choices: When deciding what to feed your family, how often do you think about healthy food choices?	"[I look for] how many calories does it have, how many you know . . . sugar, how much nutrition." Male, English language focus group "I wasn't really looking at the calories of fat my body was taking in, now I am looking at that . . . ." Female, English language focus group
Use Nutrition Facts label: How often do you use the "Nutrition Facts" on the food label to make food choices?	"The labels . . . show you how much sodium it contains, how much sugar, how much fat . . . that for me was the most important thing." Female, Spanish language focus group "Learning how to read the food labels was new for me." Female, Spanish language focus group "Now, ever since I took the nutrition class . . . I actually take time to read what I'm eating." Male, English language focus group
Use a shopping list: How often do you shop with a grocery list?	"Make a list of what you're missing because sometimes one leaves without a list and you end up buying things you already have at home." Female, Spanish language focus group "My daughter picked up on the list right away. She wants to write the list." Female, English language focus group
Eat a variety of foods: Do your meals consist of a variety of foods?	"We should consume from a variety of foods . . . fruits and vegetables should not be missing from our diet." Female, Spanish language focus group "Incorporating all the food groups, whether it be on one plate or throughout the day . . . ." Female, English language focus group
Compare prices: How often do you compare prices?	" . . . check the size of it and see if the price is better than others." Male, English language focus group "To go to a number of stores and save instead of buying at one store and spend a lot." Female, Spanish language focus group "I learned how to go shopping . . . how to compare prices . . . and how to buy canned foods and how to buy like to make . . . to cook it myself." Female, Spanish language focus group
Plan meals: How often do you plan ahead of time?	"[the lessons] . . . changed how I planned everything. Gave me a lot of good information." Female, English language focus group "Well, I learned that . . . think about what you are going to cook that day . . . think about what you are going to need to make your meals." Female, Spanish language focus group "I never did plan ahead of time. I always came home and was just asking, 'what am I going to make?'" Female, English language focus group

the dual SNAP mandate of promoting food security and diet quality, several policy options can be assessed, including incentives such as farmers' market vouchers to purchase more fruits and vegetables, restrictions on foods and beverages allowable for purchase, increased frequency of issuing SNAP benefits and improvement in the retail environment (Leung et al. 2013). Experts also agree that more effective nutrition education might be another strategy, but call for more research on the effect of SNAP-Ed on participants' diet quality.

Designing a SNAP-Ed program evaluation that captures additional dietary behaviors with a longer follow-up time can help inform the development of policies aimed at improving diet quality and food security.

Several challenges and limitations to this study should be mentioned. First, members of our target audience tend to have more transient housing situations than the general population, which poses problems in conducting follow-up interviews. In this instance, the follow-up phone calls, taking place one to six months later, could not locate many participants who were no longer at the phone number and/or email addresses they provided when the focus groups were conducted. Second, the sites where the focus group meetings occurred (the same location as the classes) often introduced noise and interruptions, which disrupted the meetings, hampered a thorough probing of the questions and hindered a clear audiotape. Finally, some focus group participants were enrolled in job training or health-related programs or did not complete all lessons, both of which may have influenced their responses.

Nonetheless, the study's qualitative findings suggest that PSSC participants learned to make healthier food choices at the store and change some cooking practices at home. While adding one or two more questions about these skills to the current evaluation tool is an option, ultimately a randomized study, possibly with a delayed control design, needs to examine the effect of building food resource management skills on food security and diet quality in SNAP audiences. Loyalty cards or other methods can be used to determine the effects of PSSC and similar curricula on food purchases of SNAP participants targeted in healthy retail environment interventions (e.g., in-store marketing such as expanded shelf space and/or signage to promote healthy foods). CA

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Low-input, low-cost IPM program helps manage potato psyllid

by Sean M. Prager, Gregory Kund *and* John Trumble

Potato psyllid is a pest of solanaceous plants throughout much of the western United States, including California, where it has increased and is now overwintering. The psyllid affects its plant hosts from direct feeding and by transmitting a plant pathogenic bacterium, Lso. Millions of dollars of damages have occurred in the U.S. potato industry, and a large acreage of crops is susceptible in California. Control is complicated because different crops have different pest complexes and susceptibilities to Lso; currently most growers use multiple pesticide applications, including broad-spectrum insecticides. Results of our field trials at South Coast Research and Extension Center indicate that the use of broad-spectrum insecticides actually increases psyllid numbers in both peppers and potatoes. We have developed a low-input IPM program, which in field trials produced encouraging results in peppers, potatoes and tomatoes compared to broad-spectrum insecticides. Economic analysis showed the low-input IPM approach was more cost effective than a standard insecticide program in tomatoes.

The potato psyllid, *Bactericera cockerelli* Sulk (Hemiptera: Triozidae), also known as the tomato psyllid, is an insect pest on many important solanaceous vegetable crops grown in California. These include tomato (*Solanum lycopersicum*), bell pepper (*Capsicum annum*) and potato (*Solanum tuberosum*) (Butler and Trumble 2012a). Potato psyllid and its associated bacterial pathogen Lso have caused considerable damage to potatoes in other states, New Zealand, and Mexico. Now the psyllid is more than an occasional pest in California and is overwintering here. Susceptible crops in California are estimated in excess of 600,000 acres (250,000 hectares), including approximately 25,000 acres (10,000 hectares) of potatoes (USDA-NASS 2015).

Control is complicated because different crops have different pest complexes and susceptibilities to potato psyllid and Lso. Solanaceous weeds are alternate hosts. Sequential sampling plans are available for each of the main host crops, but are not widely used. Resistance to effective insecticides has been documented in Texas. Growers continue to use broad-spectrum insecticides. Our goal was to develop an IPM approach that would help growers avoid unnecessary insecticide applications, particularly of broad-spectrum insecticides, which our field studies show increase the incidence of the pest.

Potato psyllid damage

Potato psyllid has multiple mechanisms of causing damage. First, feeding by potato psyllid nymphs, and sometimes adults, can result in psyllid yellows, the symptoms of which include stunting and chlorosis of leaves, and in extreme cases plant death; psyllid yellows is believed to be the result of a currently unidentified toxin (Butler and Trumble 2012a). There are reports of psyllid yellows in potatoes and tomatoes but not in peppers.

Second, potato psyllids are the only known North American vector of a phloem-limited bacterial pathogen tentatively known as *Candidatus* Liberibacter

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California has over 600,000 acres of crops that are susceptible to potato psyllid, including potato (shown here), tomato and bell pepper. The pest can be found throughout the year from San Diego to the Sacramento Valley.

Jack Kelly Clark

solanacearum (Lso) or, synonymously, *Candidatus* Liberibacter psyllaurous (Hansen et al. 2008; Munyaneza et al. 2007). In potatoes, infection with Lso leads to zebra chip disease, which results in foliar symptoms, plant death and also a characteristic striped pattern in tubers when they are fried (Butler and Trumble 2012a). These symptoms make potato chips and French fries unmarketable and have cost the U.S. potato industry millions of dollars (Greenway 2014).

In tomatoes, eggplants and peppers, Lso infection results in vein greening disease (Hansen et al. 2008). Symptoms of vein greening disease include chlorosis, shortening of internodes, stunting, curling of leaves and discoloration of veins. In older plants, symptoms can also include bleached leaves, foliar purpling, necrosis, wilting and eventually death. Importantly, infection can result in poor fruit quality, fruit with low sugar content and failure of fruit to set.

Third, feeding by potato psyllids leads to substantial honeydew (insect feces) accumulation. In bell peppers, this can result in the accumulation of sooty mold, the additional weight of which can compromise stems, and it has an economic cost because fruit requires cleaning or downgrading (Rojas et al. 2014). In California, it is typically these secondary issues, rather than Lso infection, that are problematic in bell peppers. Lso infection in California bell pepper fields is limited. In 2014, the authors collected adult potato psyllids on bell peppers ('Cal Wonder') at the South Coast Research and Extension Center (REC) in Irvine, California, that tested positive for Lso. However, when whole plants were collected from the same fields, divided into root, stems and leaves, and then tested for the presence of Lso using quantitative real-time PCR, not a single plant sample was positive. Importantly, potatoes in adjacent fields tested positive for the Lso bacteria, zebra chip symptoms or both.

Potato psyllid reports, range

As reviewed by Butler and Trumble (2012a), potato psyllid has been known as a pest in California for nearly 100 years. Reports of the psyllid date back at least to the California State Horticulture Bulletin in 1915 (Compere 1915). There it was reported on false Jerusalem cherry (*Solanum capsicastrum*), but it has since been identified on numerous other plant species (Butler and Trumble 2012a).

Since its initial detection, potato psyllid has been reported in multiple Western states, but typically as an occasional pest. This changed in 1999-2000, when it became increasingly common on fresh market tomatoes in both California and Baja, Mexico (Liu and Trumble 2004). The pest now can be found throughout the year from San Diego to the Sacramento Valley.

The potato psyllid has been especially problematic for the Texas potato industry, which has lost millions of dollars as a result of the pest (Guenthner et al. 2012). As a consequence, much of the research on management of potato psyllids has focused on potatoes and has been conducted in Texas. This is despite the considerable amount of susceptible crops grown in California, the documented occurrences of Lso in California (Crosslin et al. 2010) and the dominance of the Pacific Northwest as a potato-growing region.

California is the largest U.S. producer of both tomatoes and bell peppers, which are preferred host plants for the Western haplotype of the psyllid (Prager, Esquivel et al. 2014). Much of the research on potato psyllids on nonpotato crops has been conducted in California.

Potato psyllid has an extremely large host range, including many solanaceous weeds such as black nightshade that occur near crop fields in California (Butler and Trumble 2012a). A few studies have investigated the psyllid's ability to use alternate (noncrop) host plants in Texas and the Pacific Northwest, but information is limited on the role these plants play in disease and pest dynamics, especially in California, where no field studies of alternate hosts have been conducted. Thus, the extent to which these weeds require management is unknown.

Presently, there are sequential sampling plans for potato psyllid designed for bell pepper, potato and tomato (Butler and Trumble 2012b; Prager, Butler et al. 2013, 2014). A sequential sampling plan helps growers to determine pest infestation numbers and make treatment decisions accordingly. However, it is unclear to what extent sequential sampling plans are being used by growers.

Insecticide treatments

Management of potato psyllid and zebra chip disease is an active research topic. Researchers are looking into putatively resistant and tolerant varieties of potato (Diaz-Montano et al. 2013) and RNAi-based mechanisms of psyllid control (Wuriyanghan et al. 2011). However,

Feeding by potato psyllid can stunt the growth of potato leaves and cause leaflets to roll upward and turn yellow.

Psyllid adult, *left*, and psyllid nymphs, *right*. Adult potato psyllids are cicadalike in appearance. Although feeding by adults usually does not damage potato plants, their presence indicates a need to check for nymphs. Potato psyllid nymphs have a flattened, scalelike appearance.

currently there are no commercially available cultivars that exhibit resistance or tolerance to either the psyllid or Lso. Thus, control of potato psyllids is based on the application of insecticides (Guenthner et al. 2012).

In potatoes, where zebra chip disease is a particular threat, the set of insecticidal materials commonly used has been extensively tested and a list of recommended materials has been generated that includes systemic materials and those specific to sucking insects (Gharalari et al. 2009; Goolsby et al. 2007). In potatoes, the use of selective materials is practical, as the materials are effective against many of the common pest insects that threaten potatoes. Unfortunately, in bell pepper and tomatoes, these materials are not effective against many of the other insect pests that must be managed.

Grower resources such as the California UC IPM *Pest Management Guidelines* (ipm.ucanr.edu/PMG/crops-agriculture.html) incorporate best practices into their recommendations for pesticide use, but little information is available to growers that focuses on psyllid suppression while managing multiple other pests. Consequently, most of the current control strategies used by growers of bell peppers and tomatoes rely on broad-spectrum materials.

For example, in 2012 in bell peppers in California, the top insecticides applied (by weight) included the broad-spectrum materials permethrin (fifth most applied) and carbaryl (sixth most applied) (DPR 2013). Additionally, methomyl, a restricted use, highly toxic broad-spectrum material, was the 18th most applied pesticide when considered by area treated. Similarly, in 2012 in potatoes, the top 10 insecticides applied by weight included the broad-spectrum materials phorate, carbaryl, esfenvalerate and methomyl.

In potatoes, as mentioned above, new materials that are target-specific or systemic (and thus less harmful to beneficial insects) have been evaluated for control of potato psyllids. Among the small list of materials recommended or commonly used are two neonicotinoid materials (imidacloprid and thiamethoxam), two materials targeted at sucking insects (pymetrozine and spirotetramat) and the bacterial-derived abamectin (Guenthner et al. 2012). Some of these materials have been examined in greater detail than others. Imidacloprid and thiamethoxam have been tested for potential resistance development by the psyllid (Prager, Vindiola et al. 2013). These studies indicate that substantial resistance has developed to imidacloprid in southern Texas, and that the same population may also be developing resistance to thiamethoxam. Currently, there is no evidence of resistance in California.

Studies of the materials have led to more refined management recommendations. It has been determined that the method of application (drip versus soil drench) substantially affects the levels of active ingredient realized in the plant, with application through drip irrigation resulting in better control in potatoes and higher concentrations of the materials in plants (Prager, Vindiola et al. 2013). Foliar applications should be minimized or avoided as these are expensive and repeated use is believed to be one cause of the pesticide resistance development in Texas.

Biological control

There are no commercially available biological control agents available for potato psyllid. Biocontrol agents are available for purchase for some other pests, such as whiteflies and leafminers, that cause problems in potatoes, tomatoes and bell peppers, but in many cases these are not necessary if the native biological controls are not killed by pesticides (Trumble 1990).

For some insects like the beet armyworm, entire IPM programs have been developed based on the use of organically-approved microbial controls such as *Bacillus thuriengiensis* (Trumble et al. 1994), but pesticides still may be needed if other pests are present. When psyllids are present, conservation of existing natural enemies, such as spiders, lacewings and the parasitoid *Tamarixia triozae*, can provide additional control, though pesticides are the only currently available strategy to adequately reduce psyllids and suppress Lso. Therefore, it is critical to select pesticides that maximize the effects on the psyllids while minimizing the effects on beneficial arthropods.

Low-input IPM program

We have had success using a low-input IPM program based on pest monitoring and, as necessary, using pesticides (no organophosphates, carbamates or pyrethroids) that have few detrimental effects on beneficial insects, since beneficials have been shown to help reduce psyllid populations (Butler and Trumble 2012c). The low-input program uses an Insecticide Resistance Action Committee (IRAC) strategy for alternating the mode of action of pesticides to slow development of pesticide resistance. These concepts of resistance management and maximizing the effects of existing beneficial arthropods are incorporated in the program and do not require any specialized knowledge or action on the part of the grower adopting the program.

To use this program, pest control advisers (PCAs) first scout the fields, using a sequential sampling plan or similar approach, determine which pests are present, and then use a schematic (fig. 1) to choose the appropriate rotational strategy for the pest(s) present. When circles overlap, the rotation is expected to be effective against both pests. When a material appears in multiple circles, it can be expected to function for control against both (all) pests. When there is no overlap, pest-specific materials can be chosen for a single pest. This approach simplifies the selection of pesticides and minimizes the potential for unnecessary applications. Our research group has used the program successfully in field trials of several vegetable crops, including peppers, celery and tomato.

Tomato field trial. In multiple tomato field trials at the UC South Coast REC, we compared the low-input program with the standard chemical treatment of methomyl plus permethrin. There were four replicates per treatment, plots were four rows wide on 5-foot (1.58-meter) centers and 65 feet (20 meters) long and all applications were made with a commercial tractor-mounted boom sprayer. Yield measurements were taken at harvest from the two center rows of each plot. An economic analysis was made, including calculation of production costs and the dollar value of yields; see figure 2.

The results were encouraging. Across the range of carton values, the net profit was greater for the low-input IPM program than for the standard chemical treatment. In our experience, growers readily adopt such programs when provided evidence of an economic benefit (Trumble 1998).

Potato and bell pepper field trials. In 2011 and 2014, we conducted trials on potatoes and bell peppers at South Coast REC, comparing plots treated with the broad-spectrum insecticides methomyl (Lannate, Dupont Crop Protection, Wilmington, Delaware) and permethrin (Pounce, FMC Corp.,

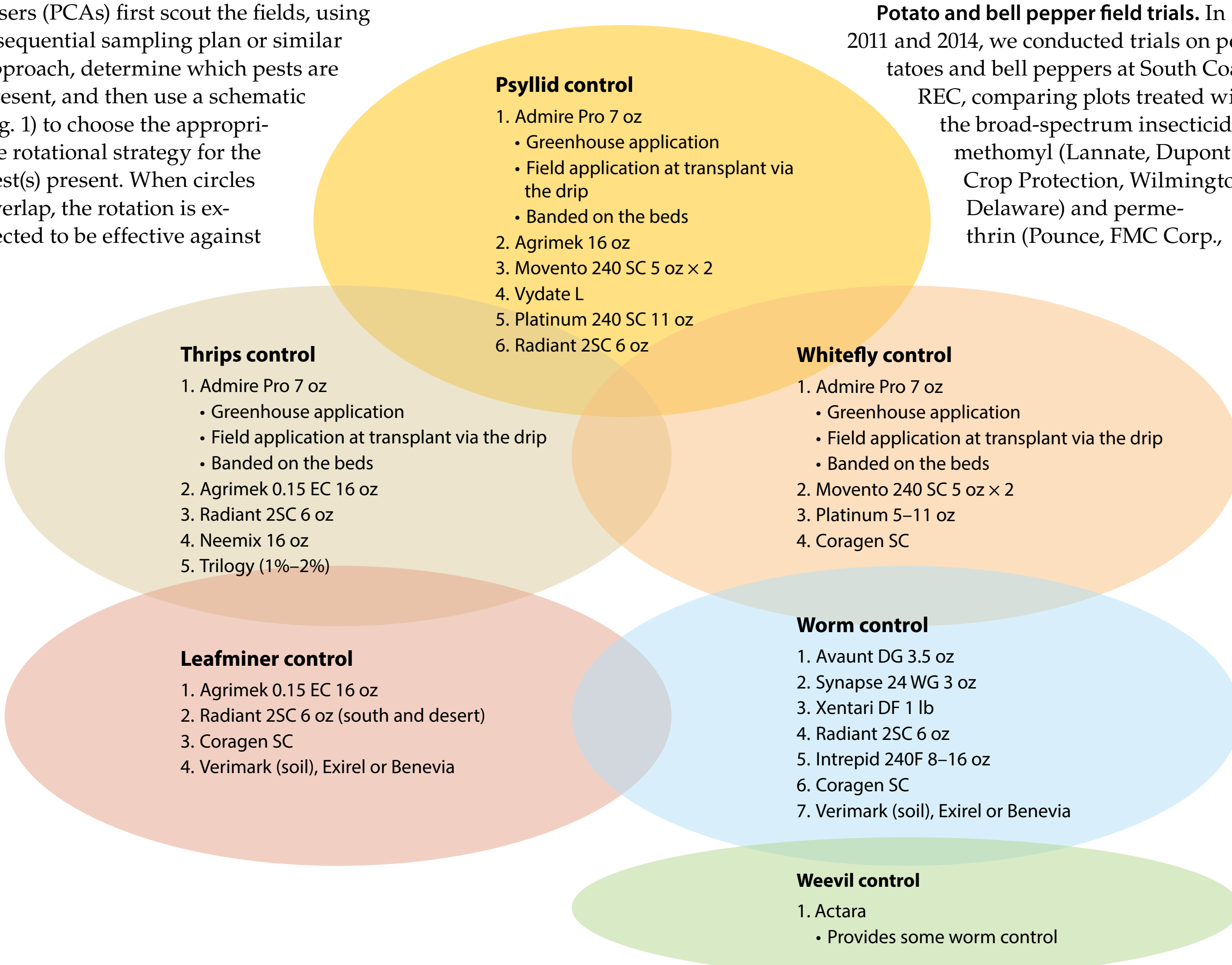

Fig. 1. A low-input IPM program for controlling potato psyllid in California bell peppers, tomatoes and potatoes includes selecting pesticides to match the pest population present and using materials with the least detrimental effects on beneficial insects. Each circle indicates an optimized IPM rotation for that particular pest. Numbers indicate order of application within the rotational strategy and do not imply efficacy (higher number ≠ greater efficacy). When circles overlap, the rotation is expected to be effective against both pests. When a material appears in multiple circles, it can be expected to function for control against both (all) pests. When there is no material in common between two circles, it may be necessary to make an additional application using a material from each of the pests' circles (rotation). Always check the insecticide label for specific crop use and rates.

Philadelphia, Pennsylvania) to untreated control plots and to plots managed with the low-input IPM treatment described above as well as several chemicals commonly used in the control of psyllids in potatoes.

Potatoes ('Atlantic') and bell peppers ('Cal Wonder' in 2011, 'Baron' in 2014) were planted in identical-sized plots (4 rows wide, 5-foot centers, 65 feet long), four replicates per treatment, using methods that approximate a commercial operation. Both bell peppers and potatoes were drip irrigated, and in 2014 potatoes were also sprinkler irrigated until approximately 1 week after emergence.

Insecticides were applied at labeled rates, using commercial application equipment, via a tractor-mounted boom, drip irrigation, or a soil drench as appropriate. Materials applied as either a drench or through chemigation were applied once at planting. All other sprays were made weekly, weather permitting. The combination methomyl and permethrin treatment was applied a minimum of six times.

Bell pepper and potato fields were sampled each year for the presence of potato psyllid. During sampling, five randomly selected whole plants per replicate (20 plants per treatment on every sample date) were inspected for the presence of eggs, nymphs and adults. In 2011 and 2014, mature-green to ripe bell pepper fruit were harvested from the center row of each replicate and examined for the presence of potato psyllid; in 2011, 200 fruit were examined from each replicate plot (800 per treatment); in 2014, 100 fruit were examined from each treatment plot (400 per treatment). Additional pests identified in the fields included Lepidoptera, aphids and lygus bugs.

These trials indicated that the use of broad-spectrum insecticides were associated with increased psyllid populations. Increased potato psyllid egg and nymph densities were documented midway (approximately 60 days) into the growing season in 2011 and 2014 bell pepper plots where methomyl and permethrin applications were made (fig. 3). In addition, increased nymph densities were associated

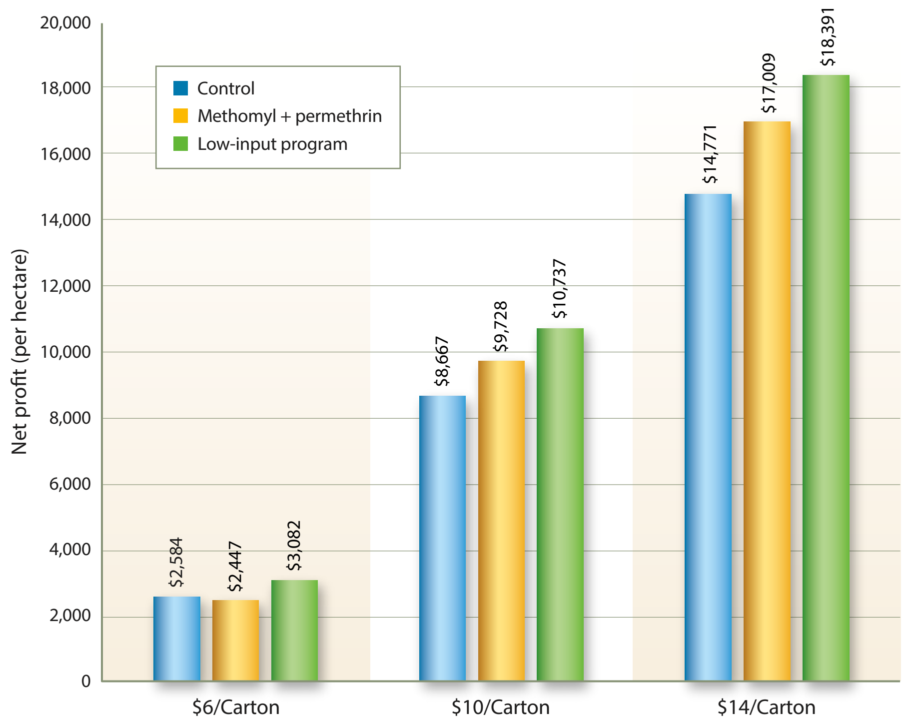

Fig. 2. Net profit per hectare in a tomato trial comparing a low-input IPM program and a standard chemical program (methomyl plus permethrin) for managing potato psyllid. Control plots (with no pesticide applications) were included to show whether the costs of pest management were warranted. The net profit was determined as the value of the marketable portion of the crop minus the horticultural costs (including the costs of pesticides and their application) needed to produce and harvest the crop. The dollar value of a 25-pound (11.3-kilogram) carton varies during the season and between years, but it generally ranges between $6.00 and $14.00.

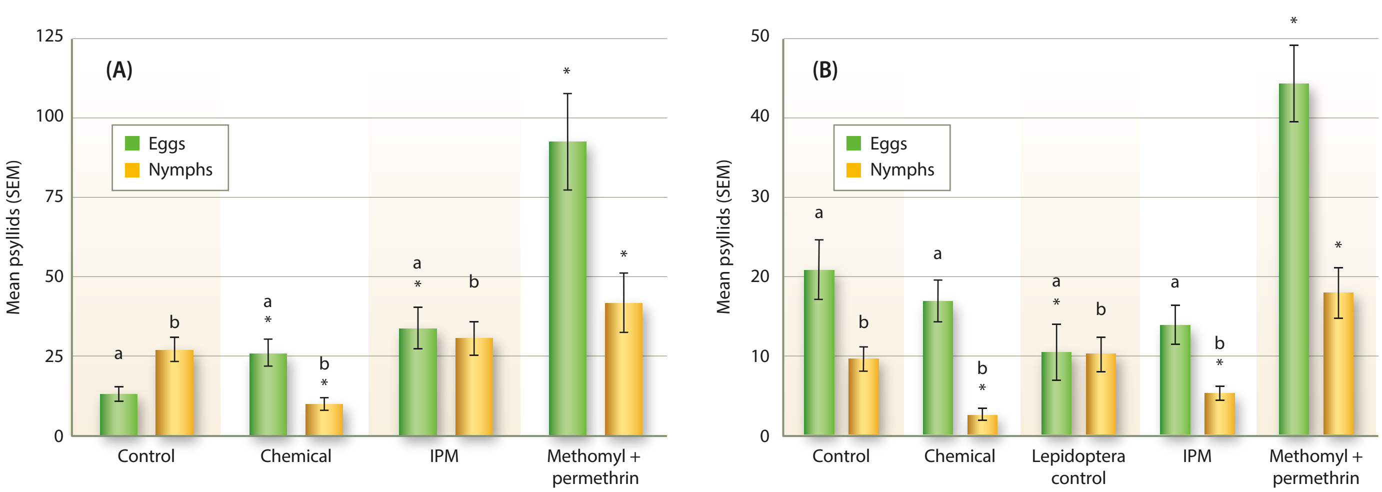

Fig. 3. The number of potato psyllid eggs and nymphs in field counts of bell peppers in (A) 2011 (GLM: $X^2 = 22.8$, $d.f. = 3, 74$, $p < 0.001$) and (B) 2014 (GLM: $X^2 = 33.0$, $d.f. = 4, 93$, $p < 0.001$). Control = untreated with any insecticide; chemical = insecticidal materials used but without applying the IPM strategy; and Lepidoptera control = the application of materials selected with a focus on controlling Lepidopteran pests. Letters indicate significant differences with the methomyl and permethrin treatment at $p < 0.05$. Asterisks indicate significant difference with the control at $p < 0.05$.

with the methomyl and permethrin treatment in bell pepper fruit at harvest in 2014 (fig. 4).

In 2014 and 2015, bell pepper growers in the Central Valley reported outbreaks of potato psyllids with large numbers of nymphs, adults and honeydew on plants and especially fruit. The growers were targeting numerous pests, including pepper weevil and potato psyllid, and applying many materials, including some broad-spectrum insecticides. It had been previously suggested, before our trials, that some broad-spectrum insecticidal materials may lead to increased potato psyllid populations; the study was done in greenhouses in Colorado (Al-Jabr and Cranshaw 2007), but the effect was not tested in the field.

In our potato plots . . . treatments of methomyl and permethrin resulted in a statistically significant increase in the number of psyllid nymphs compared to the other treatments.

In our potato plots at South Coast REC in 2014, as in peppers, treatments of methomyl and permethrin resulted in a statistically significant increase in the number of psyllid nymphs compared to the other treatments (GLM: $X^2 = 64.8$, *d.f.* = 11, 226, $p < 0.001$; fig. 5). This pattern was also observed with respect to the number of eggs (GLM: $X^2 = 49.8$, *d.f.* = 11, 226, $p < 0.001$; fig. 5), with significantly more eggs counted in the methomyl and permethrin treatment than in the other treatments. Greater numbers of nymphs and eggs are likely to have been associated with greater numbers of adults as well, although this was not examined because adults are quite difficult to count in the field.

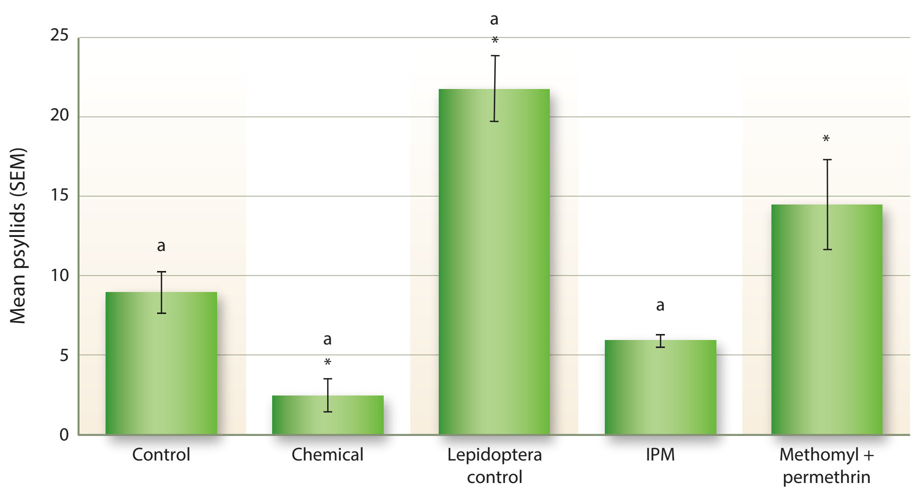

Fig. 4. The number of potato psyllid nymphs in bell pepper fruit at harvest in 2014. There is an overall significant trend (GLM: $X^2 = 87.4$, *d.f.* = 5, 29, $p < 0.001$). The insects rarely, if ever, oviposit on the fruit, so there are no data on egg numbers. Control = untreated with any insecticide; chemical = insecticidal materials used but without applying the IPM strategy; Lepidoptera control = the application of materials selected with a focus on controlling Lepidopteran pests. Letters indicate significant differences with the methomyl and permethrin treatment at $p < 0.05$. Asterisks indicate significant difference with the control at $p < 0.05$.

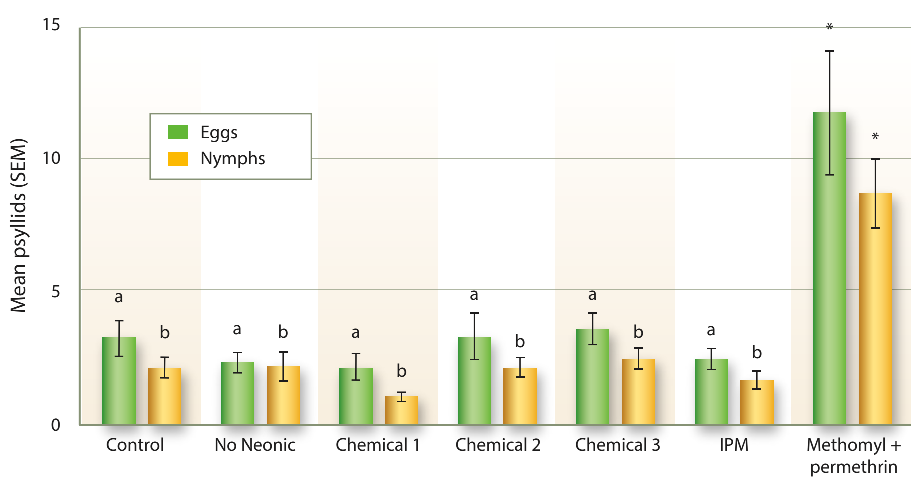

Fig. 5. The number of potato psyllid eggs and nymphs in field counts of potatoes in 2014. Chemicals 1, 2 and 3 are commonly used in the control of psyllids in potatoes, including some neonicotinoid materials, while "No neonic" includes similar common materials but no neonicotinoid insecticides. Letters indicate significant differences with the methomyl and permethrin treatment at $p < 0.05$. Asterisks indicate significant difference with the control at $p < 0.05$.

Management challenges

Management of potato psyllid in California is likely to become increasingly difficult due to a combination of factors: limits and regulations on pesticide applications, the apparently increasing range of the pest (in 2011 it was found overwintering in Washington state and Idaho), its recently acquired habit of overwintering in California rather than migrating, and the relative abundance of host crops. Additionally, since the psyllid is not the sole pest on many of its host crops, it must be managed in conjunction with other pests.

Feeding damage, and the "mechanical damage" of sooty molds, can be managed with limited insecticide applications and moderate economic thresholds. This is because the damage is associated with relatively high densities of psyllids; this is the case in both tomatoes and bell peppers. In potatoes, since zebra chip is a concern, a more conservative approach may be necessary. Our studies indicate that in peppers and tomatoes, a low-input IPM strategy can be adopted that is economically viable and effective against the complex of potential pests. The approach may also be suitable to potatoes when Lso is not a consideration, but is unlikely to be effective or adopted in areas (or cultivars) in which Lso is a particular risk.

Lso-susceptible crops present a different challenge. Lso can be rapidly transmitted by even a single psyllid given an exposure of just a few hours (Butler et al. 2012). The resulting infected plants currently cannot be cured of the infection. These severe consequences dictate a near zero-tolerance approach in crops such as potatoes grown for chipping or French fries — meaning that the low-input IPM approach we present here may not be practical. Further, the nature of Lso influences the insecticidal materials that a grower can use. For example, some systemic insecticides have proven effective against potato psyllid, yet they must be ingested by the insect — but feeding increases the risk of pathogen transmission. Some insecticidal compounds, such as imidacloprid, have been shown to have anti-feedant properties in addition to toxicity (Butler et al. 2012). Other anti-feedant materials, such as pymetrozine (Fulfill, Syngenta AG, Basel, Switzerland), may result in low insect mortality: We examined pymetrozine on tomato and potato plants in controlled greenhouse experiments, with the maximum allowable label rates, and found that following both 24-hour and 48-hour exposures, adult psyllids survived as well as those exposed to untreated control plants sprayed with water. However, it has yet to be determined if psyllids can transmit Lso following exposure to pymetrozine; it is possible that exposure to pymetrozine results in increased psyllid populations but not in the spread of Lso. In such a scenario, the efficacy would differ among crops based on the perceived threat from Lso.

Finally, it is increasingly important that management of the potato psyllid take an area-wide approach that considers all potential host crops. Psyllid movement between crops, timing of crop planting, and which crops are adjacent to others all need to be considered. There is much research that still needs to be done to address potato psyllid control. CA

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