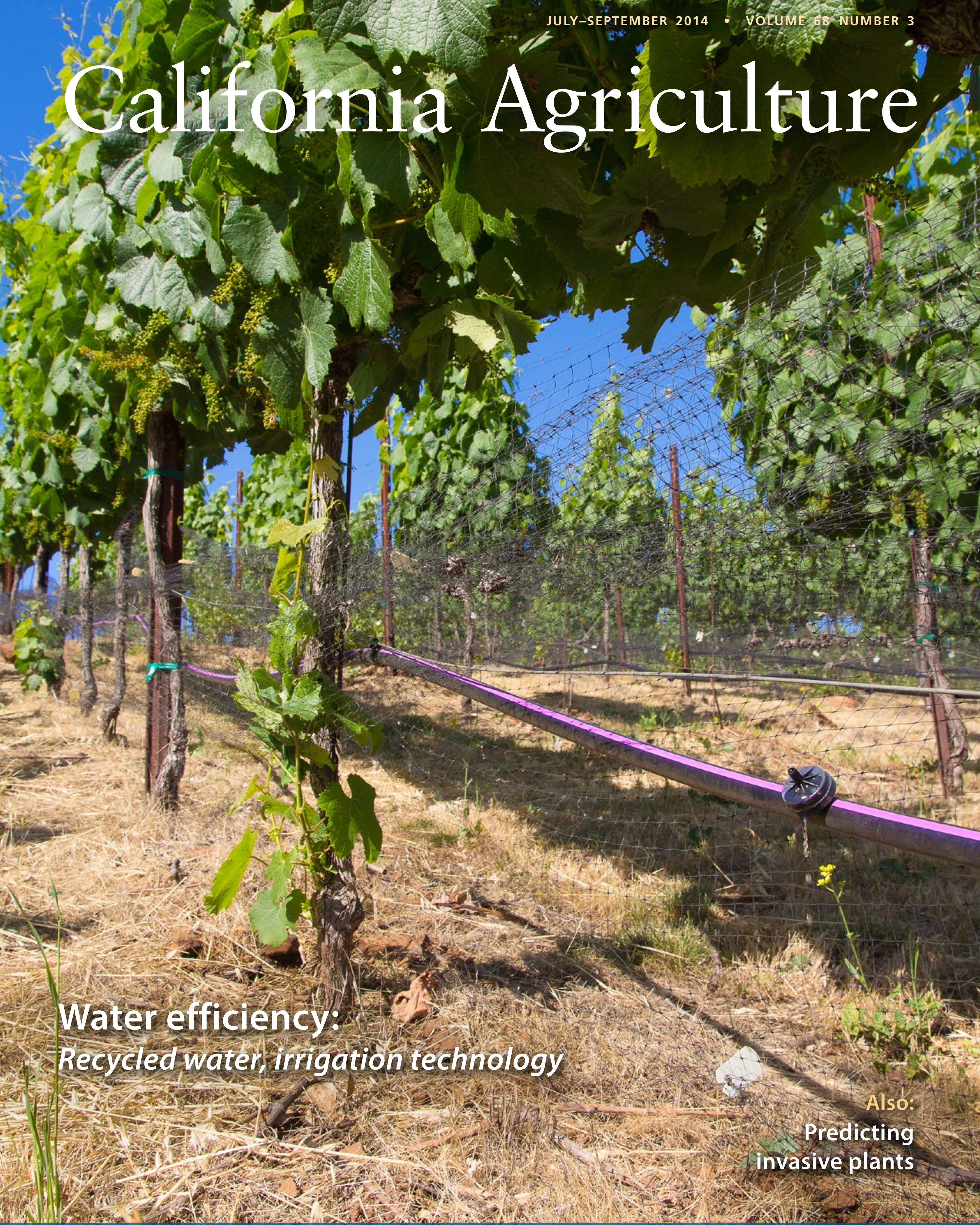
JULY–SEPTEMBER 2014 • VOLUME 68 NUMBER 3

California Agriculture



Water efficiency:
Recycled water, irrigation technology

Also:
Predicting invasive plants

About *California Agriculture*

University *of* California
Division of Agriculture and Natural Resources

California Agriculture is a quarterly, peer-reviewed journal reporting research and reviews, published by the University of California Division of Agriculture and Natural Resources (ANR). The first issue appeared in 1946, making *California Agriculture* one of the oldest, continuously published, land-grant university research journals in the country. There are about 15,000 print subscribers, and the electronic journal logs about 5 million page views annually.

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

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Photo by Will Suckow

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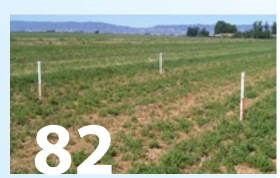

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New license plate supports youth agricultural programs

Agricultural education in California recently got a much needed boost. Last year, the state began issuing new "California Agriculture" license plates that will help fund youth development programs such as 4-H and Future Farmers of America (FFA). The timing could hardly be better. Dedicated funding for the FFA — and California's entire secondary agriculture education curriculum — is far from the sure thing that it has been for close to a century.

Funds raised by the California Agriculture license plate will go towards CDFA's educational and grant programs.

"Funding for career technical student organizations was eliminated in the state budget three years ago — the FFA lost around $230,000 annually," says FFA state advisor Bob Heuvel. This year, Gov. Jerry Brown's proposed 2014–2015 state budget cut $4 million of funding for agriculture education in public schools, but the Legislature added those funds back to the budget late in the process.

The new license plate could help avoid such funding ups and downs. "It's a way to create some sustainability for agricultural education," Heuvel says. Revenue from these special interest plates can be substantial — altogether, the state's special interest license plate program has raised more than $630 million since 1970 for causes such as the arts and the environment. The Lake Tahoe plates alone bring in more than $1.2 million per year.

But getting a new license plate approved can be a challenge. The first step was finding a state agency to sponsor the plate. Beginning in April 2010, the California FFA Foundation took the lead on shepherding the license plate through the approval process.

"One of our board members, George Gomes, was the Under Secretary of the California Department of Food and Agriculture (CDFA) at the time," says Jim Aschwanden, executive director of the California Agriculture Teachers' Association and California FFA Foundation board member. "George broached the idea of the CDFA sponsoring the plate, and the response was enthusiastic."

Next, the California Highway Patrol had to sign off on the design of the plate, as logos on special interest plates are now restricted to a 2-by-3 inch section on the far left. This too went smoothly for the FFA, thanks to a pre-existing logo that had been commissioned several years earlier by San Joaquin Farm Bureau Federation director Bruce Blodgett and others. The logo shows a yellow sun rising over a fertile green crop field and bears the slogan "Food, Fiber, Fuel, Flora."

Before manufacturing a new special interest license plate, the state Department of Motor Vehicles (DMV) requires 7,500 paid pledges within a year. "This was a hard sell because people had to pay up front with no guarantee that the plates would be made," Aschwanden says. "But we have lots of kids who were very enthusiastic about selling them."

Even so, they needed a one-year extension, and "two months before the deadline, we thought we probably wouldn't make it," Aschwanden says. Then he had a bright idea. "We got sponsors so we could give the plates away, up fronting the cost of the first year," he says. "It's a great return on our investment — for example, 7,500 plate renewals would bring in $300,000 every year."

The new strategy turned the campaign around, and by the end of the second year in April 2012, more than 8,300 orders had been placed. Last year, the California Agriculture license plates became available on the DMV website (dmv.ca.gov/online/elp/elp.htm). While the $50 fee for the first year goes to offsetting the costs of production, the bulk of the $40 annual renewal fee goes to the CDFA.

As one of the first people to order a California Agriculture plate three years ago, Aschwanden is more than ready: "Given the importance of agricultural sector, agricultural education is darned important."

—Robin Meadows

Clarification and Correction

As part of our recognition of UC Cooperative Extension's centennial year, throughout 2014 the research articles in *California Agriculture* will be paired with short historical sidebars. Some sidebars may draw from the same broad research area, while others may discuss earlier studies of a problem still being investigated or challenged by contemporary scientists. Research that was genuinely new and enlightening at one time may now be taken for granted or even proved wrong. This was the case in our January–June 2014 issue, page 21.

There, a research article on the economic impact to California of Pierce's disease in grapevines was accompanied by a sidebar on one of the most challenging aspects of Pierce's disease at the time: the identification of its causal agent. In 1974, Auger, Shalla and Kado identified a Gram-positive bacterium as the organism causing the disease. Their report was incorrect, as demonstrated 3 years later by Alexander Purcell and collaborators. One year later, in 1978, UC Berkeley graduate student Michael Davis, together with UC professors Purcell and Sherman Thompson, correctly demonstrated that a bacterium now called *Xylella fastidiosa* was the causal agent of Pierce's disease in grapevines (Davis et al. 1978).

In running historic material we aim to place the university's scientific endeavors into a larger context and remind readers how today's science builds on previous knowledge — not confuse people. We regret the latter.

Also in the January–June 2014 issue, the timeline on page 8 listed the year for the founding of the University of California incorrectly. The correct year is 1868. *—Editors*

UC ANR applies innovative research and programs to state's water scarcity

UC Division of Agriculture and Natural Resources (ANR) scientists have a long history of helping California agriculture remain productive in a varied climate. California's first drip irrigation, for example, was first introduced in the 1960s by ANR researchers in San Diego County. That spirit of innovation continues to this day. Our work introducing and helping manage new, more efficient irrigation systems enables the state's growers to increase production in our water-scarce environment. This issue of *California Agriculture* highlights UC ANR's willingness to tackle new research areas of water management, specifically the use of recycled or reclaimed water.

Ray Lucas

Doug Parker

Director
California Institute for Water Resources

Leader
Water Quality, Quantity and Security Strategic Initiative

Using recycled water for irrigation brings both new and familiar challenges to agriculture, with water quality and reliability as two major concerns. In their article "Chloride levels increase after 13 years of recycled water use in the Salinas Valley," Platts and Grismer find that while salinity levels increased less than predicted from using recycled water, chloride levels exceeded crop tolerance in some fields. The researchers furthered their work in the Salinas Valley, looking at soil water hydrologic factors controlling leaching. In the article "Rainfall leaching is critical for long-term use of recycled water in the Salinas Valley," they find that with moderate levels of salinity in irrigation water, soil salinity can reach a steady state.

While these studies focused on the Salinas Valley, the results have implications for using recycled water elsewhere. In the article "Recycled water causes no salinity or toxicity issues in Napa vineyards," Weber et. al. suggest that vineyards can thrive with recycled water under good irrigation management. Finally, the water section of this issue of *California Agriculture* includes a look at the use of new sensor technology to improve the efficiency of traditional surface water irrigation systems for alfalfa fields. This technology can increase water use efficiency and reduce potential water quality issues from end-of-field runoff.

These articles demonstrate ANR's commitment to be an innovative source of solutions for California. To this end, ANR continues to support scientific inquiries that foster creativity. ANR's *Strategic Vision 2025* serves as a guiding document for the Division and establishes the framework for how we respond to challenges that face the state. As part of this vision, we created five Strategic Initiatives to focus our research and extension programs: Water Quality, Quantity and Security; Endemic and Invasive Pests and Diseases; Sustainable Food Systems; Sustainable Natural Ecosystems; and Healthy Families and Communities. Each initiative seeks to capitalize on our science expertise to address issues of critical importance to California.

The Water Strategic Initiative, like the other four initiatives, is managed by a panel of scientists. The panel is responsible for creating and updating the initiative's 5-year strategic plan, recommending funding priorities for grants within ANR and making sure that adequate resources and staff are available to meet the plan's objectives (ucanr.edu/u.cfm?id=97).

In addition to the Water Strategic Initiative, ANR created the California Institute for Water Resources (CIWR), which coordinates and promotes water-related activities across the entire UC system. This institute works hand-in-hand with the ANR Water Strategic Initiative to expand our ability to respond to state needs. The CIWR has taken the lead at UC in organizing UC's drought-related research and outreach programs. Through its web portal (ciwr.ucanr.edu/) and Twitter feed (@ucanrwater), the CIWR provides Californians with vital information on drought response resources, workshops and seminars, and media contacts and reports.

This issue of *California Agriculture* highlights our willingness to tackle new research areas of water management.

UC President Napolitano has appointed the CIWR to be the lead UC program on drought response and to liaison with Governor Brown's drought task force to bring UC resources to current drought issues. We seek to assist the governor's task force, and indeed all state agencies, with UC expertise and knowledge to help California through the drought. With water, as with other Division programs, ANR continues to seek and provide California with ideas and solutions based on science.

Out of sight but not out of mind: California refocuses on groundwater

Thomas Harter, UC Cooperative Extension Specialist, Department of Land, Air and Water Resources, UC Davis

Helen E. Dahlke, Assistant Professor, Department of Land, Air and Water Resources, UC Davis

A deepening 3-year drought, accentuated by a record dry 2013, has focused public attention on groundwater like never before. And for a good reason: Almost everywhere in California, groundwater levels have been drawn to record depth and domestic and farm wells are drying up at an unprecedented pace. Well drillers are booked for months in advance to deepen existing wells or to construct new, much deeper ones. Even in a wet year, groundwater makes up one-third of our urban and agricultural water supply, but in 2014, as in previous dry years, nearly two-thirds of the state's water supply will be pumped from wells that are tapping into California aquifers. The economic consequences of not having this hidden resource available in future droughts would be catastrophic.

A significant number of regions in California won't have groundwater available in another generation or two if we continue business as usual.

Kings County well pumping into an irrigation system.

Yet, a significant number of regions in the state will not have this resource available in another generation or two if we continue business as usual. As groundwater depletes, damage will increase to our water, transportation and urban infrastructure due to land subsidence; critical ecosystems in groundwater-dependent streams will be lost; and costs will incur from pumping irrigation water from deepening water levels and preventing seawater intrusion into our coastal aquifer systems.

The state has seen similar crises before, particularly in Southern California, where groundwater basins are smaller, have more limited supplies, and had been overtapped soon after powerful turbine pumps were invented in the early 20th century. Extended, expensive court battles between thirsty urban neighbors have divided up the basins and resulted in adjudications that allocate specific amounts of water to specific groundwater users. The adjudications are administered through a local water master and have halted, if not reversed, the overdraft of these basins. A wide range of measures and complex arrangements between multiple stakeholders and the public have generated significant water conservation, development of alternative surface water supplies, and increased groundwater recharge and groundwater banking opportunities.

In other regions of California, particularly in the Central Valley, groundwater overdraft continues, exacerbated by below-average, or well-below-average, precipitation in 6 of the past 8 years. In some areas, including Paso Robles and the eastern San Joaquin Valley, overdraft is a recent phenomenon caused by agriculture expanding into former rangelands and growers using either stream-fed flood and furrow irrigation or high-efficiency irrigation systems that rely on groundwater that lacks recharge from streams.

Past droughts have provoked calls for groundwater action: In 1992, the California Legislature passed AB 3030, which encouraged local agencies to collaborate and develop groundwater management plans, though few guidelines were provided. Following another drought, the Legislature passed SB 1938 in 2002, which required those local agencies receiving state funding for water projects to have a groundwater management plan in place. This time, the state provided guidelines on minimum standards that the plans needed to fulfill to receive a passing grade from the state's Department of Water Resources (DWR). Following the 2007–2009 drought, the Legislature asked DWR to develop more rigorous groundwater level monitoring throughout the state, with the support of local agencies or initiatives.

Significant improvements in groundwater management occurred in some areas. Local agencies began thinking and talking about managing their groundwater; education and outreach activities have been offered to stakeholders through various organizations, including UC Cooperative Extension; and local advisory groups have engaged the public and the many local and regional agencies dealing with or affecting groundwater.

However, because none of this has stopped groundwater overdraft where it occurs, the demand for more comprehensive groundwater management has grown significantly over the past year. Last fall, the State Water Board (SWB) introduced a discussion draft of a groundwater work plan, and, in February, Governor Brown issued the Water Action Plan, which calls for significant legislative action on groundwater management. In response, the Association of California Water Agencies and a broad group involved in the stakeholder-driven process facilitated by the California Water Foundation issued these proposals, which indicate broad consensus on critical elements of groundwater management:

- Groundwater is most effectively managed at the local or regional basin level, with support from the state.
- Local groundwater management entities must be given better tools, such as clear mandates to assess, measure, monitor and allocate their groundwater and control its extraction.
- The definition of groundwater sustainability can be set at the state level and translated into specific actionable thresholds that must be enforced locally, with a credible threat of state enforcement should the local efforts be unsuccessful.
- Much better data collection, analysis, reporting and data integration are needed to provide transparency, to support local management efforts and to properly inform the public. This requires much stronger planning and support within the DWR and SWB.

But more needs to be done. Local land-use decisions on urban and agricultural development, which have critical impacts on groundwater resources, must be consistent with groundwater management objectives. This will require significant communication between land-use and groundwater managers. Effective integration with water quality management and surface water management efforts, which are governed separately, is also required. And none of these efforts can occur without sustained funding through a mix of local and state sources.

Can agricultural fields aid in water security?

Of particular interest to UC is the emphasis on the need for new tools to better manage groundwater. In 2014, a team of UC Davis faculty and Cooperative Extension specialists and advisors began exploring the feasibility of using agricultural land for transferring excess surface water during the winter rainy season into groundwater aquifers. The project is called Groundwater Banking: An Agricultural Systems Approach for Water Security. The idea is that during storms (or flood control releases) excess surface water could be directed from streams via existing water conveyance systems onto dormant agricultural fields, which would then serve as infiltration basins. If successful, several hundred or thousand acre-feet of water could be recharged annually into California's aquifers during very short periods. The banked groundwater could then be used to satisfy agricultural and urban water demand during dry years, leaving the available surface water for critical environmental uses such as enhanced streamflow.

This 3-year project, funded by UC Division of Agriculture and Natural Resources, aims to set up pilot groundwater recharge

field experiments, which would provide valuable data to address concerns about the costs and risks to crops, the influence these projects may have on groundwater levels and flows, and the possibility of recharging contaminated water or degrading groundwater quality by leaching contaminants such as nitrate from the vadose zone. Potential collaborators for the field experiments include the Glenn County Water Advisory Committee and the Bureau of Reclamation.

Besides the field experiments, the project is also developing suitability indices, such as the Soil Agricultural Groundwater Banking Index (SAGBI), to identify optimal recharge sites on agricultural land. Developed by Toby O'Geen, UC Cooperative Extension soil resources specialist, and the UC Davis Soil Resource Laboratory, the SAGBI ranks soils most suitable for groundwater recharge based on their ability to accommodate deep percolation, maintain a freely drained root zone, distribute water evenly on the landscape, minimize groundwater contamination by salts, and resist erosion and soil crust formation. This index will be combined with information on each possible site's climate, geology, irrigation infrastructure, soil water quality and surface and subsurface hydrology. If repeatedly used for groundwater recharge, a site would need to be protected from high application rates of fertilizer and pesticides; hence, the research team is investigating land with cropping systems that demand low nutrient and pesticide input, such as alfalfa fields and irrigated pasture. Recharge on fields with low-nutrient input cropping systems could sustain or even improve groundwater quality in areas where buildup of nutrients, pesticides, pollutants and salt in the soil is otherwise a concern.

A further aspect of the project is to develop knowledge of the socioeconomic effect of groundwater recharge on agricultural production, farm revenues and crop yields, all of which are fundamental factors in whether the groundwater banking program might be adopted across California. Data collected could serve as a foundation for developing economic incentives at the local, state or federal level to acknowledge the landowner's service to the local community and California's water supply reliability.

The 2013 update of the California Water Plan states that "one of the roles and goals of California is to seek statewide water supply reliability and sustainability [and] to strive for sustainable groundwater supplies throughout the state." Enhancing groundwater storage through intentional agricultural groundwater banking could potentially provide a means to attain these goals. Groundwater is California's largest source of water during droughts, and UC's research on its management, recharge and conjunctive use aims to ensure that a reliable supply is secured for farms and cities throughout the state.

UC Cooperative Extension helps Californians use water wisely

Last year was California's driest on record, and we are now facing our third straight year of drought. Growers have fallowed fields they can't irrigate and ranchers have sold cattle they can't feed, driving up food costs nationwide. Cities are feeling the pinch too because Governor Jerry Brown has asked for a voluntary 20% cut in urban water use. And rivers are so low that wildlife agencies have trucked millions of juvenile salmon from hatcheries toward the ocean. To help California adapt to drought, UC Division of Agriculture and Natural Resources (ANR) and UC Cooperative Extension (UCCE) researchers are finding ways for Californians to use less water.

"This drought is unprecedented — we've never had such a lack of rainfall since we started keeping track," says Doug Parker, who both directs UC ANR's California Institute for Water Resources and leads the Division's Strategic Initiative on Water Quality, Quantity and Security. Also unprecedented is the mere trickle that California farmers are getting from the state and federal projects that deliver surface water to users in the Central Valley and elsewhere. That said, drought is nothing new here. "California has always had droughts and will always have droughts," Parker says. "It's something we need to learn to live with."

Marin Master Gardener Jeanne Ballesttrero, right, shows client Candace Berthrong, left, how to read her water meter for water leaks, and how to use the meter to manage water usage. Ballesttrero is one of more than 100 Master Gardeners who have been trained in water conservation by the Marin Municipal Water District water district as part of the Garden Walks program.

During most years, agriculture uses 80% of the state's developed water, which doesn't include environmental allocations. "Farmers are looking for ways they can stretch their water budget," he says. Those who grow annual crops can simply plant fewer acres, and he estimates that about 5% of the irrigated cropland statewide will be fallowed this year.

But not every farmer has this option. Permanent crops like almonds and grapes need some water just to stay alive, so growers often turn to groundwater when supplies of surface water are cut. "This is not sustainable in the long run but is not a bad thing in the short run," Parker says. "It's a loan and we need to remember to pay it back." Downsides of overpumping groundwater range from depleting supplies to land subsidence.

Urban areas typically use 20% of developed water. While cities have more water than agriculture has this year, many are still getting far less than they're used to. It's not as dire as it was during the last big drought in the 1970s, however, thanks to conservation measures like low-flow toilets and showerheads. "We learned our lessons," Parker says. "We actually use less water per person now."

Water-smart gardening

There's still plenty of room for city dwellers to conserve more water. About half of the water they use statewide — nearly 200 gallons a day per household — goes to landscaping. To help gardeners use water efficiently, the Marin Master Gardeners teamed up with the Marin Municipal Water District (MMWD) to offer free water audits called Garden Walks. With training from the MMWD conservation team, well over 100 Master Gardeners visit people's gardens to evaluate and consult on plantings and irrigation systems.

"One of the biggest problems is automatic irrigation systems that aren't maintained," says Steven Swain, UCCE environmental horticulture advisor for Marin and Sonoma counties. "Every year, we find some that are dumping hundreds of gallons a day, but the leaks are often underground so no one knew." Another problem that's easy to solve is outdated controllers, which, unlike modern versions, don't shut off automatically when it rains. Other fixes include xeriscaping as well as gardening in zones to make sure that water-loving plants share a dedicated irrigation circuit.

Now in its fifth year, the Garden Walks program saves participating households an average of 1,000 gallons annually. "We're saving a lot of water — about 23 million gallons over the life of the program," Swain says. The program pencils out financially too, costing ratepayers less per gallon saved than the baseline rate for a gallon used.

Other municipalities are taking note. "There's a lot interest," Swain says. "We've gotten calls from other California counties and even Tacoma, Washington."

Efficient irrigation

Just as some garden plants are thirsty, there's no getting around that some crops need plenty of water. For example, avocados are shallow-rooted trees native to Central and South American cloud forests and need frequent irrigations throughout the day. Another difficulty is that California avocados grow along the coast from San Diego to Santa Cruz, where water is pricey and contains salts that can affect the trees' productivity.

Microsprinkler applying irrigation water in a mulched avocado grove.

Despite these challenges, California produced 151,000 tons of avocados valued at $460 million in 2011, according to the California Department of Food and Agriculture's 2012–2013 Agricultural Statistics Review. Avocados are a top 20 commodity in the state, and California is the nation's top avocado-producing state by far.

While avocado growers can't use less water, they can boost their irrigation efficiency. "Sprinkler systems are like Tinker Toys so they can get out of whack — monitoring them optimizes water delivery," says Ben Faber, UCCE farm advisor for Ventura and Santa Barbara counties. "Avocado growers tend to be the best irrigators in the state," he says, adding that too much or too little water can cause serious root diseases.

Faber also works on citrus, another top 20 commodity in California. Altogether the state produced 2.5 million tons of oranges valued at $656 million in 2011. In a trial, Faber tried watering orange trees on just one side, hoping to "fool them into thinking they were getting their usual amount." But that didn't work, so now he's testing drought-resistant rootstocks. "Deeper-rooted trees could get more of the winter rainfall, increasing orange production with less irrigation," he says.

Conserving groundwater

Unlike avocados and oranges, wine grapes are naturally water thrifty. But water is scarce in Paso Robles, a premier wine grape–growing region that — like most Central Coast agricultural land — lacks water deliveries from the state and federal projects. "We depend almost entirely on groundwater," says Mark Battany, UCCE viticulture farm advisor for San Luis Obispo and Santa Barbara counties. "That sets us apart from much of the state." Grapes were California's number two commodity in 2011, and wine grapes accounted for about half of the total production and value, at 3.4 million tons and $2.1 billion, respectively.

In contrast to surface water, groundwater is not regulated in much of the state, and trends in reserves in many areas are going steadily downward. "The water table has been dropping in Paso Robles," Battany says. "Water availability is the number one issue that threatens our long-term productivity."

He's looking for ways to make wine grapes thrive with less water. "We're trying to think out of the box," he says. For example, vines are grown close to the ground because that's what works in Europe, but that might not be best for Paso Robles, where the air near the ground is often cold at night when the vines start to leaf out in the spring. Currently, some growers protect their vineyards from frost by sprinkling them with water (the transition from liquid water to ice produces heat, which insulates the delicate buds from the cold).

Battany is exploring an alternative to using irrigation for frost protection that could also help protect vines from summer heat and climate change. His approach hinges on the fact that air near the ground is coldest at night and hottest during the day. "Training the vines to grow taller could avoid both extremes," he says. As a first step, Battany is assessing the temperature of air at a range of heights above the ground.

During temperature inversions, wind machines might also offer water-free frost protection by mixing the higher-and-warmer air into the lower-and-colder air that surrounds the grapevines. To assess the likelihood that wind machines could ward off frost, Battany

UCCE farm advisor Mark Battany is testing the range of temperature at different heights above the ground to study temperature inversions and the possibility of a water-free frost protection method for vineyards. *Below,* Battany is installing one of the precision measurement stations used to evaluate temperature profiles.

is part of a team that is surveying springtime temperature inversions in vineyards in Santa Barbara, San Luis Obispo and Sonoma counties. Altogether, more than 60 towers are measuring the air temperatures at both 5 feet and 35 feet above the ground.

Conserving surface water

Vineyards in Mendocino County get water from the Russian and Navarro rivers — most years, that is. The rivers are "horrifically low with the drought," said UCCE Mendocino County viticulture and plant science advisor Glenn McGourty in late March, adding that flows were only at 30 cubic feet per second, a third of the usual rate for that time of year. Even so, he's not too worried about the wine grapes right now. "Vineyards don't use a whole lot of water, so they can probably squeak by," he says.

McGourty is getting ready for a drier and warmer future, however. "We're rethinking and redesigning vineyards," he says. "Current rootstocks are from northern France, so they don't take the heat well." He's testing varieties that send their roots deeper and varieties that thrive in hot places like Greece and Portugal. "We want to keep up with climate change and still make very good wine," he says.

Another concern is Mendocino's endangered and threatened salmonids, including Chinook and Coho salmon and steelhead trout. As in Paso Robles, wine grape growers in Mendocino use water to protect new growth from frost during spring — and this is when young salmonids need water in the streams that lead to the ocean, where they'll spend most of their adult lives. McGourty is part of UC collaborations testing frost protection alternatives such as wind machines and applications of a mix of mineral oil and copper, which curbs the bacteria that help ice form on plants.

Saving salmon

Having water in rivers and streams is not enough to keep salmon alive — these fish also need the water to be cold. "In the middle of summer, water temperature can be more important than flow," says Lisa Thompson, UCCE fisheries specialist at UC Davis. At temperatures of up to 70°F, the pools where salmon hide from predators are already close to being too warm for the adult spring-run Chinook salmon in Butte Creek near Chico. "It's right on the line of what they can take," Thompson says. "Some days get almost lethally hot." Her fish and climate change models predict that the pools will be too hot for salmon in 50 years.

On days that are predicted to be extremely hot, resource agencies net fish and move them upstream to cooler waters. But that's so stressful for the salmon that they often die. It's also expensive, costing about $10,000 to move a few hundred salmon.

Thompson has another suggestion for getting salmon through heat waves: bring cold water to them instead of bringing them to cold water. She envisions piping cold water into the bottom of the pools, which can be 24 feet deep in mountain streams. Given the cost and casualty rate of moving salmon, this approach "may be just as feasible," she says.

Solutions can't come soon enough for all of California's water users, from salmon and other wildlife to farmers to people in cities. Not only is water demand growing, but we can't necessarily count on all the water that we've gotten used to having. "The last 150 years have been wetter than the last 2,000 years," says Lynn Ingram, professor in the UC Berkeley Department of Earth and Planetary Science. In other words, extended droughts could be the new normal — rather than the exception — in California.

—Robin Meadows

Pools in Butte Creek, near Chico, get too warm for salmon on the hottest spring days. Resource agencies have been netting hundreds of salmon at a time and trucking them to cooler waters upstream.

Lisa Thompson

Recycled water causes no salinity or toxicity issues in Napa vineyards

by Edward Weber, Stephen R. Grattan, Blaine R. Hanson, Gaetano A. Vivaldi, Roland D. Meyer, Terry L. Prichard *and* Larry J. Schwankl

In response to Napa Sanitation District's interest in expanding its delivery of recycled water to vineyards for irrigation, we conducted a feasibility study to assess the suitability of the water for this use. We adopted two approaches: comparing the water quality characteristics of the recycled water with those of other local sources of irrigation water, and evaluating soil samples from a vineyard that was irrigated for 8 years with the recycled water. Results indicate that the quality of the recycled water is suitable for irrigation, and also that long-term accumulation of salts and toxic ions have not occurred in the vineyards studied and are unlikely to occur. Nutrients in the recycled water may be beneficial to vineyards, though the levels of nitrogen may need to be reduced by planting cover crops in some vineyards.

Will Suckow

A study by UC Cooperative Extension researchers found that vineyards in Napa County irrigated with reclaimed wastewater showed no buildup of salinity or ion toxicity after 8 years.

The use of treated municipal wastewater for irrigating crops has increased dramatically in California over the past decade and is expected to expand exponentially in the next few decades (WateReuse 2009). The California Department of Water Resources (DWR) projects that the state's population will grow to 52 million people by 2030 (DWR 2005). Treated wastewater is a necessary water source to meet the needs of this expanding population. In 2009, urban California produced about 9 million acre-feet (MAF) of urban wastewater, of which, surprisingly, only 7% (0.65 MAF) was recycled (WateReuse 2009). The state has set an ambitious goal to increase reuse of wastewater to 2.5 MAF by 2030.

With this goal in mind, the Napa Sanitation District (NSD) has developed a Recycled Water Strategic Plan to explore options to maximize water recycling in Napa County; the plan includes vineyard irrigation, in particular the nearby vineyards in the Carneros region west of the city of Napa and the Milliken-Sarco-Tulocay (MST) region east of the city. Recycling water involves the management and treatment of wastewater to produce water that can be used for irrigation and other beneficial uses (Asano et al. 2007; Vivaldi et al. 2013). Water recycling benefits the environment by limiting the discharge of treated wastewater into natural waterways and helping to preserve the supply of potable water for human consumption (DWR 2003).

The production of recycled water is regulated by the California Department of Health Services through Title 22 of the California Code of Regulations, which protects public health while allowing for the safe use of recycled water for agriculture. Wastewater at NSD is treated through a series of primary, secondary and tertiary processes; the steps include settling, biological oxidation, clarification, coagulation, filtration and disinfection. The resulting water is clear and colorless and may have a slight chlorine smell due to the final disinfection treatment (residual chlorine is low enough to meet irrigation water quality standards). NSD's recycled water is "disinfected tertiary quality," the highest standard for recycled water in California.

Expanding the use of NSD recycled water has many economic and environmental advantages. It provides a reliable source of water to growers who might otherwise have no water or whose supplies diminish late in the summer and during periods of extended drought. The cost of NSD recycled water is generally less than the cost of other sources of supplemental water. Additionally, expanded use of recycled water reduces the amount of wastewater discharge to the Napa River and protects existing sources of fresh water for other uses.

Napa Sanitation District (NSD)

The NSD's National Pollutant Discharge Elimination System (NPDES) permit, issued by the San Francisco Bay Regional Water Quality Control Board, allows for the discharge of treated

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v068n03p59&fulltext=yes

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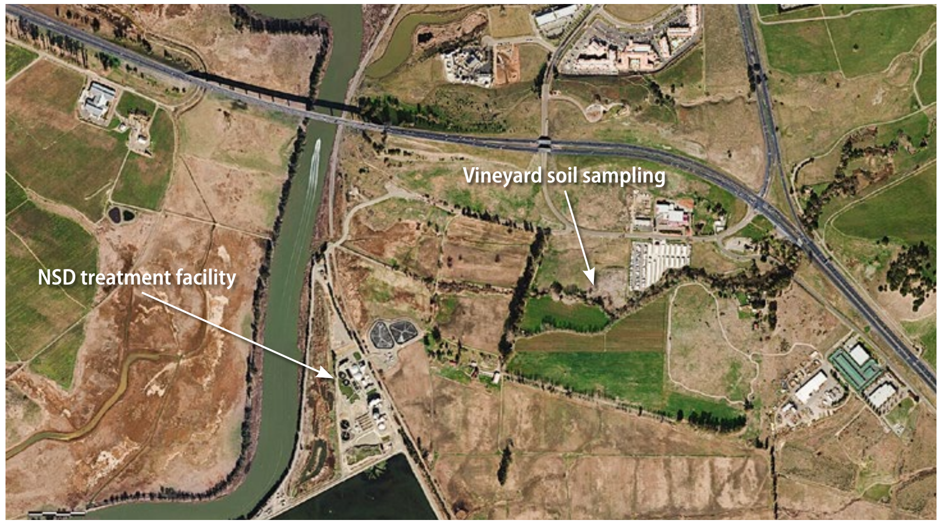
wastewater into the adjacent Napa River during the wet season (November through April), but during the dry season (May through October) river discharge is prohibited. During the nondischarge period, treated water is recycled for irrigation purposes or stored for wet season discharge. NSD currently delivers recycled water for irrigating vineyards, industrial landscaping and golf courses near the Soscol Water Recycling Facility.

The Carneros region has extensive plantings of vineyards, but water is often limited in this area and there is little surface water available from ponds or reservoirs. Groundwater is often limited in volume, and it may be high in salts or boron, especially from wells close to San Pablo Bay. The MST region includes considerable vineyard acreage and golf courses, which can potentially benefit from the availability of recycled water.



UCANR Statewide IGIS Program

Aerial view of the Napa Sanitation District's recycled water use area and the location of the soil sampling site. The use of treated municipal wastewater for irrigating crops has increased in California in the past 10 years and is expected to expand exponentially in the next few decades.

Study overview

For recycled water to be a benefit to grape growers, it needs to be suitable for vineyard irrigation and there must be no problems with it (such as high salinity or toxic constituents) that could affect the vines or soil; and growers must be confident about its quality and the effects. In 2004–2005, NSD gave UC a grant requesting a feasibility study. For this study, samples of NSD recycled water were collected in 2005 on a weekly basis during the dry season (May 1 through Oct. 31, the period when high-quality recycled water suitable for vineyard irrigation is produced by NSD). Water samples were collected from a 24-hour automatic sampler that maintains a representative sample of recycled water produced at the plant during the previous 24 hours. The sampler collects aliquots every 15 minutes. The quantity collected is based on the flow rate during that period. In this way, a truly representative, composite sample is produced. The samples were collected by NSD staff and sent to Caltest Analytical Laboratory in Napa for determination of key inorganic constituents.

To have water quality data from other local water sources to compare to the NSD samples, we also collected samples from several water sources being used for vineyard irrigation in the Carneros and MST regions. In Carneros, three wells, one surface water storage pond and a domestic tap water source from the city of Napa used for irrigating vineyards were sampled. In the MST region, three wells, one surface water storage pond, and one pond that combined surface water runoff and well water were also sampled. At each of these locations, water samples were collected in May, July and October 2005, that is, at the beginning, middle and end of the dry season, when NSD recycled water is available for irrigation.

Analyses of these samples, similar to the analyses of the NSD samples, were performed at Caltest. To meet Caltest guidelines, water was collected in three containers: one container with no preservatives added, for analysis of alkalinity, chloride (Cl), pH, electrical conductivity (EC), nitrate-nitrogen, nitrite-nitrogen, total dissolved solids (TDS), sulfate (SO_4), fluoride (F) and turbidity; another container, with nitric acid as a preservative, for analysis of boron (B), iron (Fe), silica, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K) and hardness; and a third container, with sulfuric acid as a preservative, for analysis of ammonia-nitrogen, organic nitrogen (N), total Kjeldahl N and phosphate. Samples were stored in coolers and transported to Caltest within hours of collection.

Irrigation water quality evaluations generally consider the water's pH, salinity hazard (which is indicated by the EC of the water and is associated with the total soluble salt content of the water), Na hazard based on the sodium adsorption ratio (SAR, the relative proportion of Na to Ca and Mg ions), alkalinity due to carbonate and bicarbonate ions, and the presence of specific ions such as B and Cl that can have toxic effects and other constituents such as N that can influence plant growth and vine vigor. All of these parameters were evaluated in this study and are presented in table 1.

In addition to the water sampling described above, we collected soil samples in September 2005 from a vineyard that had been drip-irrigated with NSD recycled water for eight seasons (1997 to 2005). Soil samples were collected Sept. 15, 2005, at two depths. The grower typically

Evett Kilmartin

Drip irrigation emitter using recycled water from the Napa Sanitation District.

applied 75 to 100 gallons of water per vine per season.

Because the soil samples were collected late in the growing season (but before winter rains occurred), they contained the maximum level of soil salinity likely to be found in the vineyard over the season. Soil samples were analyzed for the electrical conductivity of the saturated soil extract (EC_e), saturation percentage (SP), pH, Ca, Mg, Na, Cl, bicarbonate and carbonate. Soil analyses were conducted at UC Davis Analytical Laboratory. Data were analyzed by analysis of variance (ANOVA) using R 2.15.0 software (R Foundation for Statistical Computing); standard error (SE) values were also determined.

Salinity effect on yield

Historically, salinity hazard has been assessed using yield potential as described by the Maas-Hoffman salinity coefficients (Maas and Grattan 1999). According to Maas and Hoffman (1977), as described by Ayers and Westcot (1985), salt tolerance can best be described by plotting relative yield as a continuous function of average root zone soil salinity (EC_e). Maas and Hoffman proposed that this response curve could be represented by two line segments: a tolerance plateau with a zero slope, and a concentration-dependent line whose slope indicates the yield reduction per unit increase in soil salinity. For soil salinities exceeding the threshold of any given crop, relative yield (Yr), or yield potential, can be estimated using the following expression:

$$Yr\ (\%) = 100 - b(EC_e - a)$$

where a = salinity threshold soil salinity value expressed in dS/m; b = slope expressed in the percentage yield decline per dS/m increase above the threshold; and EC_e = average root zone salinity in the saturated soil extract. Note that an EC_e value for soil is different than the EC_w value for irrigation water. The most up-to-date listing of specific values for a and b, called salinity coefficients, are found in Grieve et al. (2012). For grapes, the a and b salinity coefficients are 1.5 and 9.6. Therefore, for grapes,

$$Yr\ (\%) = 100 - 9.6(EC_e - 1.5)$$

Note that when the salinity of the soil (EC_e) is less than the salinity threshold for grape (i.e., 1.5 dS/m), then the yield potential is 100%. This indicates that grape yields are not adversely affected by soil salinity until the seasonal average root zone salinity (EC_e) exceeds 1.5 dS/m (1 dS/m = 1 mmhos/cm [millimhos per centimeter]).

TABLE 1. Average water quality values of recycled water from NSD and water from local sources in MST and Carneros regions, 2005*

		NSD	MST water sources‡		Carneros water sources‡		
Measurement	**Units**	**Recycled water†**	**Wells (3)**	**Surface sources (2)**	**Wells (3)**	**Surface source**	**Domestic source**
pH	pH units	7.5 (0.2)	7.6 (0.15)	8.0 (1.50)	7.7 (0.38)	7.6	7.2
Salinity and sodicity							
EC	mmhos/cm	0.95 (0.1)	0.40 (0.11)	0.48 (0.25)	0.94 (0.3)	0.45	0.35
TDS	mg/L	582 (59)	316 (79)	355 (169.5)	541 (131)	267	217
SAR	SAR units	3.9 (0.7)	1.3 (0.3)	1.4 (0.15)	7.7 (4.17)	1.5	1.3
Alkalinity							
Alkalinity, total (as $CaCO_3$)	meq/L	2.1 (0.3)	2.8 (0.31)	1.8 (0.99)	4.8 (1.03)	3.3	1.6
Bicarbonate (as $CaCO_3$)	meq/L	2.1 (0.3)	2.8 (0.31)	1.4 (0.76)	4.8 (1.03)	3.3	1.6
Specific ions							
Sodium (Na)	meq/L	5.0 (0.7)	1.4 (0.17)	1.6 (0.50)	6.4 (2.16)	1.7	1.3
Chloride (Cl)	meq/L	4.3 (0.9)	0.3 (0.10)	0.6 (0.15)	3.5 (1.31)	1.0	0.4
Sulfate (as SO_4)	meq/L	1.5 (0.3)	1.2 (0.85)	2.8 (3.13)	0.8 (0.25)	0.4	1.5
Boron (B)	mg/L	0.4 (0)	0.1 (0.06)	0.4 (0.06)	0.4 (0.31)	0	0.1
Calcium (Ca)	meq/L	1.6 (0.1)	1.5 (0.51)	1.7 (0.96)	1.1 (0.47)	1.4	0.8
Magnesium (Mg)	meq/L	2.0 (0.2)	1.2 (0.40)	1.3 (0.76)	1.1 (0.40)	1.1	1.2
Potassium (K)	mg/L	18.8 (2.8)	6.2 (1.27)	7.5 (1.42)	8.5 (5.30)	7.2	2.7
Phosphate (as P), total	mg/L	0.9 (0.4)	0.1 (0.10)	0.1 (0.10)	0.6 (2.16)	0.4	0.2
Nitrogen, nitrate (as N)	mg/L	12.1 (2.0)	0 (0)	0.1 (0.15)	2.3 (2.61)	0.1	0.2
Nitrogen, total Kjeldahl	mg/L	1.0 (0.3)	0.2 (0.25)	1.1 (0.45)	0.2 (0.10)	2.2	0.2
Nitrogen, ammonia (as N)	mg/L	0.2 (0.1)	0.2 (0.20)	0.1 (0.06)	0 (0)	1.4	0
Nitrogen, organic	mg/L	0.8 (0.3)	0.1 (0.06)	1.0 (0.45)	0.1 (0.1)	0.8	0.1
Iron (Fe)	mg/L	0.1 (0.1)	0.7 (1.85)	1.5 (2.40)	0 (0)	1.0	0
Fluoride (F)	mg/L	0.1 (0.1)	0.2 (0.12)	0.2 (0.15)	0.2 (0.15)	0.1	0

* Each value is the average and standard deviation.
† 25 weekly samples were collected May to October 2005 from a 24-hour composite sampler.
‡ Samples were collected at each site once in May, July and October 2005.

Leaching, EC_w and EC_e results

To assess the impact on crop yield of irrigation water with a known EC_w, the relationship between irrigation water salinity (EC_w) and average root zone salinity (EC_e) needs to be known or predicted. This relationship depends on the salinity of the irrigation water (EC_w), the leaching fraction and whether the irrigation method is conventional (i.e., surface irrigation) or high frequency (e.g., drip irrigation).

The leaching fraction is the fraction (or percentage) of infiltrated water that drains below the root zone. For example, if 5 acre-inches of water were applied to 1 acre and 1 acre-inch of water drained below the root zone, the leaching fraction would be 0.20, or 20%. Soil salinity is controlled by applying sufficient quantities of irrigation water to leach salts from the root zone. The desired leaching fraction, called the leaching requirement, depends on the salinity of the irrigation water and the crop's soil salinity threshold.

Relationships between EC_w and EC_e at various leaching fractions under both conventional and high-frequency irrigation systems have been presented by Hanson et al. (2006). These relationships assume that water extraction by roots is proportionately higher in the upper part of the root zone, and even more so with drip irrigation. The relationships also assume steady-state conditions, in which the rate of water entering the soil surface and that draining below the root zone remains constant over time. In the case of NSD recycled water, the average EC_w is 0.95 mmhos/cm. Using the high-frequency relationship proposed by Pratt and Suarez (1990) and a long-term leaching fraction of 10%, the formula becomes $EC_e = 1.35 \times EC_w$. This indicates that soil salinity (EC_e) over the long term will not exceed 1.3 mmhos/cm. Because this is lower than the threshold EC_e value for grapes (1.5 mmhos/cm), NSD recycled water over the long term should not create salinity problems in vineyards.

This calculation, furthermore, takes no account of leaching by winter rainfall, which reduces soil salinity significantly. Leaching is particularly effective in winter, when vines are dormant and crop evapotranspiration (ET_c) is essentially zero. With winter rains averaging approximately 20 inches per year in the Carneros and MST regions, the reclamation-leaching functions provided by Ayers and Westcot (1985) predict that about 80% of salts that accumulate in the top 3 feet of soil can effectively be removed each year through leaching by rain alone. The prediction assumes that the soil profile is replenished with irrigation water before winter rains occur. It is therefore advisable for growers to apply a postseason irrigation in late fall to return soil in the crop root zone to field capacity, so winter leaching is more effective. Postharvest irrigation is already a standard practice in many Napa Valley vineyards if water for irrigation is still available.

The EC_e values were all less than 0.8 mmhos/cm, far below the yield threshold of 1.5 mmhos/cm . . . additional evidence that long-term salinity accumulation should not occur.

To determine whether there was any evidence of a long-term buildup of soil salinity at the vineyard where recycled water had been applied for 8 years, soil samples from the site were analyzed for EC_e and saturation percentage (SP) and the results compared to the threshold EC_e for grapevines. Table 2 shows EC_e, SP and pH values for an average of 10 samples from two soil depths at two locations (near drip emitters and between rows).

TABLE 2. Saturation percentage (SP), electrical conductivity of saturated soil extract (EC_e) and pH of soil samples from vineyard irrigated with NSD recycled water, 1997 to 2005 (n = 10)*

Sample depth	SP	EC_e	pH
feet	*%*	*mmhos/cm*	
0 to 1	32.5 ± 1.1	0.53 ± 0.06	5.8 ± 0.2
1 to 2	36.2 ± 0.8	0.38 ± 0.05	5.6 ± 0.1

* Values represent average and standard deviation.

TABLE 3. Maximum chloride (Cl) concentrations in irrigation water that various rootstocks and cultivars can tolerate without developing leaf injury

	Grape variety	Max. Cl concentration
		meq/L
Rootstocks	Salt Creek, 1613 C	29.6*
	Dog Ridge	22.2
Table grapes	Thompson Seedless, Perlette	14.8
	Cardinal, Black Rose	7.4

Source: adapted from Hanson et al. 2006.

* Values are for drip irrigation and a 10% leaching fraction.

The SP values were all similar, which is typical for a sandy loam soil, indicating no major changes in soil texture between the sampling locations. The maximum EC_e value among the samples was 0.79 mmhos/cm; most samples were between 0.25 and 0.5 mmhos/cm. No trends with depth or sampling location were evident. The EC_e values were all less than 0.8 mmhos/cm, far below the yield threshold of 1.5 mmhos/cm. These field study results provide additional evidence that long-term salinity accumulation should not occur when using NSD recycled water.

Ion toxicity results

Grapevines are sensitive to Cl and to some extent to Na in irrigation water and can develop leaf injury if concentrations exceed certain levels. Specific ion injury, if severe enough, reduces yields more than salinity (i.e., EC or TDS) alone. Although B is an essential element required for plant growth, it is nonetheless potentially toxic, should the concentration in the soil solution become too high. Threshold concentrations of Cl and B in irrigation water, above which toxicity can occur, were reported by Ayers and Westcot (1985) and updated more recently by Grieve et al. (2012).

Chloride. Many woody species are susceptible to Cl toxicity, with variation among varieties and rootstocks within species. The degree of tolerance is often reflected in the plant's ability to restrict or retard Cl translocation from root to shoots, and particularly to leaves (Maas and Grattan 1999; Walker et al. 2004). Salt tolerance in grapes is closely related to the Cl retention properties of the rootstock, and selection of rootstocks that exclude Cl from scions avoids most Cl toxicity problems (Bernstein et al. 1969).

The maximum Cl concentrations in irrigation water that can be used by particular crops without leaf injury are reported in several references cited above, and the guidelines specific to grapes are reproduced in table 3. This list is by no means complete since data for many cultivars and rootstocks are not available, including those currently in use in the Carneros and MST regions. Original data listed by Maas and Hoffman (1977) are in relation to maximal Cl concentrations in the soil water, but data were converted to maximal tolerance in the irrigation water by assuming that EC of soil water is twice EC_e and that a long-term leaching fraction of 10% is achieved using high-frequency drip irrigation. These are reasonable yet conservative assumptions.

For sensitive grape cultivars (i.e., Black Rose and Cardinal), the maximum Cl concentration of irrigation water to avoid crop injury is about 7.4 meq/L (milliequivalents per liter) (table 3). Since no tolerance data have been compiled for the predominant grape rootstocks in the Carneros and MST regions (101-14, 5C, 3309 and 110R), we took a conservative approach and selected 7.4 meq/L (262 mg/L, milligrams per liter) as an upper limit for Cl in our study. As more research is conducted on these rootstocks, the limit can be adjusted accordingly. Since the Cl content in NSD water averages 4.3 meq/L (table 1), this water will not likely cause Cl toxicity in grapes, assuming good irrigation water management. If winter leaching is also taken into consideration, the case is even stronger that the recycled water will not pose a problem for vineyard production.

Sodium. The ability of vines to tolerate Na varies considerably among rootstocks, but tolerance is also dependent upon Ca nutrition. Much of the early research on Na toxicity was done in the 1940s and '50s before the importance was understood of adequate Ca nutrition for maintaining ion selectivity at the root membrane level. Since then, a considerable amount of literature has indicated Na can cause indirect effects on crops, rather than toxicity exactly, either through nutritional imbalances (e.g., Na-induced Ca or K deficiency) (Grattan and Grieve 1999) or by disrupting soil physical conditions (Ayers and Westcot 1985). These indirect effects make diagnoses of Na toxicity per se very difficult. Moreover, Na toxicity is often reduced or completely overcome if sufficient Ca is made available to roots (Ayers and Westcot 1985) through the addition of gypsum or by acidifying soils high in residual lime.

Ca addition reduces the ratio of Na to Ca (Na:Ca) in the soil water, thereby reducing the SAR and exchangeable sodium percentage (ESP), resulting in both improved soil conditions and reduced Na toxicity. Ayers and Westcot (1985) indicate that there are no "restrictions on use" provided that the SAR is less than 3. They provide no concentration limits for Na above which toxicity will result, presumably because of the indirect interactions

UC Cooperative Extension Centennial

Irrigation of deciduous orchards and vineyards influenced by plant-soil-water relationships in individual situations

Today this article may seem too simplistic an explanation of basic irrigation concepts — field capacity, permanent wilting point, readily available moisture. But in 1957, much more land in California was still dry-farmed, and the widespread use of irrigation was a new idea to many.


Grapes and Deciduous Fruits

Irrigation of deciduous orchards and vineyards influenced by plant-soil-water relationships in individual situations

1957 "One of the principal cultural practices in deciduous fruit orchards and vineyards is irrigation and its successful accomplishment frequently determines whether the grower makes a profit.

"The cost of irrigation — preparing the land for surface irrigation, the labor of applying the water and the cost of the water — may be one of the important items in the production of fruit. Because experience has shown that much time and labor may be wasted, the selection of a rational program of irrigation is of great importance.

"Whether to irrigate or not, or when to irrigate, are questions that can be answered only from consideration of the moisture properties of the soil, the kind of plant, its depth of rooting, the kind of root system, prevailing climatic conditions, and whether there is a supply of water for irrigation.

"A grower should consider the soil as a reservoir for the storage of water for use by the plants. Therefore, he needs to know how much readily available water can be stored in the soil. . . ."

Veihmeyer FJ, Hendrickson AH. 1957. Grapes and deciduous fruits: Irrigation of deciduous orchards and vineyards influenced by plant-soil-water relationships in individual situations. Calif Agr 11(4):13–8.

Frank J. Veihmeyer was already an emeritus professor of irrigation at UC Davis when this article was published in 1957. He joined the university in 1918 as an assistant professor of irrigation at Davis, then still known as the University Farm. Veihmeyer was recognized and honored worldwide for his research and writings on irrigation. The home of the UC Davis Department of Land, Air and Water Resources, Veihmeyer Hall, is named in his honor.

Emeritus pomologist Arthur H. Hendrickson joined the UC Berkeley faculty in 1913 as assistant in pomology, and in 1924 moved to UC's Agricultural Experiment Station so he could conduct his research full-time. Together, he and longtime research associate Frank Veihmeyer practically invented many of the irrigation science terms defined in this article, words and ideas that today are considered fundamental to understanding hydrology on the farm.

—W. J. Coats

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between Ca and Na mentioned above. The average Na concentration of the NSD recycled water was 5.0 meq/L and the SAR was 3.9 (table 1). Although this Na level is slightly higher than the one suggested by Ayers and Westcot, it can readily be lowered by light gypsum applications in fall. Therefore, these values indicate that Na will not be a problem over the long term provided adequate Ca nutrition and soil physical conditions are maintained.

Soil samples collected from the vineyard irrigated with NSD recycled water provide further evidence that toxicities from Na or Cl are unlikely to occur. Figure 1 shows the soluble salts extracted from the soil samples. The average Na and Cl concentrations were 1.6 meq/L and 1.2 meq/L, respectively. Cl toxicity should not be a problem unless the concentration in the saturated soil extract exceeds 10 meq/L (355 mg/L). There is no specific threshold level for Na in soils, as discussed above. The results of these soil tests indicate that toxicities from Na or Cl are not occurring at this site following long-term use of NSD recycled water.

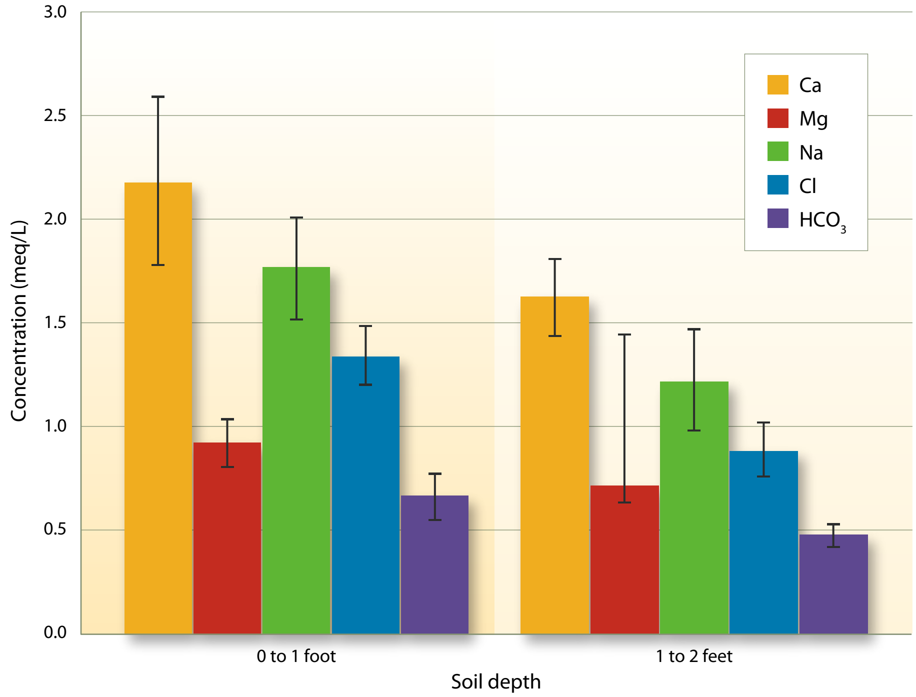

Fig. 1. Chemical constituents in the saturated soil extracts of samples collected in a vineyard irrigated with NSD recycled water from 1997 to 2005 (*n* = 10). Samples were collected at different depth intervals and distances from the emitter. Bars indicate the standard error.

Boron. B is an essential element for plants but has a small concentration range between levels considered deficient and those considered toxic. Grapes are particularly sensitive to B in irrigation water and can develop injury to leaves and developing shoots if concentrations exceed certain limits (Camacho-Cristobal et al. 2008). The characteristics of B injury are crop-specific and are related to a plant's ability to mobilize this element (Brown and Shelp 1997). In certain tree species (e.g., walnut and pistachio), B is immobile within the plant, and consequently it does not move out of the leaves once it has accumulated there, resulting in necrosis (burn) along the margins and tips of older leaves. In other tree species (e.g., almond, apricot, apple, nectarine, peach and plum), B is relatively mobile, and injury may not appear first on leaves but instead in young shoots as tip dieback.

Malbec vines at Trinitas Cellars vineyard in Napa.

Grapevines show some degree of B mobility but not to the same extent as the almond and fruit trees listed above. Threshold levels in irrigation water that produce injury are reported in Ayers and Westcot (1985). Many of these data reported by Ayers and Westcot were taken from Maas and Hoffman (1977), who extracted most of the information, including the grape data, from work conducted by Eaton (1944). When the limited data set from Eaton (1944) is examined in detail, growth of grape does not decline until B concentrations in irrigation water exceed 1 mg/L.

The guidelines for B tolerance are limited. With the exception of a few sand tank studies that provide B coefficients (i.e., threshold and slope) for some crops, most of the B classification work was conducted nearly 70 years ago by Eaton (1944). Research on common rootstocks is lacking. More importantly, the older studies defined a B tolerance limit largely on the basis of the development of incipient injury (i.e., foliar burn) or growth reduction, not on yield response under a range of B concentrations.

The average B concentration of the NSD recycled water was 0.4 mg/L (table 1), which is well below the 1 mg/L level at which grapevines have shown sensitivity. Therefore, it is highly unlikely that B will be problematic over the long term from the use of NSD recycled water. Winter rains will help in leaching soil B below the root zone.

Calcium:magnesium ratios

Some soils in Napa County and parts of the North Coast of California are derived from serpentine parent material, leading to high Mg concentrations (in relationship to Ca), which can affect plant nutrition and reduce plant growth. A review of research studies indicates that plant growth reductions may occur in some plants when the concentration of Mg in soil solution substantially exceeds the Ca concentration (Grattan and Grieve 1999). Levels of Ca and Mg in soil are usually expressed as a percentage of the cation exchange capacity, or on a concentration basis from a saturated paste extract. When comparing concentrations, the levels should be expressed in meq/L.

The relationship between Ca and Mg is often expressed as a Ca:Mg ratio. When Mg is present at three to four times the concentration of Ca (i.e., Ca:Mg ratios of 0.33:1 to 0.25:1), plants, including grapes, often exhibit reduced growth and yield and have low K concentrations in leaves and petioles (R.D. Meyer, personal observation). Ca concentrations may also be lower than desired for normal growth and development. These effects on plant growth often begin to occur when the level of Mg in soil is twice that of Ca (Ca:Mg ratio of 0.5:1).

Adding Ca to serpentine soils (normally in the form of gypsum) can increase the Ca concentration and alter the Ca:Mg ratio. If the Ca:Mg ratio of soil immediately around grape roots is adjusted to a 1:1 ratio or the Ca concentration is adjusted even higher, plant growth will improve and K concentrations in grapes will increase without addition of K fertilizers. High rates of K fertilizer are required to increase the K concentration in plants if Ca:Mg ratios are in the range of 0.5:1. Adding gypsum may be necessary depending on the Ca:Mg ratio and the clay content (greater cation exchange capacity) of soils being used for grape or other crop production.

The Ca:Mg ratio of irrigation water is also important because, over time, it may change soil characteristics — if large amounts of irrigation water are applied to soils relative to the amount of rainfall, soil characteristics eventually take on the irrigation water characteristics. MST and Carneros well and surface waters had Ca concentrations equal to or higher than Mg concentrations (table 4). NSD recycled water and Carneros domestic water had Ca concentrations slightly less than Mg concentrations, but they were not so low as to raise concerns regarding the long-term effects on soils. When irrigation waters have at least twice as much Mg as Ca (equivalent concentration bases), then gypsum additions should be made to increase Ca levels in order to keep the soil ratios in balance. The Ca and Mg concentrations in NSD recycled water do not indicate the need for growers to make gypsum additions.

Trace elements. Tests for trace elements, including heavy metals, were conducted on NSD recycled water samples, as required by the NPDES permit. Depending on the element, tests were conducted once a month from May to October, or once in May and once in October. Levels of trace elements in NSD recycled water were well below established thresholds of concern for irrigation water (table 5).

Fertilizer in recycled water

NSD recycled water contains plant nutrients N, P (phosphorus) and K in concentrations that make it a dilute fertilizer solution. Growers should take into account the value of nutrients in reclaimed water and reduce application of fertilizers accordingly, particularly since there is a risk of overapplying N when irrigating with recycled water (Wu et al. 2009). N is the most frequently deficient macronutrient in vineyard soils, and it plays a major role in many of the biological functions

TABLE 4. Average Ca and Mg concentrations in recycled water from NSD and water from local sources in MST and Carneros regions, 2005

		NSD	MST water sources		Carneros water sources		
Nutrient	Units	Recycled water	Wells (3)	Surface sources (2)	Wells (3)	Surface source	Domestic source
Calcium (Ca)*	meq/L	1.6	1.5	1.7	1.1	1.4	0.8
Magnesium (Mg)*	meq/L	2.0	1.2	1.3	1.1	1.1	1.2
Ca:Mg ratio		0.8:1	1.3:1	1.3:1	1:1	1.3:1	0.7:1

* Data is from table 1.

TABLE 5. Average concentrations of trace elements in NSD recycled water and recommended maximum levels

	Concentration							
Trace element	May	Jun	Jul	Aug	Sep	Oct	Average	Recommended max. level*
	μg/L							
Al (aluminum)	170.0	—	—	—	—	190.0	180.0	5,000
Ag (silver)	< 0.1	< 0.1	< 0.1	< 3.0	< 0.1	< 0.1	< 0.58	NL†
As (arsenic)	< 0.5	< 0.5	0.6	< 10.0	0.79	< 0.5	< 2.15	100
Ba (barium)	9.6	—	—	—	—	7.6	8.6	NL
Be (beryllium)	< 0.1	—	—	—	—	< 0.1	< 0.1	100
Cd (cadmium)	< 0.1	< 0.1	< 0.1	< 1.0	< 0.1	< 0.1	< 0.25	10
CN (cyanide)	< 3.0	< 3.0	< 3.0	—	< 3.0	< 3.0	< 3.0	NL
Co (cobalt)	< 0.5	—	—	—	—	0.5	< 0.5	50
Cr (chromium)	0.7	0.6	< 0.5	< 5.0	0.8	0.5	< 1.35	100
Cu (copper)	4.4	4.7	4.7	< 10.0	5.8	2.5	< 5.35	200
F (fluoride)	< 110.0	< 110.0	< 110.0	< 110.0	< 180.0	< 130.0	< 130.0	1,000
Hg (mercury)	0.05	< 0.01	< 0.01	< 0.2	< 0.05	< 0.01	< 0.13	NL
Li (lithium)	12.0	—	—	—	—	10.0	11.0	2,500
Mn (manganese)	0.1	—	—	—	—	93.0	46.6	200
Mo (molybdenum)	1.4	1.6	1.9	< 5.0	1.1	0.98	< 2.0	10
Ni (nickel)	4.4	4.6	3.9	< 5.0	4.0	4.4	4.38	200
Pb (lead)	< 0.25	< 0.25	< 0.25	< 5.0	< 0.25	< 0.25	< 1.04	5,000
Se (selenium)	< 1.0	< 1.0	< 1.0	< 10.0	< 1.0	< 1.0	< 2.5	20
Sn (tin)	< 1.0	—	—	—	—	< 1.0	< 1.0	NL
Sr (strontium)	210.0	—	—	—	—	240.0	225.0	NL
Ti (titanium)	6.9	—	—	—	—	3.1	5.0	NL
V (vanadium)	< 2.0	—	—	—	—	< 2.0	< 2.0	100
W (tungsten)	< 0.5	—	—	—	—	< 0.5	< 0.5	NL
Zn (zinc)	24.0	—	11.0	< 20.0	12.0	11.0	< 15.6	2,000

* Recommended maximum concentrations in irrigation water. Source: Ayers and Westcot 1985, table 21.
† NL = not listed.

Edward Weber

Terry Prichard

Vines that receive fertilizer applications balanced with their needs, *left*, show no excess vigor. Vines given too much N produce too much vegetation, *right*, which can lead to reduced yield and lowered wine quality. The N content of recycled water must be taken into account to keep vines in balance.

and processes of vines, and also of fermentative microorganisms, which can influence quality components in the grape and thus the wine (Bell and Henschke 2008).

The amount of nutrients delivered to grapevines depends upon concentrations in the recycled water and amount of water applied. Seasonal averages of nutrients in NSD recycled water (table 6) indicated approximately 13.1 mg/L of N (mostly as nitrate-nitrogen), 0.9 mg/L of P and 18.8 mg/L of K. Averages of well and surface waters in both regions were considerably lower: 1.4 mg/L of N, 0.3 mg/L of P, and 7.4 mg/L of K. Table 6 indicates the amount of nutrients in pounds per acre that were applied in NSD recycled water. For comparison, values are also given for MST and Carneros local water sources. At typical irrigation rates of 0.4 to 0.6 acre-feet per acre per season, NSD recycled water delivered approximately 14 to 21 pounds of N, 1 to 1.5 pounds of P (2.2 to 3.4 pounds of P_2O_5) and 21 to 31 pounds of K (25 to 37 pounds of K_2O) per acre. Fertilizer rates for P and K are normally expressed as P_2O_5 and K_2O, respectively.

TABLE 6. Nutrients, in pounds per acre, in NSD recycled water and water from local MST and Carneros sources, at various water application rates

		Nutrients in applied water*					
		NSD	MST water sources		Carneros water sources		
Nutrient	Applied water	Recycled water	Wells (3)	Surface sources (2)	Wells (3)	Surface source	Domestic source
	acre-feet	*pounds/acre*					
Nitrogen (as N)	1.0	35.6	1.6	4.1	6.8	6.3	1.1
	0.8	28.5	1.3	3.3	5.4	5.0	0.9
	0.6	21.4	1.0	2.4	4.1	3.8	0.7
	0.4	14.3	0.7	1.6	2.7	2.5	0.4
Phosphorus (as P)	1.0	2.4	0.5	0.8	1.6	1.1	0.5
	0.8	2.0	0.4	0.7	1.3	0.9	0.4
	0.6	1.5	0.3	0.5	1.0	0.7	0.3
	0.4	1.0	0.2	0.3	0.7	0.4	0.2
Phosphorus (as P_2O_5)	1.0	5.6	1.2	1.9	3.7	2.5	1.2
	0.8	4.5	1.0	1.5	3.0	2.0	1.0
	0.6	3.4	0.7	1.1	2.2	1.5	0.7
	0.4	2.2	0.5	0.7	1.5	1.0	0.5
Potassium (as K)	1.0	51.1	16.9	20.4	23.1	19.6	7.3
	0.8	40.9	13.5	16.3	18.5	15.7	5.9
	0.6	30.7	10.1	12.2	13.9	11.8	4.4
	0.4	20.5	6.7	8.2	9.2	7.8	2.9
Potassium (as K_2O)	1.0	61.4	20.2	24.5	27.7	23.5	8.8
	0.8	49.1	16.2	19.6	22.2	18.8	7.1
	0.6	36.8	12.1	14.7	16.6	14.1	5.3
	0.4	24.5	8.1	9.8	11.1	9.4	3.5

* Based on data in table 1.

The levels of P and K in NSD recycled water have no detrimental effects on vines; in fact, vines may benefit from application of these nutrients. N is required for proper growth and development of grapevines, but high levels of N can create problems due to excess growth and vigor. Vines with high vigor produce large amounts of vegetation, which takes carbohydrates and sugars away from the fruit and also shades the fruit, which in turn can lead to reduced fruit yields and lowered wine quality. Fruit produced under shaded conditions is likely to be higher in pH, lower in sugar and color, and may have herbaceous characteristics that are undesirable. In addition, high-vigor vines often have a greater incidence of Botrytis bunch rot and powdery mildew diseases.

Table 7 shows the amounts of major plant nutrients (in pounds) present in 1 ton of grapes. Assuming a typical yield of 3 to 5 tons per acre, 9 to 15 pounds of N are removed from the vineyard each year with the harvested crop. In comparison, the amount of N delivered in NSD recycled water during the 2005 season was not exceptionally high (14 to 21 pounds per acre), but it may be high enough to be of concern to some growers and winemakers, especially on sites that typically exhibit vines with vigorous growth. Many vineyards in the Carneros and MST regions are fertilized with N at rates approaching or exceeding these levels, but others are not, or they may not be fertilized with N every year. There are some vineyards that rarely (if ever) receive N additions.

Growers concerned about the additional N supplied with recycled water should consider the use of cover crops to remove the excess N. The choice of cover crop species is important: Legumes fix atmospheric N, which will increase the supply of N to vines and aggravate the problem; cereals and other grasses, which do not fix N, are best grown over the winter dormant period, because they compete with vines for water and nutrients other than N.

Our work here suggests that treated municipal wastewater from the NSD is suitable for irrigation of vineyards over the long term. There was no indication from the water quality parameters assessed that salinity, sodicity or specific ions will limit the use of the water for irrigation. Nutrients in the wastewater can be beneficial, but the N can produce excess vegetative growth in vineyards with high background soil N levels. Ingredients in personal care products and pharmaceuticals are not listed in table 1 and were not evaluated in this study. Although it is unlikely those constituents will be problematic, future research is needed to determine whether they can be accumulated by the vine and transported to fruit tissue.

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TABLE 7. Nutrients in 1 ton of grapes*

	Pounds per ton of fruit		
Nutrient	**Average**	**High**	**Low**
Nitrogen (N)	2.92	4.12	1.80
Phosphorus (P)	0.56	0.78	0.44
Potassium (K)	4.94	7.38	3.18
Calcium (Ca)	1.00	1.86	0.54
Magnesium (Mg)	0.20	0.32	0.10

* Data compiled by Larry Williams, Dept. of Viticulture and Enology, UC Davis.

Ray Lucas

Recycled water can be a reliable source of water to growers whose supplies diminish late in the summer and during periods of extended drought. *Above*, Malbec vines at Trinitas Cellars vineyard, which has been irrigated with recycled water for over 7 years.

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Chloride levels increase after 13 years of recycled water use in the Salinas Valley

by Belinda E. Platts *and* Mark E. Grismer

The use of recycled water for agriculture is a long-term water strategy in California. A study in the 1980s in Monterey County showed recycled water increased soil salinity but not to a level unacceptable for agriculture. Most growers in the northern Salinas Valley have been using it since 1998, and yet providers of the water and many growers are concerned that the sustained use of recycled water might cause deterioration of the soil. An ongoing study, initiated in 2000, compares the changes in soil salinity between a field receiving only well water and eight fields that receive recycled water. In 13 years of data, the average soil salinity parameters at each site were highly correlated with the average water quality values of the recycled water. Soil salinity did increase, though not deleteriously. Of most concern was the accumulation of chloride at four of the sites, to levels above the critical threshold values for chloride-sensitive crops.

MCWRP

A study started in 2000 is evaluating possible long-term effects of using various levels of recycled water to irrigate Monterey County strawberry and vegetable fields.

In 1987, *California Agriculture* described a 5-year study (from 1980 to 1985) evaluating the effects of recycled water use on soil salinity and the quality of cool-season vegetables at one location in the Salinas Valley (Engineering-Science 1987). The Monterey Wastewater Reclamation Study for Agriculture (MWRSA) concluded that soil salinity increased with the use of recycled water for irrigation, but no deleterious effects on crop production were observed. The water was delivered by the Monterey Regional Water Pollution Control Agency (MRWPCA), and the study location was in the Monterey County Water Recycling Projects (MCWRP) area.

As in all irrigated agriculture, increased soil salinity was expected (Richards 1969), and, at the end of the study, concentrations of chloride (Cl), calcium (Ca), magnesium (Mg) and sodium (Na), and the sodium adsorption ratio (SAR) were consistently higher in the soils irrigated with recycled water than in the soils irrigated with well water (Engineering-Science 1987). It was concluded that the higher values were in an acceptable range for agriculture (Oster and Rhoades 1985). Since the study found no differences in soil permeability due to the higher salinities, it appeared that long-term use would not be deleterious to the soils or require mitigation measures.

The recycled water in the MWRSA had an SAR value of 5.58, containing 8.35 meq/L (milliequivalents per liter) of Na and 7.03 meq/L of Cl, and an electrical conductivity (EC_w) of 1.4 (Engineering-Science 1987). These values were higher than what was considered optimal (table 1). Na concentrations were greater in the shallow soil profiles (1 to 12 inches) than in deeper soil profiles (Burau et al. 1987). In contrast, long-term salinity research indicates that soil salinity is usually greater in the deeper soil profile, because crops take up salts in the shallow soil profile, and irrigation and rainfall leach salts out of the root zone into the lower soil profiles (Rhoades et al. 1992).

In the fall of 1999, after two full seasons of irrigation with the recycled water, some growers in the MCWRP area observed significant increases in soil salinity. The Water Quality and Operations Committee of the MCWRP, a collaborative grower and agency committee, recommended that the agency evaluate the potential problem with salts. A Salt Reduction, Monitoring and Mitigation Plan for the MCWRP was developed that included a long-term soil salinity study (Sheikh et al. 2000). This ongoing study,

TABLE 1. Optimal general agriculture and average recycled water quality values, 2000–2012

Parameter	Optimal	Average recycled water
SAR	< 4.4	4.94
Na (meq/L)	< 5.0	7.64
Cl (meq/L)	< 7.0	7.36
EC_w (dS/m)	< 1.0	1.62

Source: Ayers and Westcot 1985.

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v068n03p68&fulltext=yes

doi: 10.3733/ca.v068n03p68

started in 2000, is evaluating the possible long-term effects from use of varying levels of recycled water (tertiary-treated wastewater) in Monterey County on soil salinity and cool-season vegetable and strawberry production.

The soils in the study area contain relatively high levels of Ca and Mg, but growers also add amendments of these elements to maintain SAR levels that ensure adequate soil permeability (infiltration) due to the high clay content of the soils. The use of recycled water with moderate salt content should not be deleterious to crop production provided there is adequate leaching of the salts out of the root zone from excess irrigation and winter rainfall. However, there is little, if any, long-term assessment of possible adverse soil impacts from recycled water use on salt-sensitive crops grown in coastal California climates.

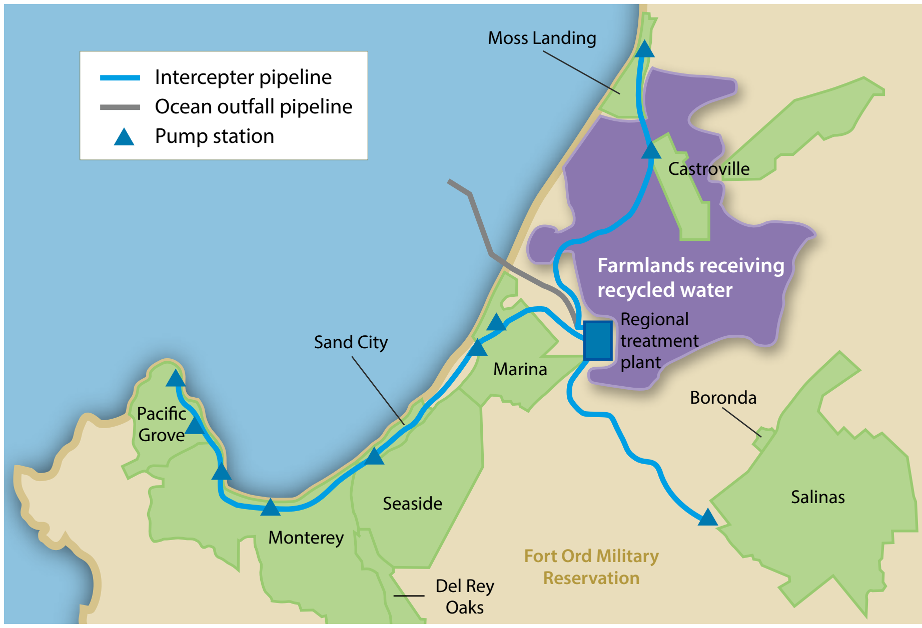
This paper presents the data from 2000 to 2012 on factors associated with salinity, and a second paper (Platts and Grismer 2014; page 75, this issue) presents an analysis of the soil hydrology processes behind the salinity data at the test sites.

Water and soil sampling, analysis

Water sampling was conducted throughout the recycled water delivery system as a standard MCWRP monitoring procedure required by permit. For the soil salinity study, the agency added irrigation water quality tests to the monitoring program. First, the undiluted recycled water (MRWPCA's tertiary effluent) was sampled on a weekly basis to determine the levels of salt present in it before blending with the supplemental well water supplied within the distribution system to meet peak irrigation demand. Second, monthly delivery system sampling confirmed the quality of the water received by growers after dilution with supplemental well water. In addition, the quality of the well water delivered to the control site was sampled monthly. These data were used to calculate the annual average quality of water delivered to each site in the study. The water samples were analyzed for pH, EC_w, Na, Mg, Cl and K (potassium) by an accredited laboratory run by MRWPCA.

The one control and eight test sites were randomly distributed throughout the area and were chosen based on soil characteristics, drainage systems, types of crops grown (lettuce, cole crops and strawberries), irrigation method and farming practices. The sites had Pacheco clay, clay-loam and sandy loam soils (USDA Soil Conservation Service 1978) and subsurface tile drainage systems, and had been irrigated with recycled water since 1998.

At each site, soil samples were collected from depths of 1 to 12 inches, 12 to 24 inches and 24 to 36 inches at four different locations within 3 feet of a designated global positioning system (GPS) point. Generally, two lettuce or cole crops per year are grown in the region, with plantings often in early spring and a short



One control and eight test sites in the Monterey County Water Recycling Projects (MCWRP) area were chosen for the study. The control received only well water.

TABLE 2. Average applied water quality at treatment plant and field sites, 2000–2012

Location	% of recycled water	SAR	Na (meq/L)	Cl (meq/L)	EC_w (dS/m)
WWTP*	100	4.94	7.60	7.40	1.62
2000–2009†					
Control	0	1.97	2.54	1.85	0.63
Site 1	69	3.42	5.27	5.09	1.13
Site 2	46	2.28	3.51	3.39	0.75
Site 3	94	4.62	7.11	6.88	1.52
Site 4	58	2.86	4.40	4.25	0.94
Site 5	93	4.60	7.09	6.85	1.51
Site 6	70	3.46	5.34	5.14	1.14
Site 7	96	4.73	7.29	7.05	1.56
Site 8	87	4.37	6.60	6.37	1.41
2010–2012‡					
Control	0	2.44	3.17	2.30	0.78
Site 2	92	3.87	5.81	5.55	1.12
Site 3	98	4.03	6.19	6.25	1.19
Site 4	96	4.13	6.06	6.35	1.17
Site 5	100	4.21	6.38	6.58	1.21
Site 6	90	3.81	5.71	5.72	1.09
Site 7	96	4.02	6.03	6.06	1.17

* WWTP = wastewater treatment plant, average of weekly recycled water concentrations.
† Water quality based on recycled water diluted with supplemental well water.
‡ Water quality based on recycled water diluted with water diverted from Salinas River.

fallow period in midsummer followed by a second planting. Strawberries are grown once every several years, and during the study period were generally planted in October or November and removed about one year later. Efforts were made to obtain comparable data from year to year by collecting soil samples at three specific times in the production cycle: (1) following winter rains and prior to spring planting, (2) mid–growing season, after harvest of the first crop and (3) at the end of the growing season, after the second crop and before winter rains. However, in most cases, deep percolation (root zone leaching) occurred between soil sampling dates due to the amount of irrigation water used.

Soil samples at the four locations at each site were composited by soil depth. Sample analysis was done by an independent accredited lab (Valley Tech, Tulare, CA) and included pH, electrical conductivity (EC_e), extractable cations B (boron), Ca, Mg, Na, and K, and extractable anions Cl, NO_3 (nitrate) and SO_4 (sulphate). The results from the three sampling dates at each site were averaged to summarize the salinity level for each site for each year.

Applied water quality

On an annual basis, the MRWPCA water recycling facility provides 65% of the water delivered to growers in the area, and supplemental well water makes up the remaining 35%. The supplemental wells are distributed throughout the MCWRP area, and the water is added to the system when irrigation demand is greater than MRWPCA's recycled water production. Applied water at two test sites (2 and 4, with 46% and 58% recycled water, respectively) had optimal values for SAR, Na, Cl and EC_w (table 2). Applied water at three test sites (1, 6 and 8, with higher percentages of recycled water) had intermediate water quality values.

Applied water at three sites (3, 5 and 7) was fairly undiluted recycled water and had the highest levels of SAR, Na, Cl and EC_w. Note that in the most recent 3-year period, 2010 to 2012, fractions of recycled water used at sites 2, 4 and 6 all increased due to the addition of another supplemental water source (Salinas River), resulting in higher levels of SAR and related salt concentrations. The weekly Na monitoring data for each site was used to calculate the annual average Na values for the applied water at the field sites.

Salinity data

Figures 1 to 4 illustrate the variation in soil EC, Na, Cl and SAR at the sites from 2000 to 2012. Note that in the most recent 3 years, as a result of the increased salinity of the applied water, soil salinity

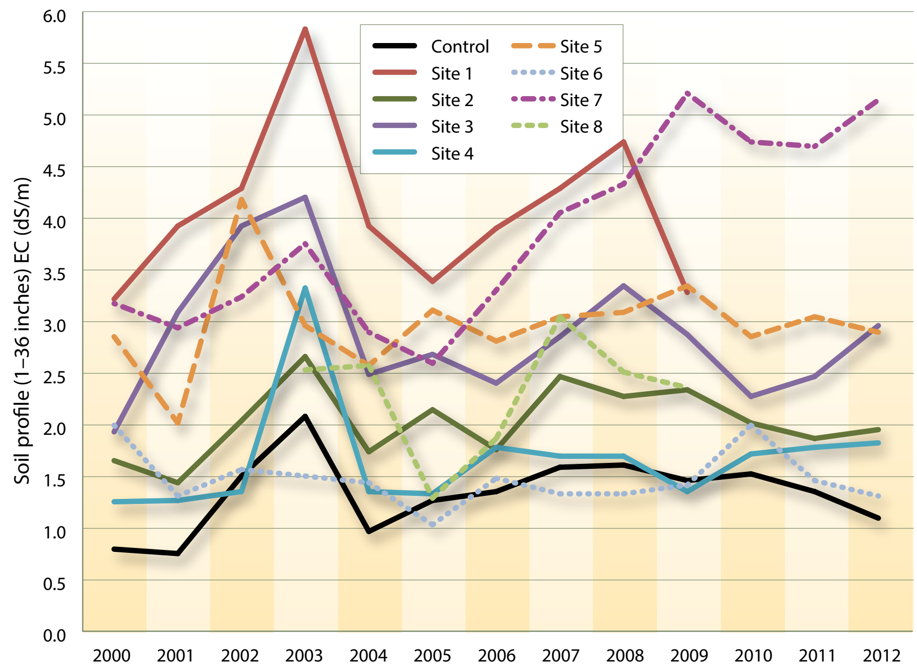


Fig. 1. Variation in soil profile EC during study period.

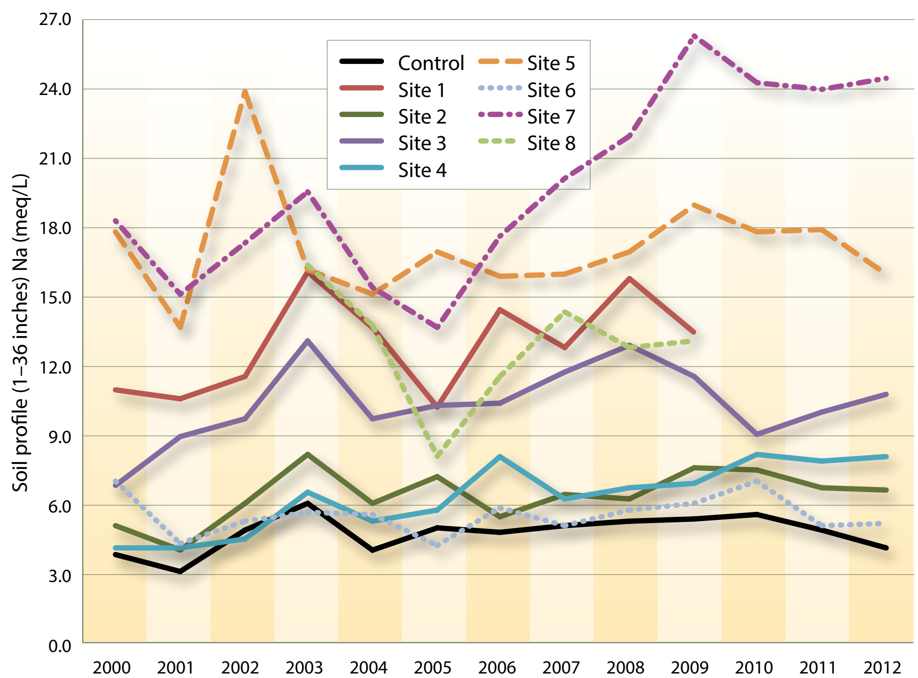


Fig. 2. Variation in soil profile Na during study period.

The recycling facility provides 65% of the water delivered to growers in the MCWRP area.

parameters increased at sites 2 and 4. Otherwise, with the exception of site 7, the soil salinity parameters show a fluctuation about a relatively constant value that is likely associated with the salinity of applied water.

Statistically, the whole profile (1 to 36 inches) and each subprofile (e.g., 1 to 12 inches, data not shown) means for the soil salinity parameters (EC, Na, Cl and SAR) were significantly greater ($p < 0.01$) for the test sites than the control site with the exception of sites 2, 4 and 6 and the SAR values at one soil depth (1 to 12 inches) at site 3. Though not significantly greater, mean soil salinity parameters at sites 2, 4 and 6 were greater nonetheless. Sites 1 and 7, and to a lesser degree site 5, had larger soil EC, Na and Cl values than the other sites, which may be related to unquantified factors including irrigation water quality prior to delivery of recycled water.

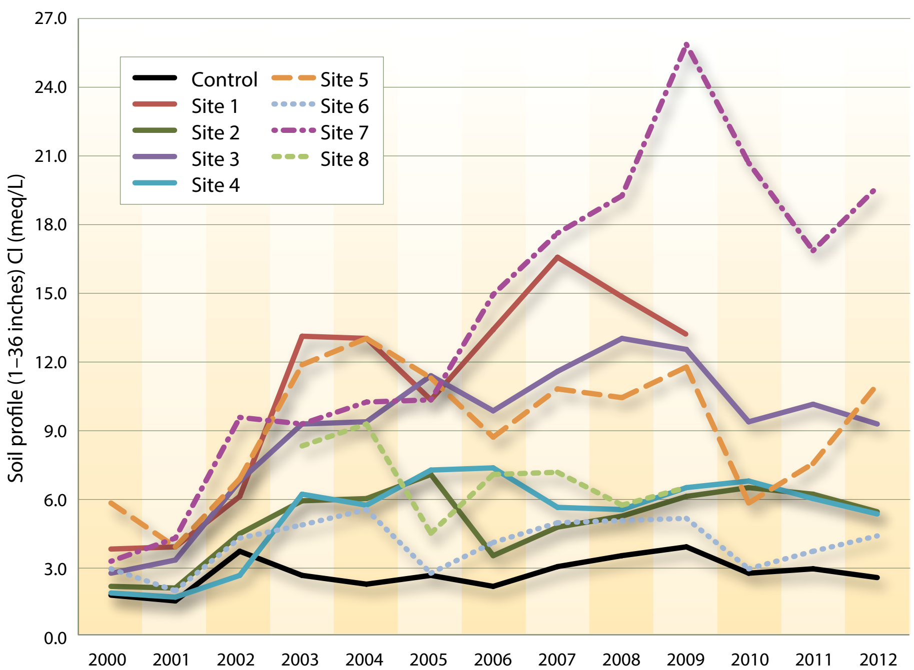


Fig. 3. Variation in soil profile Cl during study period.

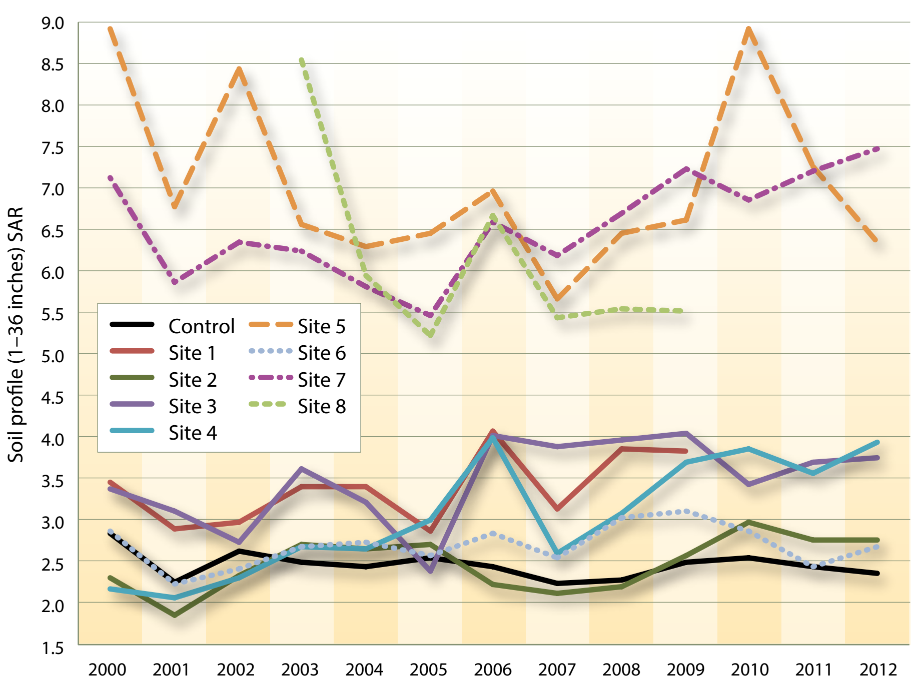


Fig. 4. Variation in soil profile SAR during study period.

Overall, soil EC, Na and Cl increased at site 7, while only soil Cl accumulated at site 1. The greatest SAR values were generally at a depth of 24 to 36 inches at all sites (data not shown), suggesting that salts were generally leaching from the root zone deeper into the soil profile. SAR values increased at site 4 following the change in the quality of the applied water. The soil Ca, Mg and SAR values are not as well correlated with the percentage of recycled water, as these are highly influenced by grower amendment practices.

With the exception of sites 5, 7 and 8, the average site soil profile SAR values, which ranged from roughly 2 to 4, suggest that the Ca and Mg ions balancing the Na ions are at satisfactory concentrations, and therefore soil infiltration problems are not anticipated at these sites. However, in the shallow root zone (1 to 12 inches) at the control site and sites 2, 4 and 6, the EC_e was 1.5 to 2.0 dS/m (deciSiemens per meter; data not shown), suggesting possible yield losses with lettuce and strawberries, though this is an acceptable level for celery; while at sites 5 and 8, values of EC_e between 2.5 and 3.0 dS/m remained acceptable for artichokes, broccoli, cauliflower and rapini. The EC_e values of about 4 dS/m found at sites 1 and 7 are just below the threshold yield loss for less-salt-sensitive artichokes (Grieve et al. 2012). While the EC data indicates that decreases in yield are possible based on total salt load, Cl concentrations remained below yield loss thresholds specific to Cl sensitivity for all crops grown in the region at seven of the sites (excluding site 7).

Growers in the project area annually test their soils and make planting decisions based on this data. For example, a grower with fields testing above the recommended Cl threshold for strawberries will not plant strawberries in those fields. In addition, fields that tend to have higher salinity levels for the second vegetable planting of the season will be planted with a more-salt-tolerant vegetable crop. This soil-testing strategy has prevented any significant yield losses during the study (no significant yield losses have been reported to or observed by MRWPCA during the study). In addition, actual yields are highly influenced by market conditions, which were quite variable during the study period; poor market prices result in the growers leaving a certain amount of product unharvested in the field.

Statistical analysis

A key agronomic concern is the relationship between applied water salinity, the resulting soil salinity and its potential adverse impacts on crop yields. Figures 1 to 4 clearly demonstrate the variability of soil salinity between sites and over time. In contrast, figures 5 to 8 illustrate the dependence of average soil salinity parameters regardless of site on applied water salinity parameters during the periods 2000 to 2009 and 2010 to 2012.

As anticipated, increased applied water EC_w resulted in greater soil EC, particularly in the shallow (1 to 12 inches) portion of the soil profile. While the individual depth interval linear regression slopes did not differ significantly, the soil profile EC_e was significantly correlated with the applied water EC, and the slope shown in figure 5 was significant (CL = confidence level). The linear regression slope indicates that the root zone soil EC averages were about twice those of the applied water EC_W. However, the shallow soil (1 to 12 inches) EC was only about 7% greater than that deeper in the soil profile (12 to 36 inches).

Compared with EC, soil Na, Cl and SAR values showed much less dependence on applied water values up to thresholds of approximately 5.5 meq/L for Na (fig. 6) and Cl (fig. 7) and about 4 for SAR (fig. 8). At applied water values greater than these, soil Na, Cl and SAR values increased dramatically, though with considerable variability. When applied water values for Na, Cl and SAR were below the thresholds, soil values were equivalent to the values of the applied water, suggesting the applied water was leaching through the profile. Leaching of Na deeper into the soil is evident from the increasing linear regression slopes (not shown), with soil Na ranging from approximately four times that of the applied water Na at 1 to 12 inches, to five times at 12 to 24 inches and more than

A key agronomic concern is the relationship between applied water salinity, the resulting soil salinity and its potential adverse impacts on crop yields.

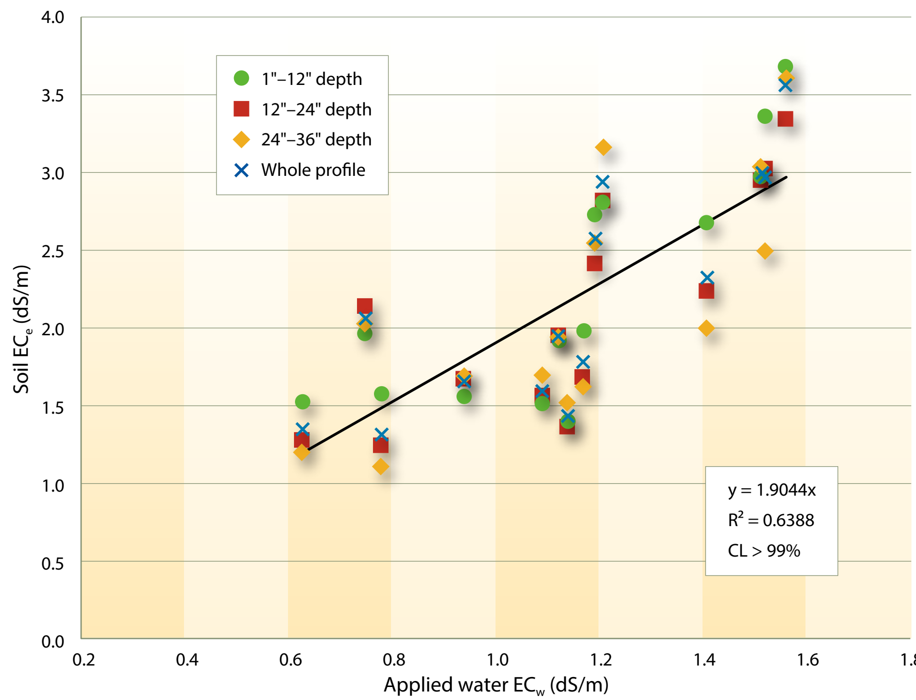


Fig. 5. Dependence of soil EC_e on applied water EC_w during study period.

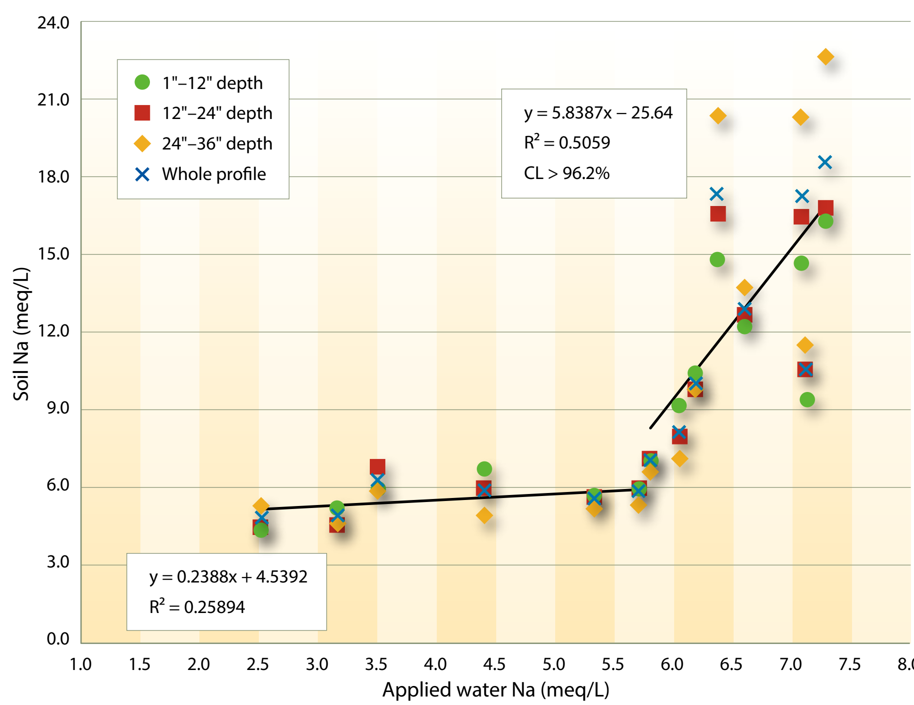


Fig. 6. Dependence of soil Na on applied water Na during study period.

Recycled water was sampled at the treatment plant and at delivery to growers' fields.

eight times at 24 to 36 inches, and averaging nearly six times for the soil profile as a whole.

Not surprisingly, the dependence of soil Cl on applied water Cl shows a similar relationship to that of Na (fig. 7), though the increases in soil Cl at applied water values greater than about 5.5 meq/L across the soil subprofiles are less than those for Na. This likely reflects the greater mobility of Cl in the soil compared to Na. It is of major concern that at applied water Cl values more than 5.5 meq/L, soil Cl concentrations increased across all depths.

Soil SAR values roughly match those of the applied water SAR values up to about 4, after which soil SAR values are about 1.5 times greater than the values of the applied water, though the correlation of soil SAR and applied water SAR was less than significant (CL < 95%).

These results indicate that the effect of the quality of applied water on soil salinity is dependent on the level of salts present in the applied water. It is important to note that there may be other factors responsible for the variation in soil salinity parameter values, including growers' use of soil amendments, and the combined effects of applied water and winter rainfall leaching must be considered. A second paper in this issue contains an analysis of the data from the perspective of soil water balance and addresses these effects (Platts and Grismer 2014, page 75).

Accumulation of chloride

As competition for water supplies intensifies and associated sea water intrusion affects the use of well water in coastal California areas, the long-term effects on soil salinity from use of recycled water are important to investigate. Our primary objective was to quantify the changes in salinity in Monterey County fields under intensive production and determine whether the long-term use of recycled water there has been deleterious to the types of soils in the area.

Our analysis of study data from 2000 to 2012 supports the general conclusions of the MWRSA in the 1980s: The use of recycled water has caused an increase in soil salinity in the area; however, SAR values are not deleterious and Na has shown little accumulation in the rooting zone (1 to 12 inches).

UC Cooperative Extension Centennial

Can irrigation with municipal wastewater conserve energy?

Water conservation and energy costs were concerns 35 years ago, just as they are today. This study looked at whether reuse of wastewater on farmland would require less energy than discharging it to the ocean. If so, would it require more or less energy than importing fresh water for irrigation? In 1977, the energy costs came out about even. Would today's energy costs and irrigation/wastewater technologies yield a different result?

1977 "Approximately 80 percent of the potential for reclamation in California is in basins where wastewater is being discharged to brackish or saline water — mainly the Pacific Ocean.

"One of the expected benefits of wastewater reuse is energy savings in those situations where reuse is an alternative to importation of fresh water. . . . . Two important questions, then, are: (1) Would reuse of wastewater on farmland require less energy than discharge to the ocean? (2) If so, would it require more or less energy than importation of fresh water for irrigation?

"Municipal wastewater discharged to the Pacific Ocean requires considerable energy for secondary treatment (biological oxidation and assimilation of organic matter) and pumping through a long ocean outfall. Since wastewater reused for irrigation of fodder, fiber, and seed crops requires only primary treatment (screening and settling processes), each acre-foot reused could save about 200 KWH in direct energy requirements — compared to ocean disposal — by eliminating the secondary treatment and ocean outfall pumping.

"Under current health regulations wastewater reused for pasture irrigation and surface irrigation of food crops requires secondary treatment. Therefore reuse instead of ocean disposal would save only the approximately 50 KWH otherwise required for outfall pumping. Wastewater reused for sprinkler irrigation of food crops requires secondary treatment plus chemical coagulation and filtration. Such reuse would require slightly more direct energy — possibly 10 KWH/AF — than ocean disposal of the wastewater.

"When only these direct energy requirements are considered, it appears that irrigation with wastewater could save very large amounts of energy compared with importing fresh water. However, elevation and quality differences tend to offset the benefits."

Roberts EB, Hagan RM. 1977. Energy: Can irrigation with municipal wastewater conserve energy? Calif Agr 31(5):45.

Robert Hagan served the UC Davis community as professor of water science from 1948 until his retirement in 1987. In addition to his expertise on agricultural water use under arid conditions, Hagan sought to increase constructive communication between growers and environmental groups on issues of water and resource use. The UC Davis Robert M. Hagan Endowed Chair in Water Management and Policy was established in his honor.

Co-author Edwin B. Roberts served as a staff research associate at UC Davis, working with Professor Hagan.

—W. J. Coats

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Although MRWPCA has worked to reduce the levels of Na and Cl in the water delivered to growers, there has been accumulation of Cl and increased EC_e values in the soil profile that were not documented during the earlier study. It appears that winter rainfall has been inadequate to leach out the Cl and reduce EC_e. This accumulation of Cl needs to be mitigated in order for growers to continue producing high yields of chloride-sensitive crops such as strawberries and leafy greens. Mitigation options include eliminating amendments that contain Cl, increasing the leaching fraction and improving drainage. Given that using recycled water is an important water strategy in California, further research may be needed to determine the cause of the Cl accumulation and to develop effective mitigation strategies when recycled water is used to grow chloride- and salt-sensitive crops.

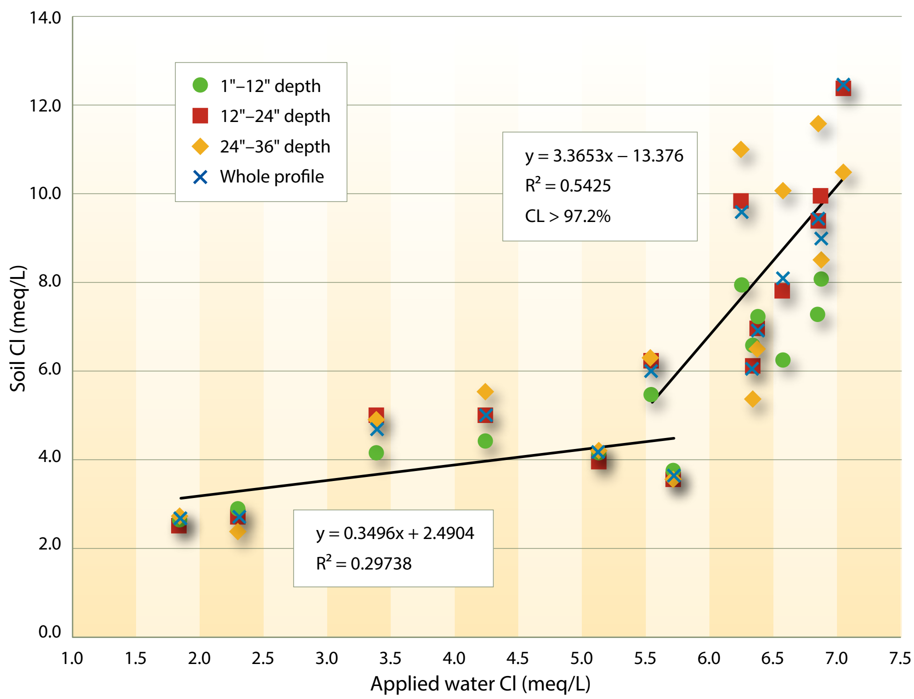

Fig. 7. Dependence of soil Cl on applied water Cl during study period.

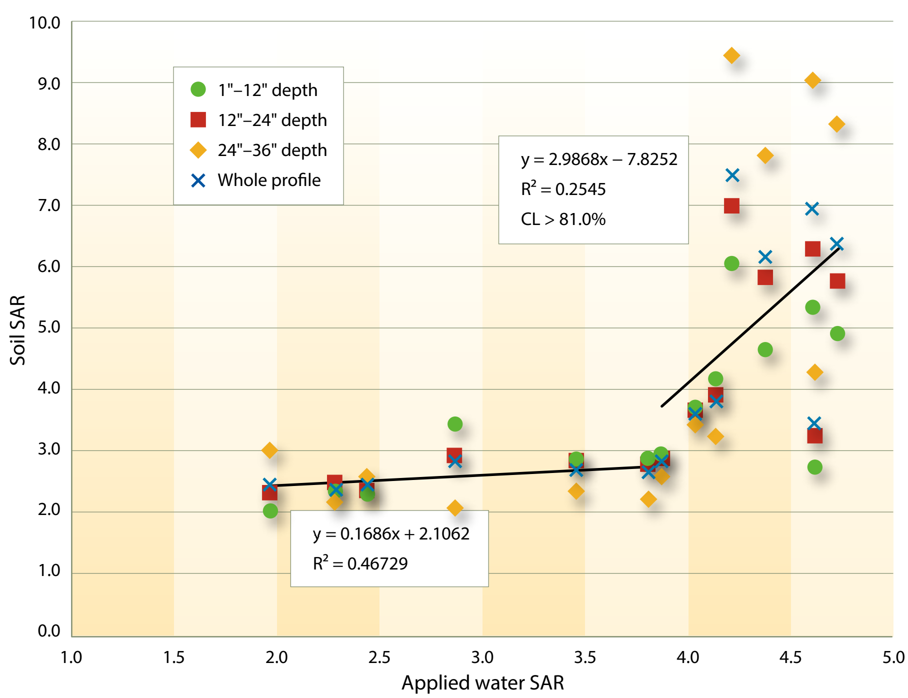

Fig. 8. Dependence of soil SAR on applied water SAR during study period.

B.E. Platts is Agricultural Consultant, Monterey Regional Water Pollution Control Agency (MRWPCA); and M.E. Grismer is Professor of Hydrologic Science and Biological and Agricultural Engineering, Department of Land, Air and Water Resources, UC Davis.

Monterey County Water Resources Agency (MCWRA) has voluntarily funded the research. We acknowledge the support of MRWPCA personnel and growers within the MCWRP area. William Franks and Jesse Chacon of MRWPCA diligently collected the soil and water samples every year. Patrice Parsons and Bob Holden of MRWPCA have been instrumental in providing water quality data and reviewing the data annually. The grower representatives on the Water Quality and Operations Committee have provided the sampling sites and a high level of interest in this research.

California Agriculture *thanks Guest Associate Editor Stephen R. Grattan for his work on this article.*

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Rainfall leaching is critical for long-term use of recycled water in the Salinas Valley

by Belinda E. Platts *and* Mark E. Grismer

In 1998, Monterey County Water Recycling Projects began delivering water to 12,000 acres in the northern Salinas Valley. Two years later, an ongoing study began assessing the effects of the recycled water on soil salinity. Eight sites are receiving recycled water and a control site is receiving only well water. In data collected from 2000 to 2012, soil salinity of the 36-inch-deep profile was on average approximately double that of the applied water, suggesting significant leaching from applied water (irrigation) or rainfall. In this study, we investigated some of the soil water hydrology factors possibly controlling the soil salinity results. Using soil water balance modeling, we found that rainfall had more effect on soil salinity than did leaching from irrigation. Increasing applied water usually only correlated significantly with soil salinity parameters in the shallow soil profile (1 to 12 inches depth) and at 24 to 36 inches at sites receiving fairly undiluted recycled water. Winter rains, though, had a critical effect. Increasing rainfall depths were significantly correlated with decreasing soil salinity of the shallow soil at all test sites, though this effect also diminished with increased soil depth. When applied water had high salinity levels, winter rainfall in this area was inadequate to prevent soil salinity from increasing.

In a study of Salinas Valley fields irrigated with recycled wastewater, researchers found that rainfall leaching is an important factor in maintaining satisfactory root zone salinity levels for salt-sensitive crops such as lettuce and strawberries.

Using recycled wastewater for agriculture and landscaping has environmental benefits because it limits the wastewater discharge into natural waterways while helping to preserve the supply of potable water for human consumption. Recycled water (tertiary-treated wastewater) has been used by a majority of growers in the Monterey County Water Recycling Projects (MCWRP) Salinas Valley area since 1998. An ongoing study, initiated in 2000, is comparing the changes in soil salinity between a field that has received only well water and eight field sites in the MCWRP area that have received recycled water since 1998. Each test site uses a specific blend of recycled water (the fraction ranges from 40% to 90%) and well water for irrigation, allowing assessment of the relative impacts of the water quality on soil salinity parameters.

Recently, a feasibility study of the use of recycled water for vineyard irrigation in the Carneros and Milliken-Sarco-Tulocay (MST) regions near Napa indicated that leaching by winter rains averaging more than 20 inches a year was sufficient to maintain soil salinity, sodium (Na) and chloride (Cl) levels within acceptable ranges for grape production (Weber et al. 2014; page 59, this issue). Winter rainfall is about 13 inches a year in the MCWRP area, and our goal in this study was to ascertain the effectiveness of irrigation leaching compared with rainfall leaching.

Overall, the average soil salinity parameters — electrical conductivity (EC_e), Na, Cl and sodium adsorption ratio (SAR) — at the test sites were highly correlated with the average recycled water quality values, as we describe in our other article on this study (Platts and Grismer 2014; page 68, this issue). At the same time, with the exception of two sites (1 and 7), average soil salinity parameter values remained roughly constant from one year to the next, suggesting the possibility of relatively steady-state leaching of the soil profile to a depth of 36 inches (i.e., on an annual basis the amount of salt added with irrigation is roughly equal to the amount leaving the bottom of the root zone).

Assuming that strawberry production is the most sensitive to soil Cl concentrations, the irrigation leaching requirement predicted from an annual salt balance consideration using the fairly undiluted recycled water (Cl at 7 meq/L [milliequivalents per liter]) for irrigation would be about 23% as compared to about 5% for well water with Cl at about 1.5 meq/L. However, it was not clear from initial water quality analyses whether the differences in soil salinity parameters between the periods 2000–2009 and 2010–2012 were the result of irrigation alone, irrigation and rainfall, or rainfall alone.

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v068n03p75&fulltext=yes
doi: 10.3733/ca.v068n03p75

Distinguishing the soil water hydrologic factors controlling this apparent steady-state leaching situation (Grismer 1990) is critical for developing long-term sustainable recycled water use strategies in the region. To this end, we developed a root zone soil water balance model to determine the deep percolation from applied water (irrigation) and rainfall between soil sampling dates for comparison with changes in soil profile salinity parameters that occurred at the control and test sites.

Root zone leaching processes

For equivalent soil conditions, use of soil amendments and atmospheric dry deposition rates, the root zone salinity of irrigated soils largely depends on the applied water quality (salinity), frequency and duration of irrigation, evapotranspiration (ET) and rainfall depths, presuming adequate root zone drainage. Of course, irrigation usually occurs during the periods of the year with greater ET, resulting in a concentration of applied water salinity in the root zone through evaporation and transpiration processes. Irrigations at depths greater than that necessary to meet crop water demands generally occur either because of application inefficiency or for the purpose of leaching the root zone of accumulated salinity.

Generally, the salinity of rainwater is less than that of applied water, and in California deep percolation and leaching of root zone salinity occur during the winter rainy season, when ET rates are generally low. As a result, when there is sufficient rainwater displacement of concentrated applied water in the root zone, a greater decrease in root zone salinity per unit depth of rain is expected than that which would occur from the application of the same depth of more-saline applied water. Management of applied water and rainfall leaching of the soil root zone salinity is especially critical when growing salt-sensitive, high-value crops such as strawberries and leafy greens in the Salinas Valley.

Soil water balance modeling

With knowledge of the crop type, planting and harvest dates, soil type, typical applied water depths and local reference ET and rainfall, a daily root zone water balance can be developed to compute daily irrigation requirements as well as deep percolation (root zone drainage) depths. Water balances have been used to estimate deep percolation rates from desert alfalfa hay production (Bali et al. 2001; Grismer 2012) and from Sonoma County wine grape production (Grismer and Asato 2012) and also to corroborate field-measured soil profile drainage rates for avocado and citrus orchards on the central California coast (Grismer et al. 2000).

Grismer and Asato (2012) provide a detailed description of the general root zone water balance methods that were used here. However, we determined crop water use for the crops grown in the MCWRP region differently because water use changes daily as the crop grows. Water use by artichokes, strawberries, lettuce and cole (broccoli, cauliflower and rapini) crops depends on the relative canopy coverage of the crop, which in turn depends on the overall seasonal reference ET available to grow the crop. For our calculations, we used modified crop coefficient functions that depend on seasonal reference ET, and thus canopy coverage, originally developed by Gallardo et al. (1996), Grattan et al. (1998) and Hanson and Bendixen (2004) for the Salinas Valley region. From the crop season total reference ET and the canopy coverage functions, a daily increasing crop coefficient was determined and used to reduce reference ET to that of the crop ET. Daily rainfall and reference ET for the years 2000 to 2012 were taken as the average of the values from the three California

TABLE 1. Crops and planting schedules at two sites, 2000–2012

	Control site		Site 6	
Year	**Crop**	**Plant date, harvest date**	**Crop**	**Plant date, harvest date**
2000	Lettuce	4/1, 6/14	Lettuce	4/20, 6/28
	Broccoli	7/15, 10/21	Broccoli	7/20, 10/20
2001	Lettuce	5/13, 7/20	Lettuce	4/7, 6/20
	Lettuce	8/15, 10/20	Cauliflower	7/6, 10/19
2002	Lettuce	5/23, 7/28	Lettuce	4/12, 6/25
	Lettuce	8/22, 10/31	Lettuce	7/12, 9/20
2003	Cabbage	4/15, 7/22	Broccoli	4/10, 7/7
	Lettuce	8/24, 11/7	Celery	7/21, 10/25
2004	Lettuce	5/1, 7/10	Lettuce	3/17, 5/30
	Broccoli	8/20, 12/5	Cauliflower	6/15, 9/20
2005	Lettuce	4/3, 6/15	Lettuce	3/29, 6/12
	Cauliflower	7/15, 10/21	Lettuce	6/29, 9/4
2006	Lettuce	5/10, 7/18	Lettuce	4/13, 6/20
	Lettuce	8/10, 10/27	Broccoli	7/12, 10/15
2007	Cauliflower	11/20, 4/7	Cauliflower	1/30, 5/15
	Lettuce	6/10, 8/15	Lettuce	6/2, 8/7
2008	Lettuce	3/15, 6/8	Strawberries	11/1/2007, 10/24/2008
	Lettuce	7/4, 9/15		
2009	Lettuce	4/7, 6/22	Lettuce	4/3, 6/15
	Broccoli	7/22, 10/28	Lettuce	7/4, 9/11
2010	Lettuce	3/19, 6/5	Lettuce	1/2, 4/20
	Cauliflower	6/26, 9/28	Celery	5/15, 8/16
2011	Lettuce	5/4, 7/12	Cauliflower	3/14, 6/12
	Lettuce	8/5, 10/18	Lettuce	7/10, 9/18
2012	Broccoli	2/17, 6/6	Strawberries	11/20/2011, 10/15/2012
	Lettuce	6/30, 9/6		

Department of Water Resources CIMIS stations (Watsonville, Castroville and N. Salinas) in the study region.

As described in our companion paper (Platts and Grismer 2014; page 68), the salinity study involved a control site and eight test sites that had similar soil characteristics, drainage systems, types of crops grown (lettuce, cole crops and strawberries), irrigation method and farming practices. Table 1 presents cropping schedules from the control site and site 6, which are representative of the study sites. Generally, growers followed the management practices described in UC ANR Publications 7211 and 7216 (LeStrange et al. 2011; Smith et al. 2011), with three or four early-season sprinkler irrigations to establish the crops, followed by drip, furrow or additional sprinkler irrigations necessary to bring the crops to harvest.

In our root zone soil water balance modeling, an average 2.0 inches (5.1 centimeters) of water was applied when irrigation was needed to replenish root zone soil moisture levels necessary to meet crop water demands. Rainfall was assumed to be 60% effective as infiltration, and after the three or four initial planting irrigations, additional irrigations were triggered when soil moisture storage declined to less than half of capacity. A 2-inch water application depth is typical of the sprinkler systems used in the region, is greater than that from drip systems, and less than that from furrow irrigation systems. Our seasonal applied water depths ranged toward the low end of those reported for the region (Cahn et al. 2011; M. Cahn, UC Cooperative Extension Monterey County, personal communication) and, as is discussed below, most of the irrigation season deep percolation occurred as a result of the early-season irrigations used to establish the crop. Excess applied water or rainfall beyond that necessary to refill soil root zone water-holding capacity and meet daily crop ET was assumed to become deep percolation, or drainage, from the root zone.

Water and soil sampling, analysis

The recycled water (tertiary effluent from Monterey Regional Water Pollution Control Agency, MRWPCA) was sampled on a weekly basis to determine the levels of salt present in it before blending with the supplemental well water used to meet peak irrigation demand. Monthly delivery system sampling confirmed the quality of the water received by growers after supplemental well water was added to the recycled water. In addition, the quality of the well water delivered to the control site was sampled monthly. The water samples were analyzed for pH, EC_w, Na, Mg, Cl and K (potassium) by an accredited laboratory run by MRWPCA.

The sites had Pacheco clay, clay-loam and sandy loam soils and subsurface tile drainage systems. At each site, soil

Improved Leaching Practices SAVE WATER, REDUCE DRAINAGE PROBLEMS

This 1962 article from the *California Agriculture* archives demonstrated that intermittent water applications—in the form of rainfall or sprinkler irrigation—leach unwanted or excess minerals from the topsoil much more effectively than the more-common ponded or flood applications.

Early research on improved leaching practices

1962 "Field studies conducted at Tule Lake provide striking evidence that ponding water is not always an efficient method of leaching. In some plots, as much as 6 acre-ft. of water per foot of soil depth was applied, yet the soil salinity was not reduced below one half of the original amount present. Of the six feet of water applied, the first one-half foot was responsible for the leaching obtained.

"During the winter months, 4 inches of rainfall was recorded. In this case the soil salinity was reduced by one half again, yet the quantity of water involved was 18 times less. Irrigation techniques can also be used to produce similar results. Reasons for these effects involve consideration of the structure of the soil and the variation in the pore velocity. Similar results have been found in other parts of the world. Reclamation of soils inundated by the sea in the Netherlands flood disaster of 1953 was more efficiently carried out by rainfall than by ponding."

Biggar JW, Nielsen DR. 1962. Improved leaching practices save water, reduce drainage problems. Calif Agr 16(3):5.

James W. Biggar was assistant irrigationist, Department of Irrigation, at UC Davis when this article was published in 1962. By the time of his retirement more than 30 years later, he was professor and water scientist in the UC Davis Department of Land, Air and Water Resources. Respected worldwide among agriculture professionals and environmental advocates for his research on soil properties, irrigation and the environmental fate of agricultural chemicals, Biggar was also highly regarded as a teacher and mentor by his students and eventual colleagues.

Co-author Donald R. Nielsen was, at the time of original publication, assistant professor in the UC Davis Department of Irrigation. Today he continues his work at UC Davis as emeritus professor in the Department of Land, Air and Water Resources.

—W. J. Coats

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samples were collected from depths of 1 to 12 inches, 12 to 24 inches and 24 to 36 inches at four different locations within 3 feet of a designated global positioning system (GPS) point. Efforts were made to obtain comparable data year to year by collecting soil samples at three specific times in the production cycle: (1) following winter rains and prior to spring planting, (2) mid–growing season, after harvest of the first crop and (3) at the end of the growing season, after the second crop and before winter rains.

Soil samples at the four locations at each site were composited by soil depth. Sample analysis was done by an independent accredited lab (Valley Tech, Tulare, CA) and included pH, EC_e, extractable cations B (boron), Ca, Mg, Na and K, and extractable anions Cl, NO_3 (nitrate) and SO_4 (sulphate).

TABLE 2. Average annual hydrologic parameters associated with soil water balance calculations at the control site and eight test sites, 2000–2012

		Irrigation season			Non–irrigation season	
Location	Years monitored	Rain	AW*	AW DP†	Rain	Pre–spring planting rain DP
	no.	*inches*				
Control	13	2.91	24.31	15.76	11.60	4.55
Site 1	10‡	2.89	24.80	14.79	11.62	5.35
Site 2	13	2.83	24.00	16.77	11.68	5.42
Site 3	10‡	3.45	25.80	18.18	11.06	4.18
Site 4	13	3.01	22.15	16.75	11.50	4.99
Site 5	13	3.01	22.15	16.75	11.50	4.99
Site 6	13	4.49	25.38	18.13	10.02	4.82
Site 7	13	2.06	25.85	18.31	13.30	5.51
Site 8	7§	1.21	23.14	16.92	13.30	6.39
Average of sites 1–8		2.87	24.16	17.08	11.75	5.44

* AW = applied water.
† DP = deep percolation.
‡ Monitored from 2000 to 2009 only.
§ Monitored from 2003 to 2009 only.

Control and test site hydrology

Despite the range in crops grown across the control and test sites, the average annual applied water depths ranged only from 22 to 26 inches, with an average of about 24 inches (60 centimeters) for all years, the same for the eight sites as a whole and the control site (table 2). Similarly, applied water deep percolation during the irrigation season ranged from about 15 to 18 inches, with the average amount at the test sites a little over an inch greater than that at the control site. Average rain depths during the irrigation season were more variable, ranging from just over 1 inch to about 4.5 inches, though the average of the test sites was essentially equivalent to that of the control site. Deep percolation leaching from rain between irrigation seasons (i.e., before spring planting) was practically the same at the control site as the average amount at the test sites, about 5.4 inches. The data in table 2 underscores the relative hydrologic similarity of the test sites and the control site, suggesting that reasonable leaching comparisons can be made.

Figures 1 and 2 show the accumulated daily rainfall, applied water and deep percolation at the control site and site 6 during an average ET and rainfall year, 2009. They illustrate the soil water balance modeling processes important for the leaching of soil salinity: At both sites, rainfall recharge incurs soil water deep percolation leaching during the first 2 months of the year and to a lesser extent the last month of the year, whereas applied water recharge, primarily from early-season planting irrigations, is responsible for most of the annual deep percolation leaching during the remainder of the year.

Albert Ulrich

Toxic levels of salt cause strawberry leaf margins to turn brown and dry.

Control and test site salinity

Using daily soil water balance modeling, it was possible at each site to more precisely determine the deep percolation (leaching) from rain, irrigation or a combination of irrigation and rain that occurred between the soil sampling days in early spring, midsummer and late fall. The changes in soil salinity parameters are described in detail in our other article (Platts and Grismer 2014; page 68, in this issue). As noted there, three of the four primary salinity parameters, Na, Cl and SAR, followed a similar pattern in changes from year to year that contrasted in part with that for EC. As the pairs of parameters — Cl and EC, Na and SAR — are closely related, for brevity here we focus on changes in EC and Na concentrations at each soil depth and the hydrological processes associated with them.

In 2000, soil EC ($EC_{e)}$ and Na concentrations generally increased with increasing depth at all the sites (table 3). The values at sites 2, 3, 4 and 6 were roughly equivalent to those at the control site; at sites 1, 5, 7 and 8, values were much greater. Approximately a decade later, EC_e and Na concentrations had increased slightly in the 1 to 12 inches subprofile at the control site and sites 2, 3 and 4, while decreasing at site 6. Changes in the whole profile averages (the sum of the amounts at the three subprofiles) of EC_e and Na were mixed at the control site (i.e., there was a slight increase in EC_e and a decrease in Na) and site 4 (i.e., an increase in Na and a slight decrease in EC_e); at sites 2 and 6, EC_e and Na decreased; and at site 5, they increased slightly. At sites 3 and 7,

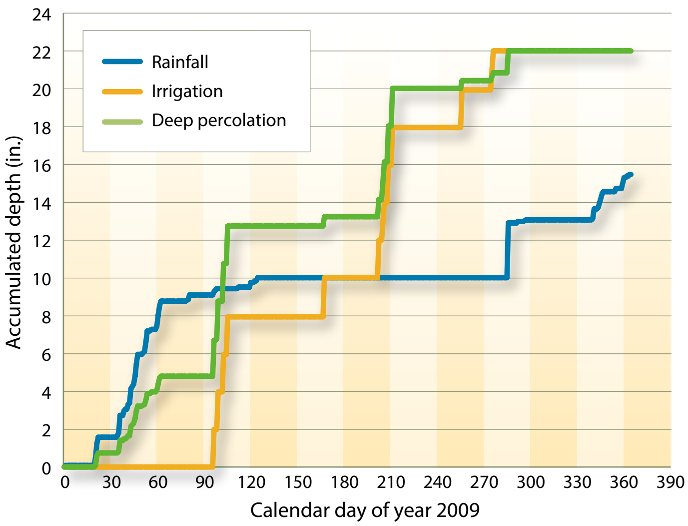

Fig. 1. Accumulated rainfall, irrigation and deep percolation depths at control site, 2009.

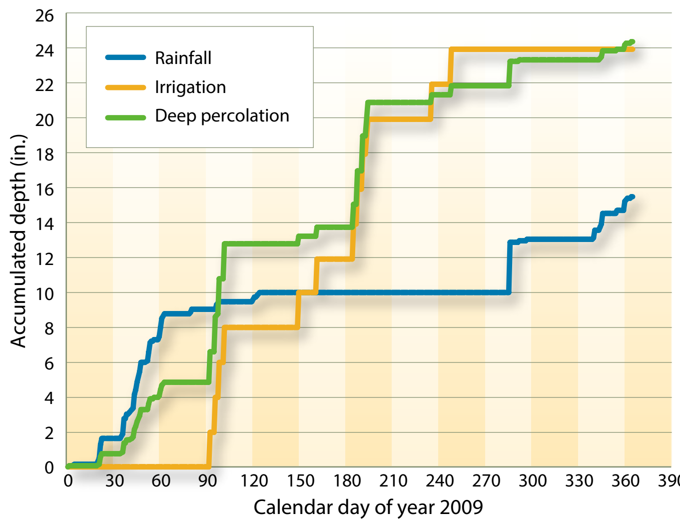

Fig. 2. Accumulated rainfall, irrigation and deep percolation depths at site 6, 2009.

TABLE 3. Hydrologic parameters associated with soil water balance modeling and changes in EC and Na levels after 7 to 13 years of monitoring

Site (no. years monitored)	AW* Total AW	AW* Recycled water fraction	AW* EC_w	AW* Na_w	AW DP†	Rain DP	Soil depth	Spring 2000 EC_e	Spring 2009 or 2012 Change in EC_e	Spring 2000 Na_e	Spring 2009 or 2012 Change in Na_e
	inches	*%*	*dS/m*	*meq/L*	*inches*	*inches*	*inches*	*dS/m*	*dS/m*	*meq/L*	*meq/L*
Control (13)	316	0	0.78	3.52	204.8	54.6	12	0.82	0.62	3.4	1.8
							24	0.87	0.14	4.4	−0.5
							36	1.00	−0.01	6.0	−1.9
Site 1 (10)	248	69	1.13	5.85	147.9	42.8	12	1.87	−0.33	6.8	−0.2
							24	2.63	0.18	10.2	0.9
							36	3.28	0.72	12.9	0.5
Site 2 (13)	312	46	1.12	5.81	218.1	65.0	12	0.80	0.36	3.7	1.2
							24	1.52	−0.34	5.7	−0.8
							36	2.53	−1.03	6.4	−0.6
Site 3 (10)	258	94	1.19	6.19	181.8	37.7	12	0.93	0.15	2.3	3.7
							24	0.77	1.98	3.5	8.7
							36	0.89	1.36	3.1	9.4
Site 4 (13)	288	58	1.17	6.06	217.8	59.8	12	1.19	0.22	5.1	2.2
							24	2.08	−0.37	5.6	2.7
							36	1.79	−0.20	4.7	3.3
Site 5 (13)	288	93	1.21	6.38	217.8	59.8	12	1.06	0.04	7.0	−0.9
							24	1.70	0.51	11.8	0.4
							36	2.27	0.89	18.2	3.0
Site 6 (13)	330	70	1.09	5.71	235.7	48.2	12	1.28	−0.32	5.9	−3.4
							24	2.07	−0.30	7.7	2.4
							36	1.97	−0.69	7.2	−7.2
Site 7 (13)	336	96	1.17	6.03	238.0	66.2	12	3.33	2.20	14.0	8.8
							24	3.97	0.24	17.3	4.1
							36	5.21	−1.54	28.3	−3.7
Site 8 (7)	162	87	1.41	7.32	118.5	44.7	12	1.37	−0.34	9.2	−3.3
							24	3.33	−0.61	22.8	−8.1
							36	2.57	−0.29	17.7	−2.8

* AW = applied water.
† DP = deep percolation.

there were relatively larger increases in EC_e and Na concentrations in the whole profile after 13 years; and at site 8, substantial decreases occurred in these values after 7 years. Generally, whole profile averages of both EC_e and Na increased.

Considering the long-term changes in salinity parameters occurring between spring soil sampling in 2000 and spring soil sampling in 2009 or 2012, we found that none of the changes in EC_e and Na concentrations at the subprofile or whole profile levels were correlated with the amount of applied water, or the applied water and rain deep percolation depths. This suggested that we needed to do a more detailed (shorter time period) analysis to distinguish differences in leaching effectiveness associated with rain or excess irrigation; the results of that analysis are described below.

Leaching of soil salinity

Using the soil water balance calculations to determine the deep percolation (leaching) from applied water or rainfall between the soil sampling dates (1 to 5 months), we did correlation analyses of the dependence of soil salinity parameter changes at each subprofile on the increasing deep percolation. Deep percolation depths from applied water or rainfall were computed at the control site and each test site at each of the three soil subprofiles, compared with measured changes in soil salinity parameters and tested for significance using the Student's t-distribution.

In many cases, both applied water and rainfall deep percolation occurred between soil sampling periods, and in the first analyses of the 108 correlations possible, 13 correlations were significant at > 95% confidence and 25 at > 90% confidence. Generally, increasing applied water deep percolation was correlated with increasing salinity (positive r value, table 4), whereas increasing rainfall deep percolation was correlated with decreasing salinity (negative r value, table 5).

In the second correlation analyses, which considered the changes in soil salinity that were associated with deep percolation from only applied water or only rainfall (i.e., no combination of both), only 66 comparisons were possible because of the limited frequency of rainfall-only events, so we pooled the rainfall-only events at all the test sites. Of the 66 possible correlations, 14 were significant at > 90%, and of these, eight were significant at > 95% confidence (table 6).

At the control site and sites 1 and 6, rainfall leaching appeared to displace salinity to the deeper soils (24 to 36 inches), where there was a slight accumulation. At the remaining sites, rainfall leaching decreased soil salinity at different depths depending on the site. Increasing applied water depths tended to increase soil salinity at the test sites, particularly at sites 3, 5 and 8, which received the fairly undiluted recycled water.

No significant correlations between soil salinity and deep percolation from applied water and/or rainfall were found at test sites 2 and 4, where the blending with well water was highest, which supports our observation in our other paper of little salinity accumulation at these sites. The greatest reductions in soil salinity per unit of rainfall deep percolation occurred at sites 5 and 8, where the greatest salinity accumulations from applied water occurred (see last column of

TABLE 4. Significant (> 90% confidence level) correlation statistics between changes in soil salinity parameters and associated applied water deep percolation from all data after 7 to 13 years of monitoring

Site	Salinity parameter	Soil depth	Sample pairs	Correlation coefficient *r*	Confidence level	Linear regression slope
		inches	*no.*		*%*	*dS/m/inch* or *meq/L/inch*
Control	EC	12–24	31	−0.316	91.9	−0.06
Site 1	Na	0–12	34	−0.335	94.8	−0.36
Site 3	Na	0–12	27	0.396	96.0	0.48
Site 5	Na	24–36	35	0.362	96.8	0.46
Site 8	EC	0–12	14	0.667	99.2	0.18
	EC	24–36	14	0.504	93.7	0.05
	Na	0–12	14	0.681	99.4	0.67
	Na	24–36	14	0.479	92.0	0.35

TABLE 5. Significant (> 90% confidence level) correlation statistics between changes in soil salinity parameters and associated rain deep percolation from all data after 7 to 13 years of monitoring

Site	Salinity parameter	Soil depth	Sample pairs	Correlation coefficient *r*	Confidence level	Linear regression slope
		inches	*no.*		*%*	*dS/m/inch* or *meq/L/inch*
Control	EC	24–36	17	0.468	94.4	0.30
	Na	24–36	17	0.444	92.8	0.09
Site 1	EC	24–36	17	0.460	93.9	0.31
	Na	24–36	17	0.413	90.3	0.92
Site 3	EC	0–12	15	−0.435	91.0	−0.34
	Na	0–12	15	−0.480	93.3	−0.90
Site 5	EC	0–12	23	−0.661	99.9	−0.45
	Na	0–12	23	−0.663	99.8	−0.24
	EC	12–24	23	−0.611	99.9	−1.78
	Na	12–24	23	−0.473	97.8	−0.78
Site 6	EC	0–12	23	−0.518	98.9	−0.25
	Na	0–12	23	−0.528	96.7	−0.81
	EC	24–36	23	0.444	99.1	0.07
	Na	24–36	23	0.399	94.2	0.20
Site 7	EC	0–12	20	−0.429	94.2	−0.19
	Na	0–12	20	−0.405	92.5	−0.69
Site 8	Na	0–12	9	−0.749	98.5	−1.49

TABLE 6. Significant (> 90% confidence level) correlation statistics between changes in soil salinity parameters and associated deep percolation from applied water only or rain only after 7 to 13 years of monitoring

Site	Type of DP*	Salinity parameter	Soil depth	Sample pairs	Correlation coefficient *r*	Confidence level	Linear regression slope
			inches	*no.*		*%*	*dS/m/inch* or *meq/L/inch*
Control	AW†	EC	12–24	26	−0.335	90.7	−0.05
Site 1	AW	Na	0–12	14	−0.461	90.6	−0.47
Site 3	AW	Na	0–12	16	0.463	93.2	0.38
Site 5	AW	EC	0–12	17	0.427	90.4	0.17
	AW	EC	24–36	17	0.679	99.7	0.15
	AW	Na	24–36	17	0.613	99.0	1.00
Site 7	AW	EC	24–36	17	0.569	98.4	0.20
	AW	Na	24–36	17	0.541	97.7	0.98
Site 8	AW	EC	0–12	10	0.688	97.7	0.16
	AW	EC	24–36	10	0.584	93.1	0.04
	AW	Na	0–12	10	0.785	99.5	0.55
Average of all sites	Rain	EC	0–12	29	−0.466	99.0	−0.33
	Rain	Na	0–12	29	−0.489	99.3	−1.21

* DP = deep percolation.
† AW = applied water.

Overall, rainfall leaching of the soil profile is critical for the sustained irrigation of the salt-sensitive crops in this area with recycled water.

table 5). Crop yields from all of the sites appeared to be acceptable with an applied water EC_w of 1.1 to 1.2 and Na as high as 6 meq/L, values which are greater than those generally assumed to be suitable. Overall, the correlation analyses underscore the importance of rain-driven soil water leaching for maintaining satisfactory root zone salinity conditions.

Rainfall leaching critical

Comparison of the overall changes in soil salinity parameters from the beginning of soil sampling in spring 2000 to that in 2012 (or 2009 at two sites) yielded mixed results with little clear conclusion possible. However, when we considered the changes occurring between sampling events (1 to 5 months), the effects of rain and irrigation leaching became more apparent. At the control and the test sites, rainfall leaching of salinity was critical for maintaining agronomically acceptable soil salinity parameters in the root zone.

Irrigation leaching of the soil profile at the control site reduced salinity in the near-surface soil depth (1 to 12 inches) but may be resulting in a slight increase in Na concentrations at deeper depths (24 to 36 inches). At the test sites using irrigation water with greater salinity (high amounts of recycled water), despite considerable leaching fractions, irrigation leaching resulted in greater salinity concentrations in the near-surface soils and possible accumulation at deeper levels. Overall, rainfall leaching of the soil profile is critical for the sustained irrigation of the salt-sensitive crops in this area with recycled water of the quality documented in this study, and this should be considered in the water use management strategies of the region.

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Water advance model and sensor system can reduce tail runoff in irrigated alfalfa fields

by Brad J. Arnold, Shrinivasa K. Upadhyaya, Jedediah Roach, Parasappa S. Kanannavar *and* Daniel H. Putnam

Brad J. Arnold

Surface irrigation can result in large amounts of water lost to runoff and excess percolation. UC researchers found that runoff in commercial alfalfa fields can be reduced significantly by using a mathematical model and sensors (*above*, white poles) to predict and track the advance of water in the field. Information from the sensors is relayed wirelessly to a central module, which notifies the irrigator via text message when the input water needs to be turned off.

Surface irrigation, such as flood or furrow, is the predominant form of irrigation in California for agronomic crops. Compared to other irrigation methods, however, it is inefficient in terms of water use; large quantities of water, instead of being used for crop production, are lost to excess deep percolation and tail runoff. In surface-irrigated fields, irrigators commonly cut off the inflow of water when the water advance reaches a familiar or convenient location downfield, but this experience-based strategy has not been very successful in reducing the tail runoff water. Our study compared conventional cutoff practices to a retroactively applied model-based cutoff method in four commercially producing alfalfa fields in Northern California, and evaluated the model using a simple sensor system for practical application in typical alfalfa fields. These field tests illustrated that the model can be used to reduce tail runoff in typical surface-irrigated fields, and using it with a wireless sensor system saves time and labor as well as water.

Although drip irrigation and other similarly precise irrigation methods have made significant improvements to on-farm irrigation efficiency, a large percentage (around 43% in 2011) of growers still use surface irrigation methods, such as flood or furrow (DWR 2013). These methods tend to be less water-use efficient due to excess deep percolation and tail water drainage (i.e., runoff) (Walker 1989). Because of the potential for greater water usage and loss, surface-irrigated crop production has come under severe scrutiny and is the target of many agricultural water-use efficiency programs in the United States, particularly in California.

Growers are being encouraged to either increase the efficiency of their current irrigation systems or decrease the size of their farmland. In many situations, simple changes in water management or irrigation scheduling practices can decrease water losses and significantly increase a system's water-use efficiency (Bali et al. 2010; Grismer 2001).

Alfalfa (*Medicago sativa L*) is grown extensively in the western United States (Putnam et al. 2000) and frequently is surface irrigated (Schwankl and Pritchard 2003). Needing irrigation throughout the summer and fall months, it is the greatest water user of all California crops, accounting for about 19% of the state's agricultural water use (Putnam 2012). An alfalfa field is typically divided into checks (bays) separated by parallel ridges of soil, called borders. Water flows down the field slope, guided by the borders, to the tail end (bottom) of the check and then into a drainage ditch; this is frequently called check flood irrigation. Key limitations of this system include ponding of excess water at the tail end of fields, excessive runoff into drainage ditches or, if the inflow is turned off too early, deficient irrigation at the tail end of fields. These limitations lead to possible poor growth and crop yields at the tail ends of checks, applied water running off the site instead of being used for crop growth, and inferior water distribution uniformity (Hanson et al. 2008).

Research with surface-irrigated alfalfa has shown that proper water management can increase water-use efficiency while retaining production values such as crop yields and quality (Bali et al. 2004). Tail water runoff has been shown to have a strong correlation to cutoff distance (i.e., how far the wetting front, the front trajectory of the moving water, has advanced downfield when the inflow water is turned off) (Bali et al. 2010; Saha et al. 2011). As such, a significant opportunity for management improvements in check flood systems lies in developing strategies for cutting off the input water more precisely according to the advancement of the wetting front.

Irrigators usually do not apply a formulated cutoff strategy but instead use trial and error when establishing a cutoff

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v068n03p82&fulltext=yes
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distance. They make several trips to a field to determine when the water has reached a certain distance from the tail end of a check, based on field experience and using landmarks or following the path of birds or burrowing animals as the water advances. Then they turn off the inflow water to multiple checks, not just the check they have watched. However, the ideal cutoff distance is not always the same for all checks within a field or even for the same check over different irrigation events, due to spatial and temporal variability (e.g., soil moisture conditions). Even after making several trips to a field, an irrigator may miss the intended cutoff location or make an incorrect judgment of its location, leading to excessive runoff or inadequate irrigation.

Saha et al. (2011) reported details of a water advance model for managing water inflow cutoff in alfalfa fields with check flood irrigation. The model calculates an effective cutoff time using volume balance principles in an irrigated check, allowing an irrigator to define the desired amount of runoff. Their results in a controlled irrigated alfalfa field on the UC Davis campus using wired sensors that monitored the advance of the wetting front indicated that the model could reduce runoff to almost negligible levels compared with conventional cutoff practices.

Our goal was to assess this water advance model (Saha et al. 2011) for practical use by irrigators in commercially producing alfalfa fields with check flood irrigation, and determine its potential for decreasing runoff in these fields. Our specific objectives were (1) to compare runoff from a conventional cutoff practice to a retroactively calculated runoff from the model and (2) to assess the input measurements required to apply the model in typical alfalfa operations.

Field studies

Field tests were conducted in four check flood–irrigated alfalfa fields in Solano and Yolo counties. All fields were either a majority Capay silty clay (Yolo series, *Typic Haploxerets*) or Marvin silty clay loam (Yolo series, *Aquic Haploxeralfs*), both heavy clay soils typical to these areas. Four typical alfalfa fields with three irrigation events monitored per field, except for one (field D) due to scheduling constraints, provided the replications. The details of these field sites, where we performed tests during the 2011 growing season between August and October, are presented in table 1.

TABLE 1. Characteristics of four field test sites, 2011

Characteristic	Field A	Field B	Field C	Field D
Approximate size, acres (hectares)	54.0 (21.9)	75.5 (30.6)	68.0 (27.5)	37.0 (14.9)
Number of checks	46	98	91	21
Check length, feet (meters)	1,336–1,696* (407–517)	1,247–1,310* (380–399)	1,292 (394)	1,184–1,276* (361–389)
Check width, ± 1.0 foot (0.3 meter)	31.0 (9.5)	27.0 (8.2)	27.0 (8.2)	57.0 (17.4)
Average check slope (longitudinal)	0.21%	0.32%	0.18%	0.24%
Inflow method at each check	Two 6 in (15 cm) diameter siphon tubes, supplied from head ditch	Single 8 in (20 cm) diameter capped valve (alfalfa valve)	Single 12 in (30 cm) diameter gated pipe along head of field, supplied by off-site pump, with seven 1.5 by 2 in (4 by 5 cm) gates on the pipe	Four or five† 6 in (15 cm) diameter siphon tubes, supplied from head ditch

* Lengths differ because of the slope or curvature of the checks along the field width.

† Inflow methods were generally maintained between irrigations, except for one instance in which a different number of tubes was used for an unknown reason.

For each of the three irrigation events, two checks were selected at random from the set being irrigated (not the same checks at each irrigation event). To monitor a predetermined (i.e., based on prior experience) cutoff location within each check, a wireless contact-type water arrival sensor pole (sensor) was placed by the irrigator at that point. When the wetting front arrived at the sensor, the sensor sent a wireless signal to a central module device, which delivered a time-stamped text alert message to the irrigator's cellphone. The wireless sensor system and central module, which is capable of monitoring up to 256 sensor poles within a half-mile range, were designed specifically for developing a practical cutoff strategy to reduce irrigation runoff (Arnold 2013).

Extra sensors were placed in each of the two checks (equidistantly before and after the cutoff location) to gather wetting-front advance data and assess the speed of the wetting front as it moved downfield. We recorded the times of all water arrival notifications at the sensors, from the text alert cellphone messages to the irrigator, as well as the corresponding sensor locations downfield from the head end of the check.

Inflow to each check was monitored with a calibrated portable Doppler flow meter (PDFM 4.0; Greyline, Massena, NY), which was used to take hourly measurements manually prior to cutoff. As the wetting front proceeded toward the cutoff location, surface water depth was manually measured at the various sensor locations and averaged. The layout of our experiment, including the randomly chosen two checks, the sensors and the


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Siphon tubes, used in alfalfa fields A and D, deliver water from a head ditch to the checks.

locations of water depth measurements, is shown in figure 1.

Conventional cutoff assessment

To assess the conventional cutoff method, irrigator-selected cutoff locations were used in the tests performed at each of the four fields. Table 2 lists, for each test, the cutoff distance, measured from the head of the check to the selected cutoff

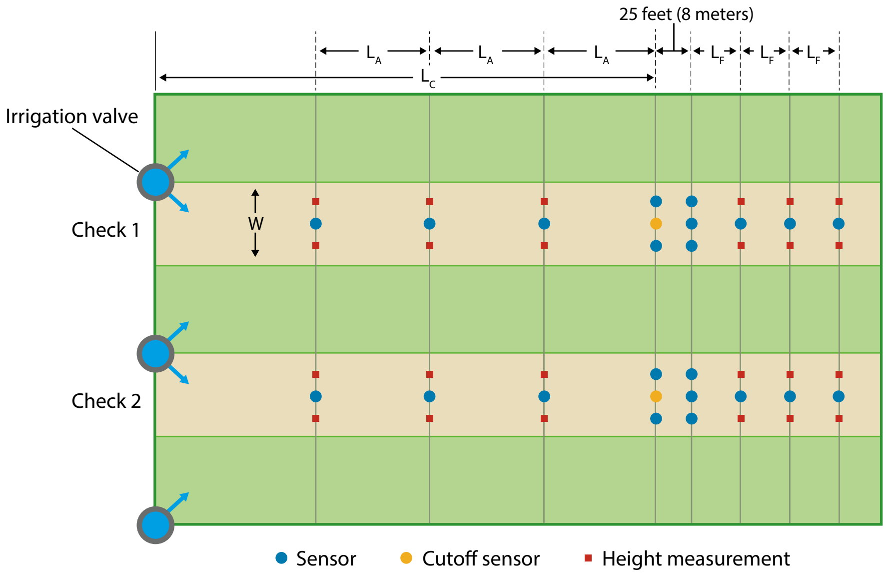

Fig. 1. Experiment layout: Each test included two checks, with an irrigation inflow at the head of the field, a sensor (the cutoff sensor, orange) at the irrigator-determined cutoff distance (L_C), additional sensors (blue) to monitor the progression of the wetting front and the locations where the depth of the surface water was measured (red). The additional sensors were placed equidistantly before (L_A) and after (L_F) the cutoff location.

TABLE 2. Additional sensor locations, irrigation inflow rate, cutoff distance, time to cutoff, and runoff volume in two checks during three irrigation events, at four fields, 2011

Irrigation event	Check	Distance between additional sensors: Before cutoff location, L_A	Distance between additional sensors: After cutoff location, L_F	Average inflow rate	Cutoff distance: From head of field	Cutoff distance: % of check length	Time from irrigation start to cutoff	Runoff: Volume	Runoff: % of applied water
		feet (m)	feet (m)	L/min (gpm)	feet (m)	%	hours	acre-foot (L)	%
Field A									
1	1	100 (30)	60 (18)	1,097.9 (285.5)	1,446 (441)	85	13.58	0.17 (216,000)	24
	2	100 (30)	60 (18)	1,401.5 (364.4)	1,446 (441)	85	9.92	0.23 (284,000)	34
2	1	100 (30)	60 (18)	1,450.3 (377.1)	1,446 (441)	85	15.87	0.15 (184,000)	31
	2	100 (30)	60 (18)	1,434.5 (373.0)	1,430 (436)	85	8.88	0.20 (250,000)	36
3	1	100 (30)	60 (18)	1,158.9 (301.3)	1,178 (359)	83	6.02	0.23 (288,000)	69*
	2	100 (30)	60 (18)	1,054.8 (274.2)	1,086 (331)	81	6.57	0.27 (334,000)	81*
Field B									
1	1	100 (30)	50 (15)	1,487.3 (386.7)	1,047 (319)	84	5.27	0.11 (135,000)	29
	2	100 (30)	50 (15)	1,492.6 (388.1)	1,047 (319)	84	4.81	0.09 (105,000)	25
2	1	100 (30)	50 (15)	1,746.3 (454.0)	1,110 (338)	85	4.55	0.24 (292,000)	61*
	2	100 (30)	50 (15)	1,761.0 (457.9)	1,110 (338)	85	3.93	0.21 (257,000)	62*
3	1	100 (30)	50 (15)	1,322.9 (344.0)	1,047 (319)	84	5.18	0.13 (164,000)	40
	2	100 (30)	50 (15)	1,583.9 (411.8)	1,047 (319)	84	5.20	0.12 (153,000)	31
Field C									
1	1	75 (23)	40 (12)	1,054.3 (274.1)	1,128 (344)	87	10.22	0.11 (139,000)	22
	2	75 (23)	40 (12)	1,174.7 (305.4)	1,128 (344)	87	10.47	0.09 (106,000)	14
2	1	75 (23)	40 (12)	1,323.9 (344.2)	1,128 (344)	87	8.05	0.12 (152,000)	24
	2	75 (23)	40 (12)	1,257.2 (326.9)	1,128 (344)	90	9.53	0.11 (131,000)	18
3	1	75 (23)	40 (12)	1,218.7 (316.9)	1,128 (344)	87	7.17	0.12 (147,000)	28
	2	75 (23)	40 (12)	1,119.4 (291.0)	1,128 (344)	87	7.95	0.14 (175,000)	33
Field D									
1	1	100 (30)	75 (23)	2,252.9 (585.8)	868 (265)	73	4.83	0.07 (82,000)	13
	2	100 (30)	75 (23)	2,549.8 (662.9)	868 (265)	73	4.43	0.18 (227,000)	34
2	1	100 (30)	50 (15)	2,669.0 (693.9)	960 (293)	77	4.10	0.12 (145,000)	22
	2	100 (30)	50 (15)	2,727.9 (709.3)	960 (293)	77	4.03	0.17 (204,000)	31

* Checks were subject to severe cross-flow of water from neighboring checks, so percentages do not represent solely tail water runoff; these results were considered outliers and are not included in the runoff analysis (see sidebar, page 85).

point. The inflow of water was cut off once a text alert was received that water had arrived at the cutoff sensor. Runoff was calculated using a volume balance model (see sidebar, page 85) and the sensor-collected wetting-front advance data.

Table 2 also lists the calculated runoff volume from each check and the runoff calculated as a percentage of the water applied to the check (illustrated in figure 2). Cutoff distances were typically between 75% and 88% of the length of the checks. Runoff volumes were generally estimated between 13% and 40% of applied water (around 0.15 acre-foot per check on average), much larger than expected for heavy clay soils (Bali et al. 2001). These results suggest that, in typical practice, irrigators are waiting too long to cut off water inflow.

Cutoff model assessment

Using a model developed by Saha et al. (2011), the ideal cutoff distance in each check to avoid excess runoff was determined retroactively (see sidebar, page 86) using the sensor-collected data. The results illustrate where cutoff sensors should have been placed, and when the inflow water should have been turned off. Further verification of this model was performed during the 2012 growing season in field C (Arnold 2013).

Table 3 shows the model-defined cutoff distances for approximately 5% and 10% surface runoff (i.e., percentage of applied water), an equivalent of 0.25 and 0.5 inch of tail-end surface water depth (h_L, see sidebar, page 86), respectively, which are both sufficient to ensure optimized crop production while improving upon typical values. Results indicate the cutoff sensor locations should have been at approximately 60% to 65% of check length, 220 to 245 feet (67 to 75 meters) farther upfield from where irrigators had placed them. This placement would have reduced runoff volumes significantly.

The difference between irrigating for 5% and 10% runoff was about 0.02 acre-foot, or 24,670 liters, on average and approximately 46 feet (14 meters) in terms of cutoff distance, indicating that slight modifications to the cutoff distance can have significant effects on applied water use. For an average field size of around 58 acres (23.5 hectares) with 64 checks (table 1), the difference between model-calculated (i.e., 5% runoff) and irrigator-determined cutoff distances, and the presumed reduction in runoff, could mean around 8.5 acre-feet of water saved, or approximately $216 per field per irrigation using a conservative estimate for alfalfa production of $25.47 per acre-foot (Long et al. 2013).

Savings could be even greater for growers with higher water costs (e.g., in

Capped valves (alfalfa valves) provided consistent water inflow rates in field B.

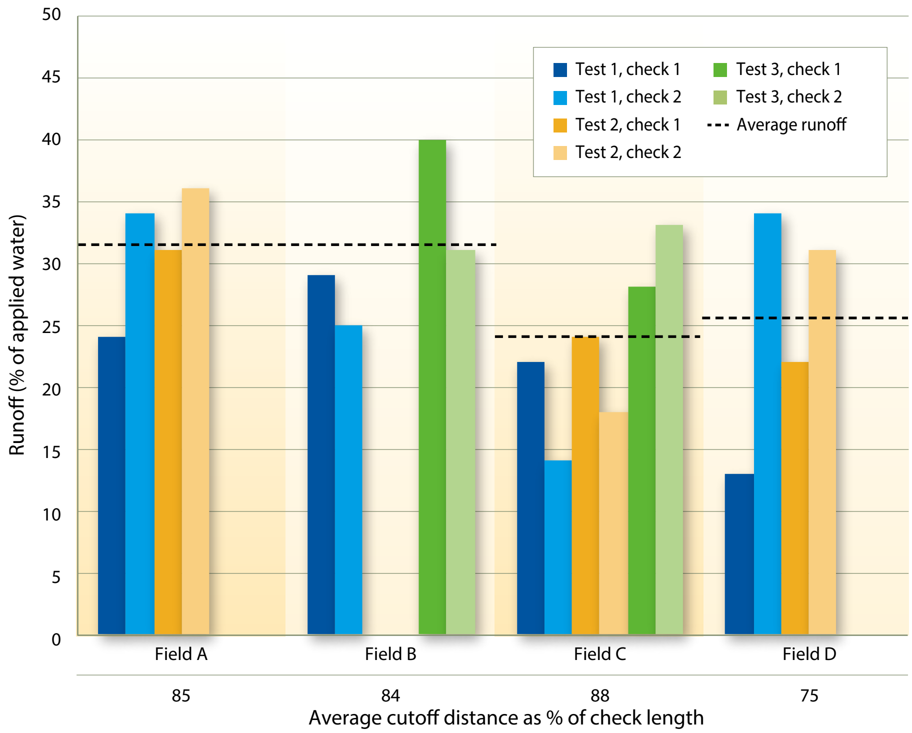

Fig. 2. Runoff percentages for each irrigated check and average cutoff distance per field. Differences in the configuration of field C (primarily the least amount of average check slope; see table 1) and lower inflow rates (see table 2) likely caused the runoff percentages in field C to be lower than for the other fields. Outlier results in fields A and B are not shown; see note, table 2.

Runoff estimation model

The following volume balance model was used to calculate the runoff (R) in cubic feet from each irrigated check. The model assumes final infiltration rates, the long-term infiltration rate to the underlying soil following an initial saturation impulse of infiltration, considered negligible (Saha 2010):

$$qt_C - wL\left[\frac{qt_C}{wL_C} - h_A + h_F\right] = R \qquad (1)$$

Where the check width (w) and length (L), cutoff distance (L_C), and cutoff time (t_C) are measured in feet and minutes, respectively; the inflow rate (q) is measured in feet per minute; and the average surface water depth prior to cutoff (h_A) and average surface water depth after cutoff (h_F) are measured in feet. The model assumes negligible recession (i.e., retreating of water away from the head of the checks as the surface progressively dries) by the time the wetting front has advanced to the tail end of the check; this assumption was verified by Arnold (2013) through extensive field tests. It also assumes that the runoff value (R) in the model includes any cross-flow of water (i.e., uncontrolled water moving between checks due to deteriorated borders and soil cracking, which cannot be measured separately, as noted in table 2).

Kern County), and they would also multiply during the growing season with each irrigation. Savings might also be made from minimizing crop production losses at the tail ends of fields, due to better irrigation management. Note that the data in table 3 are dependent on the field conditions at the time of the irrigation tests and may be different for other irrigation events in the same field.

Practical application of model

For practical application of the model presented by Saha et al. (2011), certain values must be known or measured before and during irrigation to complete the model calculations (see sidebar, this page). Field dimensions such as the check width and length and the sensor distances are easily measured using a tape measure or GPS before the start of the irrigation season and are assumed to be static over an entire season. The sensors are placed in each monitored check according to the setup shown in figure 3. The sensors may remain at their locations between irrigation events, moved between irrigated checks, or removed for cultural or machining operations and then replaced in the same configuration.

For each irrigation event, the average depth of water prior to cutoff (h_A) is calculated by the irrigator once a text message is received for water arrival at sensor S_3, by averaging (using a calculator) the manually measured depths at S_1 and S_2. The cutoff time (the number of minutes from the arrival of the wetting front at S_3) is then calculated with a calculator in the field by the irrigator, using the mathematical model (sidebar, this page, equation 3).

Although the irrigator must make these calculations during each irrigation event, which could be made easier with spreadsheet or calculation software, the

Brad J. Arnold

In field C, water was delivered to alfalfa checks from a gated pipe.

Water advance model

In development of the cutoff model, Saha et al. (2011) showed that in surface-irrigated alfalfa the wetting-front speed (v) in feet per minute becomes constant once the wetting front advances sufficiently downfield. That is,

$$v = \frac{q}{w(I_I + h_A)} \rightarrow I_I = \frac{q}{vw} - h_A \qquad (2)$$

Assuming the inflow rate (q) in cubic feet per minute, check width (w) and average surface depth of water (h), both in feet, are known or measured values, equation 2 can be solved for the magnitude of initial infiltration (I_I) in feet since the wetting-front speed is known from water advance data. This value of I_I is substituted into equation 3 to obtain the irrigation water cutoff time (t_0) in minutes:

$$t_0 = \frac{wL(I_I + h_L)}{q} - \frac{L_3}{v} \qquad (3)$$

Where t_0 is the time (minutes) that water is cut off following wetting-front arrival at sensor S_3, L_3 is the distance (feet) from the head of the check to S_3 downfield, L is the total check length, and h_L is the surface depth of water (feet) when the wetting front arrives at the tail end. Note the irrigator selects a value of h_L based on an acceptable amount of drainage.

TABLE 3. Irrigator-determined cutoff distances and cutoff distances calculated using water advance model

		Field A	Field B	Field C	Field D
Irrigator-determined cutoff distances					
Average distance from head of field	feet (meters)	1,339 (408)	1,068 (326)	1,128 (344)	914 (279)
Average % of check length		84	84	88	75
Cutoff distances calculated for 5% runoff (h_L = 0.25 inch)					
Average distance from head of field	feet (meters)	1,160 (354)	743 (226)	908 (277)	739 (225)
Average % of check length		69	60	71	61
Distance upfield from irrigator-determined cutoff	feet (meters)	282 (86)	304 (93)	220 (67)	175 (53)
Water savings per acre per irrigation	acre-feet/acre	0.18	0.14	0.15	0.06
Cutoff distances calculated for 10% runoff (h_L = 0.50 inch)					
Average distance from head of field	feet (meters)	1,204 (367)	788 (240)	939 (286)	801 (244)
Average % of check length		71	63	73	66
Distance upfield from irrigator-determined cutoff	feet (meters)	238 (73)	259 (79)	189 (58)	113 (34)
Water savings per acre per irrigation	acre-feet/acre	0.16	0.12	0.13	0.04

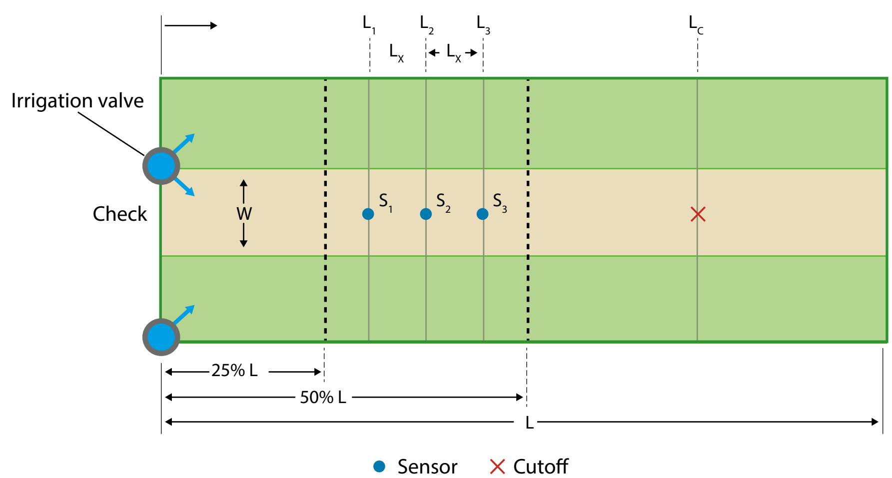

Fig. 3. To use the cutoff model, three sensors, S_1, S_2 and S_3, must be placed equidistantly (L_X) within a span of 25% and 50% of the check length (L); the cutoff distance (L_C) is almost always beyond half of the length. The locations of all sensors must be measured from the head end of the check.

primary benefit of the model-based cutoff system is that the irrigator now needs to return to the field only once, to turn off the inflow after receiving a cellular text message, thereby saving valuable time and labor costs. In conventional cutoff practice, the irrigator makes five or six or even more trips back to the field to visually monitor the water advancement downfield.

Beyond these measurements, the most tedious and time-consuming variable to acquire for the model during each irrigation event is the water inflow rate (*q*). Expensive flow meter equipment that is readily adaptable to field-specific inflow setups is typically required to obtain a reliable value. Our tests were performed in fields with different inflow setups: siphon tubes, alfalfa valves and gated pipes (table 1). Based on field data, it seemed conceivable that regulated inflow setups with uniform application rates could be developed and applied to the entire irrigation season for a particular setup.

Regardless of the inflow setup, in our tests the wetting-front speed remained constant for an irrigated check as the wetting front advanced downfield (Arnold 2013), indicating a constant inflow rate prior to cutoff (Saha 2010). Recall that all tests were performed in the same fields but not necessarily within the same checks. Therefore, to verify that separate irrigations illustrate similar behavior, inflow rates must be consistent between irrigated checks during a given irrigation (i.e., across the entire irrigated set of checks). Table 4 shows the variation in measured inflow rates (Arnold 2013) within a single irrigated check during one irrigation event, between different checks during the same irrigation event (i.e., for an irrigated set of checks) and between different checks during different irrigation events.

When a sensor (white pole) detects water arrival, a wireless signal is sent to the central module (black box), which generates a text message alert to the irrigator.

UC Cooperative Extension Centennial

Placement of Tensiometers as guides to irrigation practices

With the introduction of new tools to measure soil moisture, agricultural research took a major step forward in the development of efficient crop irrigation techniques. In this 1960 article, researchers explain how tensiometers work and give specific, practical advice on where to place them in the field.

1960 "The moisture sensing unit — a porous cup — of tensiometers must be reached by the irrigation water if the moisture measuring instruments are to be of practical value as guides to irrigation practices.

"In most soils a good location for a tensiometer station is often next to the furrow, but it may be necessary to locate the porous cup under the furrow in orchard soils with little or no lateral movement of water during irrigation. In sprinkler-irrigated orchards the cup must be in soil that is re-wetted by the sprinkler at each irrigation but is not shielded by a low hanging branch nor is flooded by runoff from a branch. Also the porous cup should be in areas of active feeder roots as determined by root density studies, or by digging at different sites until a general pattern of root densities is apparent.

"Some traffic between the tree rows is necessary in most orchards, so the soil moisture measuring instrument must be in a protected spot reached by irrigation water and where feeder root density is average for the tree. In general, a good location for a tensiometer is at the drip line on the tree side of the first furrow, south or west of the tree."

Solzy LH, et al. 1960. Placement of tensiometers as guides to irrigation practices. Calif Agr 14(3):11–2.

Lewis H. Stolzy joined UC Riverside's Department of Irrigation and Soil Science in 1954 as an irrigation engineer. He was instrumental in the invention of new soil oxygen and water sensors, including a portable neutron probe for use in the field. He also studied how soil contents and constituents affect plant development — and, therefore, how data from the new technology could help improve farming practices.

Like Stolzy, Albert W. Marsh was an irrigation innovator. A Cooperative Extension irrigation and soils specialist at UC Riverside, Marsh is credited with introducing drip irrigation to California, which has allowed the state's agriculture to conserve inestimable volumes of water and allowed farming to continue in many areas despite sometimes arid conditions. An environmental sciences scholarship at UC Riverside honors Marsh's memory.

Richard E. Puffer and Dwight C. Baier were well-known and respected UC Cooperative Extension farm advisors serving Southern California growers.

—W.J. Coats

100 UC Cooperative Extension
A Celebration of Science and Service

The variation between measurements during the same irrigation was generally low (coefficient of variation, CV, < 10%) for each inflow setup (table 4). In one instance with the siphon tubes, variation was large due to a loss of siphon charge midway through the test. Although the total inflow rate into the check was skewed as a result, separate measurements of the head ditch water height (Arnold 2013) indicated little variation (CV < 4%) from the time the ditch was filled, indicating the inflow rates should have remained constant. This suggests that the loss of charge may have been caused by improper tube setup by the irrigator. As seen in table 4, the pump-based systems (alfalfa valves, gated pipe) produced better consistency in inflow values.

Overall, the results indicated reasonable stability in inflow values between checks irrigated at the same time, as well as in inflow values between irrigations (without the outlier). These data suggest that if inflow is properly maintained between irrigations (e.g., six siphon tubes used to feed every check from same head ditch), inflow rates will be relatively similar, and therefore an inflow measurement taken during the first irrigation of a season can be used for subsequent irrigations during the rest of that season with negligible error, thus reducing the effort needed to collect this data.

TABLE 4. Inflow variation (coefficient of variation) by type of inflow setup

	Coefficient of variation (CV) %		
Inflow type	Within check	Between checks	Between irrigations
Siphon tubes	8.0	14.5	23.4
Siphon tubes without outlier	4.3	7.8	11.9
Alfalfa valve	1.9	4.4	10.2
Gated pipe	3.8	5.8	8.6

Application of sensors

Although the use of wireless sensors with the water advance model provides a suitable method for reducing tail water runoff in irrigated fields, the widespread use of these sensors may be limited because of the number of setups (multiple sensors per check, 64 checks per field) and measurements the irrigator must make. Due to the spatial and temporal differences between irrigated checks, multiple sensors are required in all checks to accurately apply the model; it is not feasible to apply the model to a "representative check" in an irrigated set.

The extra setup of the sensors required in the field may be of concern, but the sensors can be left in the field (at location) between irrigations and quickly removed for any cultural or machining processes, as mentioned above. Alternatively, the sensors can be moved from check to check following the arrival of water at a sensor or at the tail end of the field, making it easy for an irrigator to track multiple irrigated checks using the same set of sensors.

For monitoring the accuracy of the cutoff distance, irrigators may place a sensor toward the tail end of a check to receive a text alert to return to the field and record the results — whether irrigation is sufficient at the end of the check, whether runoff is reduced. Irrigators have the option, and are encouraged, to alter the cutoff sensor location in future irrigations, either upfield from the previous spot to further reduce runoff or downfield to ensure that water sufficiently covers the entire check (crop).

Potential uses

The level of savings in terms of irrigation water, reduced labor costs and reduced environmental impacts due to excess runoff makes the sensors and model system a viable option for most surface-irrigated fields similar to those in this study (check flood, furrow, etc.). Our results in the test fields showed that large quantities of water became runoff during irrigation and were not beneficial to crop production, and this water could have been saved. More importantly, the sensors and model combination offers a practical method for irrigators to enhance their irrigation practices while saving the time and labor needed to manually monitor an irrigated check. Beyond these immediate savings, the system also provides a path toward automating the surface irrigation process in the future, through the use of sensor alert messages that would be relayed to automatic inflow setups (e.g., electronic gates) or remotely controlled pump control panels.

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Predicting invasive plants in California

by Elizabeth D. Brusati, Douglas W. Johnson *and* Joseph M. DiTomaso

Preventing plant invasions or eradicating incipient populations is much less costly than confronting large well-established populations of invasive plants. We developed a preliminary determination of plants that pose the greatest risk of becoming invasive in California, primarily through the horticultural industry. We identified 774 species that are invasive elsewhere in Mediterranean climates but not yet invasive in California. From this list, we determined which species are sold through the horticulture industry, whether they are sold in California and whether they have been reported as naturalized in California. We narrowed the list to 186 species with the greatest potential for introduction and/or invasiveness to California through the horticultural trade. This study provides a basis for determining species to evaluate further through a more detailed risk assessment that may subsequently prevent importation via the horticultural pathway. Our results can also help land managers know which species to watch for in wildlands.

Joseph M. DiTomaso

Giant reed (*Arundo donax*) infesting a wetland area in Southern California. Giant reed was introduced as both an ornamental and erosion control species and is now one of the most invasive species in the state.

Plants have been transported around the world for centuries, as agricultural commodities, ornamental species or inadvertent contaminants of imported materials. Naturalized plants are those that have spread out of cultivated areas, including gardens, into more wild areas, and invasive plants are the subset of naturalized species that cause ecological or economic harm. In general, only a small proportion of plants introduced into a new region have been invasive plants. However, the number of invasive plants with horticultural origin is high, making it critically important to natural resource managers, ecologists and policymakers to predict which newly introduced species pose the greatest risk of escape and invasion.

The geographic diversity of California has led to broad evolution in native plants. California has approximately 3,400 species of native plants, of which 24% are found only in the state (Baldwin et al. 2012). However, California is also something of a hotspot for nonnative plants, with over 1,500 nonnative species naturalized, weedy in agricultural systems or invasive in natural areas (DiTomaso and Healy 2007). As a result, California not only faces a high risk of escape, establishment and invasion of introduced ornamental plants, but also has a high proportion of native species threatened by invasive plants.

Within California, there are two lists that identify invasive plants. First, based on 13 questions that assess impacts, invasiveness and distribution, the California Invasive Plant Council's list includes 214 species that cause ecological harm in the state's wildlands (Cal-IPC 2013). Approximately 63% of these species were deliberately introduced to California, mostly as ornamental plants (Bell et al. 2007). Second, the California Department of Food and Agriculture (CDFA) Noxious Weed List primarily lists plants that cause, or have the potential to cause, economic damage to the state's agricultural industry; CDFA has legal authority to regulate plants on this list through Section 4500 of the California Code of Regulations (CDFA 2013). Because the criteria for these lists have a different focus, the listed species overlap but are not the same. Few species derived from the horticultural trade are included on the state Noxious Weed List.

The high number of invasive plants with horticultural origin makes it critically important to natural resource managers, ecologists and policymakers to predict which newly introduced species pose the greatest risk of escape and invasion.

The horticultural trade is one of the major pathways for invasive plants in California and elsewhere (Drew et al. 2010; Okada et al. 2007; Reichard and White 2001). For example, higher market frequency (as measured by availability in seed catalogs) and lower prices were shown to be good predictors of a plant's probability of invasion in Britain (Dehren-Schmutz et al. 2007). Horticulture is also

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v068n03p89&fulltext=yes
doi: 10.3733/ca.v068n03p89

Joseph M. DiTomaso

Joseph M. DiTomaso

After being introduced as an animal forage species, kudzu (*Pueraria montana*) escaped to invade forested areas in the southern United States. Kudzu is neither naturalized nor sold in California.

a major agricultural sector in California, accounting for $2.5 billion in sales in 2011 (CDFA 2012).

The ability to predict potential invasiveness is important both for species that have already been introduced to a region but are not yet invasive and for species that may be introduced through the horticultural industry in the future. In both cases, prediction of invasiveness before it occurs can, through collaborative efforts with the nursery industry, lead to voluntary restrictions in sales, preventing the potential for damage should the species escape cultivation.

Knowing that a plant is invasive in one region can give insight into whether it might be problematic in another region, particularly if the two regions have similar climates. For woody ornamental species, for example, being invasive elsewhere was the single best predictor of potential invasiveness in a new region of introduction (Reichard and Hamilton 1997). In addition, Caley and Kuhnert (2006) showed that four variables were most important for screening potential invasive plants: human dispersal, naturalized elsewhere, invasiveness elsewhere and a high degree of domestication. Two of these variables, human dispersal and high degree of domestication, are characteristics of horticultural species.

California is one of five Mediterranean climate regions in the world, along with the Mediterranean Basin of Europe and northern Africa, central Chile, the Cape Region of South Africa and western Australia. All these regions are characterized by a winter rainy season and a summer dry season and are likely to share invasive species due to their similar climates.

The primary objective of this study was to identify ornamental species at high risk of becoming newly invasive in California. To develop this list, we considered the single most important factor to be a species' invasiveness in other areas of the world with a similar Mediterranean climate or in a state neighboring California. While we recognize that this list is not comprehensive, we believe that it provides a good starting point for subsequently conducting risk assessments that could reduce the threat of introducing new invasive ornamentals to the state. This approach might also help determine which naturalized species should be monitored to see if they will become truly invasive.

Identifying potential invaders

Invasive plant data were collected through online databases and published lists from other regions with Mediterranean climates. We also used established invasive plants reported from states neighboring California, including Arizona (Northam et al. 2005), Nevada (Nevada Department of Agriculture 2005) and Oregon (Oregon Department of Agriculture 2006). We included species on the California Noxious Weed List (CDFA 2007) as well as those that have been shown to invade wildlands (Cal-IPC 2013; personal communications with land managers in California).

Of the plants that have invaded other Mediterranean regions, we first removed species native to California and those already known to be invasive in wildland areas within the state. Then for each of the remaining plant species, we evaluated the Mediterranean-type region(s) invaded, location of origin, human uses (especially in horticulture) and whether the species was native, cultivated, naturalized or invasive in California (Baldwin et al. 2012; Cal-IPC 2013). For species already naturalized but not yet invasive in California, we determined the year they were first reported as naturalized based on the online Consortium of California Herbaria database (ucjeps.berkeley.edu/consortium/). In addition, we determined if plants are currently sold in the horticultural and ornamental trade in California using the

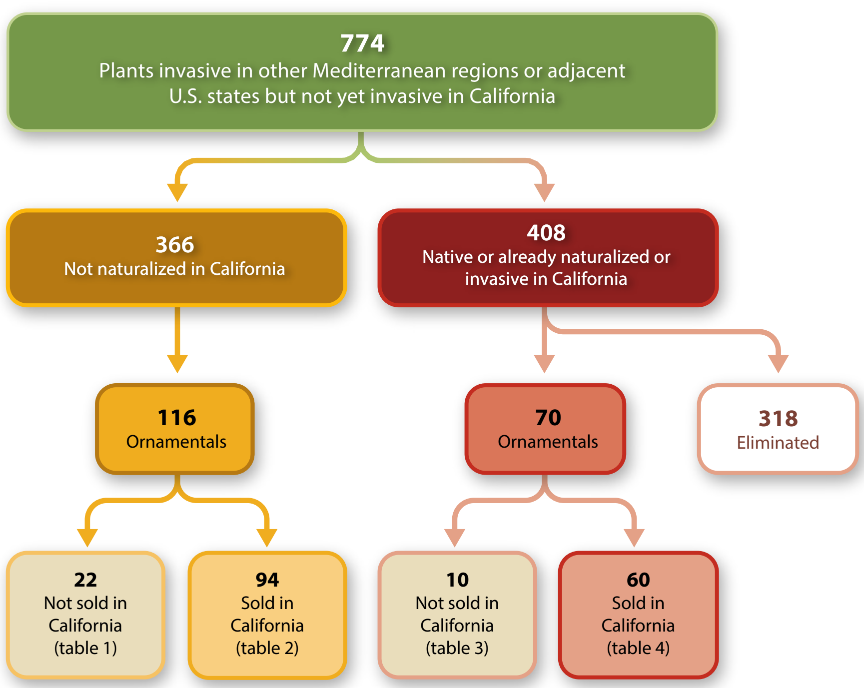

Fig. 1. Process used to determine the species with potential to become invasive in California through surveys of other Mediterranean climatic regions and adjacent U.S. states, with a focus on species sold as ornamentals. Tables 1 to 4 list these 186 species (22 + 94 + 10 + 60). The 318 eliminated species were eliminated because they are native to California, already invasive in California or have been naturalized in California since before 1940 without becoming invasive.

Sunset Western Garden Book (Brenzel 2007) and the *Plant Locator* (Hill and Narizny 2004), a directory of nurseries stocking particular species. While these references do not include all of the species available by mail order or via the Internet, they represent plants most commonly available in nurseries.

Which plants are likely threats?

Based on our criteria, we found 774 plants listed as invasive in other Mediterranean regions or adjacent states (fig. 1). Of these, 366 (47%) are not naturalized in California and therefore fit our focus on potential new invaders. Of the remaining 408 species (53%), we eliminated 318 species that did not fit our focus on new invaders: they were either native to California (Baldwin et al. 2012) or already invasive in California (DiTomaso and Healy 2007), or had naturalized in the state before 1940 without becoming invasive (Consortium of California Herbaria 2008). This left us with 90 species that naturalized after 1940.

We assumed that species that naturalized before 1940 and that have not yet become invasive in California are unlikely to become invasive in the future. Many of the naturalized species have been present in the state for over a century, with 20 recorded in the 1860s and 144 recorded before 1900. While we believe that 70 years of naturalization without significant spread and harm is sufficient to consider a species as having low potential for invasion, this may not be true for all species. There may be some instances where longer lag periods — a length of time when a species is present in natural areas before beginning to spread and cause ecological harm — could occur prior to rapid expansion of a species. Furthermore, the movement of ornamental plants is facilitated by humans, thus increasing the opportunity for introduction to suitable habitats. In addition to possibly increasing the potential for invasion by introduced plants, this facilitation could also reduce the time between introduction and invasion.

Next, we subdivided the 90 species that became naturalized after 1940 and the 366 species that are not naturalized in California based on whether they are sold as ornamentals. We also noted whether they are sold in California (fig. 1). Of the 90 naturalized species, 70 (78%) are currently sold as ornamentals somewhere in the world, with 60 (67%) sold in California. Of the 366 nonnaturalized species in California, only 32% (116 species) were ornamentals. The majority of these species (94, or 81%) are currently sold in California, while the other 22 are ornamentals not sold in the state. Thus, in total, we listed 186 species of ornamentals as the greatest concern for introduction and/or invasiveness to California through the horticultural pathway. This total

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EUCALYPTUS

Fuel Dynamics, and Fire Hazard in the Oakland Hills

Eucalyptus trees were introduced to California from Australia in the 1850s and have become invasive in some coastal areas since then. In 1973, following a two-year study of eucalyptus stand densities, caloric content of fuel and dynamics of fuel accumulation in the Oakland Hills, researchers recommended a fuel reduction program. Eighteen years later, a firestorm in the Oakland Hills fueled by high winds and dense groves of freeze-damaged eucalyptus and pine trees killed 25 people and destroyed nearly 4,000 dwellings.

1973 "Eucalyptus has been a scenic and aromatic addition to the California landscape for over a century. The rapid growth of early plantations caught the eye of timber speculators around 1900 and millions of eucalyptus seedlings, predominately blue gum *(Eucalyptus globulus)* were planted. They soon covered the crest of the Berkeley-Oakland Hills, and have created a serious fire hazard since that time at the urban-wildland interface.

". . . The late 1972 freeze has resulted in a proposed fuel management program for the Berkeley-Oakland Hills. Management of eucalyptus groves is an integral part of such a program. The results of this study indicate that fuel buildup occurs very rapidly in unmanaged eucalyptus stands, and to maintain low fuel levels a fuel reduction program should be implemented."

Agee JK, et al. 1973. Eucalyptus fuel dynamics, and fire hazard in the Oakland hills. Calif Agr 27(9):13–5.

Of the article's four co-authors, the two research assistants went on to distinguished professorial careers in forestry and ecological sciences, James K. Agee at the University of Washington College of Forest Resources and Ronald H. Wakimoto at the University of Montana, Missoula.

Ellis F. Darley was a plant pathologist at UC Riverside and did pioneering work on the effects of air pollution on plants and on the overall environment. At UC Berkeley, Harold H. Biswell was professor of forestry and an early proponent of controlled burning for wildland fuel management. When he retired in 1973, UC awarded him the Berkeley Citation, its highest honor for distinguished achievement. In 1994, a symposium on "Fire Issues and Solutions in Urban Interface and Wildland Ecosystems" was held in his honor.

—W. J. Coats

100 UC Cooperative Extension

A Celebration of Science and Service

Joseph M. DiTomaso

Fanwort (*Cabomba caroliniana*) is an invasive aquatic weed in California that was introduced through the aquarium industry.

TABLE 1. Species neither naturalized nor sold in California, but sold as ornamental plants elsewhere*

Family	Species	Common name
Asteraceae	*Ageratina riparia* (Regel) King & H. Rob.	Creeping croftonweed
	Gymnocoronis spilanthoides (D.Don) DC.	Senegal tea
	Senecio angulatus L.f.	Creeping groundsel
	Sphagneticola trilobata (L.C. Rich.) Pruski	Wedelia
Crassulaceae	*Kalanchoe pinnata* (Lam.) Pers.	Cathedral bells
Fabaceae	*Acacia nilotica* (L.) Willd. ex Delile	Gum arabic tree
	Albizia lebbeck (L.) Benth.	Woman's tongue
	Caesalpinia decapetala (Roth) Alston	Shoofly
	Pueraria montana (Lour.) Merr.	Kudzu
	Senna pendula (Humb. & Bonpl. ex Willd.) Irwin & Barneby	Valamuerto
Iridaceae	*Gladiolus undulatus* L.	Wild gladiolus
	Moraea flaccida (Sweet) Steud.	One-leaf Cape tulip
	Moraea lewisiae (Goldblatt) Goldblatt (= *Hexaglottis lewisiae* Goldblatt)	Cape tulip
	Sparaxis bulbifera (L.) Ker Gawl.	Wandflower
	Watsonia versfeldii J.W. Mathews & L. Bolus	Bugle-lily
Meliaceae	*Toona ciliata* Roem.	Australian redcedar
Polygalaceae	*Polygala virgata* Thunb.	Purple broom
Polygonaceae	*Rumex sagittatus* Thunb. [= *Acetosa sagittata* (Thunb.) L.A.S. Johnson & B.G. Briggs]	Rambling dock, garden sorrel
Proteaceae	*Hakea gibbosa* (Sm.) Cav.	Hairy or rock hakea
Salicaceae	*Salix fragilis* L.	Crack willow
Sapindaceae	*Cardiospermum grandiflorum* Sweet	Showy balloonvine
Solanaceae	*Cestrum laevigatum* Schltdl.	Inkberry

* Scientific and common names of nonweedy species in all tables are from the United States Department of Agriculture Plant Database (http://plants.usda.gov/) or Germplasm Resources Information Network (www.ars-grin.gov/npgs/aboutgrin.html). Plants considered naturalized in California wildlands are based on Baldwin et al. (2012). These tables do not include species that have been present in California since before 1940 without becoming invasive.

includes both those species currently sold and those that could be sold in the future (tables 1 to 4).

This study, however, did not take into consideration the potential effects of climate change on habitat suitability and plant invasions within California. It is possible that warmer temperatures or modified precipitation patterns due to climate change will allow some currently noninvasive ornamentals to spread and become invasive. However, predictions of the spread of invasive plants in the western United States indicate that

TABLE 2. Species sold as ornamentals in California but not yet naturalized in the state*

Family	Species	Common name
Acanthaceae	*Thunbergia grandiflora* Roxb.	Thunbergia, Bengal trumpet
Aceraceae	*Acer pseudoplatanus* L.	Sycamore maple
Agavaceae	*Agave sisalana* Perrine	Sisal hemp
	Yucca gloriosa L.	Moundlily yucca
Aloaceae	*Aloe vera* (L.) Burm. f.	Barbados aloe
Asclepiadaceae	*Cryptostegia grandiflora* (Roxb. ex R. Br.) R. Br.	Palay rubbervine
	Periploca graeca L.	Silkvine
Asparagaceae (formerly Liliaceae)	*Asparagus africanus* Lam.	African asparagus
	Asparagus plumosus (Kunth) Jessop	Common asparagus fern
	Asparagus scandens Thunb.	Climbing asparagus fern
Asteraceae	*Baccharis halimifolia* L.	Eastern baccharis
	Coleostephus myconis (L.) Reichenb.	Corn marigold
	Schkuhria pinnata (Lam.) Kuntze ex Thell.	Pinnate false-threadleaf
	Solidago chilensis Meyen	Brazilian arnica
Balsaminaceae	*Impatiens glandulifera* Royle	Balsam, policeman's helmet
Bignoniaceae	*Spathodea campanulata* P. Beauv.	African tuliptree
Boraginaceae	*Echium vulgare* L.	Blueweed
Cactaceae	*Echinopsis spachiana* (Lem.) Friedrich & G.D. Rowley	Echinopsis, golden torch
	Harrisia martini (Labouret) Britt.	Mooncactus
	Opuntia fulgida Engelm. [=*Cylindropuntia fulgida* (Engelm.) F.M. Knuth]	Jumping cholla
	Opuntia humifusa Raf.	Spreading pricklypear
	Opuntia imbricata (Haw.) DC. [= *Cylindropuntia imbricata* (Haw.) F.M. Knuth]	Walkingstick cholla, tree cholla
	Opuntia microdasys (Lehm.) N.E. Pfeiffer	Angel's-wings, bunny ears
	Opuntia robusta J.C. Wendl. ex Pfeiff.	Wheel cactus, silver dollar
	Opuntia stricta (Haw.) Haw.	Erect pricklypear
Cannabaceae	*Humulus japonicus* Sieb. & Zucc.	Japanese hops
Cannaceae	*Canna indica* L.	Indian shot
Caprifoliaceae	*Leycesteria formosa* Wall.	Himalayan honeysuckle
Casuarinaceae	*Casuarina equisetifolia* L. ex J.R. & G. Forst.	Australian-pine
Convolvulaceae	*Turbina corymbosa* (L.) Raf.	Christmasvine

while some will likely spread, others may contract their ranges (Bradley et al. 2009). Thus, it was not possible to determine the impact of climate change on all the species evaluated in this study.

Management implications

To reduce the sale of invasive plants in California, environmental groups, scientists, government agencies and the horticulture industry are participating in the PlantRight partnership, a coalition that works with retail nurseries and growers on voluntary measures to reduce the sale of invasive plants and promote non-invasive alternatives (plantright.org); the authors serve on its steering committee. Specific guidelines or recommendations could be established for the high-risk species we identified in tables 1 to 4 to minimize future introduction, establishment and invasion. Cooperative efforts can discourage the introduction of ornamental plants in other regions that are neither naturalized nor sold in California (table 1), and these plants also could be included in a cautionary list that would require

TABLE 2. ***Continued from previous page***

Family	Species	Common name
Dryopteridaceae	*Nephrolepis cordifolia* (L.) C. Presl	Narrow swordfern
	Nephrolepsis exaltata (L.) Schott	Swordfern, Boston fern
Ericaceae	*Erica arborea* L.	Briar root, tree heath
Euphorbiaceae	*Euphorbia polygonifolia* (L.) Small	Seaside sandmat
Fabaceae	*Acacia karroo* Hayne	Karroothorn
	Acacia podalyriifolia A. Cunn. ex G. Don	Pearl wattle
	Acacia stricta (Andrews) Willd.	Hop wattle
	Cassia fistula L.	Golden shower, senna
	Dalbergia sissoo Roxb. ex DC.	Indian rosewood, Himalayan raintree
	Psoralea pinnata L.	Blue psoralea, fountainbush
	Retama raetum (Forssk.) Webb & Berthel.	Weeping white broom
	Senna alata (L.) Roxb.	Emperor's candlesticks, candlebush
	Senna bicapsularis (L.) Roxb.	Christmasbush
Fagaceae	*Quercus robur* L.	English oak
Iridaceae	*Ferraria crispa* Burm.	Black flag, starfish iris
	Freesia leichtlinii F.W. Klatt [= *F. alba* (G.L. Mey.) Gumbl. *x F. Leichtlinii*]	Freesia
	Moraea miniata Andrews	Two-leaf Cape tulip
Lamiaceae	*Plectranthus comosus* Sims.	Woolly coleus
Liliaceae	*Agapanthus praecox* Willd. subsp. *orientalis* (F.M. Leight.) F.M. Leight.	African lily, lily-of-the-nile
	Alstroemeria aurea Graham	Peruvian-lily, alstroemeria
	Asparagus densiflorus (Kunth) Jessop	Sprenger's asparagus fern
	Gloriosa superba L.	Glory lily, flame lily
Meliaceae	*Azadirachta indica* A. Juss.	Neem
Myrsinaceae	*Ardisia crenata* Sims	Hen's eyes
Myrtaceae	*Eucalyptus conferruminata*	Bushy yate
	Eugenia uniflora L.	Surinam cherry
	Psidium cattleianum Sabine	Strawberry guava
	Psidium guajava L.	Guava
	Syzygium paniculatum Gaertn.(= *Eugenia myrtifolia* Sims)	Brush cherry
Oleaceae	*Ligustrum sinense* Lour.	Chinese privet
	Ligustrum vulgare L.	European privet
Onagraceae	*Oenothera drummondii* Hook.	Beach eveningprimrose
Papaveraceae	*Argemone ochroleuca* Sweet	Pale Mexican pricklypoppy
Pinaceae	*Pinus canariensis* C. Sm.	Canary Island pine
	Pinus elliottii Engelm.	Slash pine
	Pinus nigra Arnold	Austrian pine
	Pinus patula Schiede ex Schltdl. & Cham.	Jelecote pine, Mexican weeping pine
	Pinus pinaster Aiton	Maritime pine
Poaceae	*Glyceria maxima* (Hartm.) Holmb.	Reed mannagrass
	Paspalum vaginatum Sw.	Seashore paspalum
Polygonaceae	*Polygonum campanulatum* Hook. f.	Bellflower smartweed
Proteaceae	*Hakea drupacea* (C.F. Gaertn.) Roem. & Schult.	Sweet hakea
	Hakea salicifolia (Vent.) B.L. Burtt	Willow-leaved hakea
	Hakea sericea Schrad. & J.C. Wendl	Needlebush, silky hakea
Rhamnaceae	*Rhamnus alaternus* L.	Italian buckthorn
	Ziziphus mauritiana Lam.	Indian jujube, Chinese apple
Rosaceae	*Cotoneaster divaricatus* Rehder & E.H. Wilson	Spreading cotoneaster
	Cotoneaster glaucophyllus Franch.	Cotoneaster
	Rubus fruticosus L. (species aggregate)	European blackberry
Malaceae/ Salicaceae	*Populus* x *canescens* (Aiton) Sm.	Gray poplar
	Populus deltoides Marshall	Common cottonwood
	Salix cinerea L.	Large gray willow, pussy willow
Scrophulariaceae	*Scrophularia auriculata* L.	Shoreline figwort
Solanaceae	*Cestrum aurantiacum* Lindl.	Orange jessamine
	Physalis peruviana L.	Peruvian groundcherry
	Solanum pseudocapsicum L.	Jerusalem-cherry
Ulmaceae	*Celtis sinensis* Pers.	Chinese hackberry
Verbenaceae	*Glandularia pulchella* (Sweet) Troncoso (= *Verbena tenuisecta* Briq.)	South American mock vervain
	Stachytarpheta spp.	Snakeweed
Vitaceae	*Vitis riparia* Michx.	Riverbank grape
Zingiberaceae	*Alpinia zerumbet* (Pers.) B.L. Burtt. & R.M. Sm.	Shellplant
	Hedychium coronarium J. Koenig	White ginger, garland-lily
	Hedychium flavescens Carey ex Roscoe	Yellow ginger lily, cream garland-lily

Based on Brenzel (2007) or Hill and Narizny (2004).

* These should be reviewed by the horticulture industry and also watched for any spread into wildlands.

TABLE 3. Plants already naturalized in California, but not sold as ornamentals in California

Family	Species	Common name
Asteraceae	*Chrysanthemoides monilifera* (L.) Norlindh	Boneseed, bitou bush
Boraginaceae	*Heliotropium amplexicaule* Vahl	Clasping or blue heliotrope
Fabaceae	*Acacia paradoxa* DC.	Kangaroothorn
	Acacia pycnantha Benth.	Golden wattle
	Cytisus multiflorus (L'Hér.) Sweet	White spanishbroom
Iridaceae	*Romulea rosea* (L.) Eckl.	Rosy sandcrocus
Poaceae	*Agrostis capillaris* L.	Colonial bentgrass
Polygonaceae	*Polygonum aviculare* L.	Prostrate knotweed
Rosaceae	*Rubus ulmifolius* Schott	Elmleaf blackberry
Solanaceae	*Solanum mauritianum* Scop.	Woolly nightshade

Rosy sandcrocus (*Romulea rosea*), a fairly new invasive species along the central coast of California, was introduced as a garden ornamental.

TABLE 4. Plants naturalized in California and also sold as ornamentals in the state*

Family	Species	Common name
Aizoaceae	*Malephora crocea* (Jacq.) Schwantes	Coppery mesembryanthemum
Apocynaceae	*Catharanthus roseus* (L.) G. Don	Pink periwinkle, Madagascar periwinkle
	Nerium oleander L.	Oleander
Aponogetonaceae	*Aponogeton distachyos* L. f.	Cape pondweed
Arecaceae	*Phoenix dactylifera* L.	Date palm
Asphodelaceae (formerly Liliaceae)	*Kniphofia uvaria* (L.) Oken	Redhot poker
Asteraceae	*Coreopsis lanceolata* L.	Garden coreopsis
	Erigeron karvinskianus DC.	Mexican daisy, Latin American fleabane
	Gazania linearis (Thunb.) Druce	Treasureflower
	Helianthus tuberosus L.	Jerusalem artichoke
	Osteospermum ecklonis (DC.) Norl.	African daisy
	Osteospermum fruticosum (L.) Norl.	Trailing African daisy, shrubby daisybush
Berberidaceae	*Berberis darwinii* Hook.	Darwin's berberis
Bignoniaceae	*Jacaranda mimosifolia* D. Don	Jacaranda, black poui
	Macfadyena unguis-cati (L.) A. Gentry	Cat's claw creeper, catclaw-vine
Cabombaceae	*Cabomba caroliniana* Gray	Fanwort
Caprifoliaceae	*Lonicera japonica* Thunb.	Japanese honeysuckle
Celastraceae	*Maytenus boaria* Molina	Mayten
Clusiaceae	*Hypericum androsaemum* L.	Sweet-amber
	Hypericum calycinum L.	Aaron's beard, rose of Sharon
Convolvulaceae	*Ipomoea indica* (Burm. f.) Merr.	Blue morningglory
Ebenaceae	*Diospyros lotus* L.	Persimmon, date plum
Fabaceae	*Acacia baileyana* F. Muell.	Bailey acacia, cootamundra wattle
	Acacia elata A. Cunn. ex Benth.	Cedar wattle
	Dipogon lignosus (L.) Verdc.	Okie bean
	Gleditsia triacanthos L.	Honey locust
	Senna didymobotrya (Fresen.) Irwin & Barneby	African senna
	Senna multiglandulosa (Jacq.) Irwin & Barneby	Glandular senna
Geraniaceae	*Geranium lucidum* L.	Shining geranium
	Geranium robertianum L.	Herb-robert
Iridaceae	*Chasmanthe floribunda* (Salisb.) N.E. Br.	African cornflag
Lamiaceae	*Lavandula stoechas* L.	French lavender
	Salvia verbenaca L.	Wild clary
Malvaceae	*Hibiscus trionum* L.	Venice mallow
Myrtaceae	*Eucalyptus cladocalyx* F. Muell.	Sugargum
Oleaceae	*Ligustrum japonicum* Thunb.	Japanese privet
	Ligustrum lucidum Ait.	Glossy privet
Onagraceae	*Fuchsia magellanica* Lam.	Hardy fuchsia
Oxalidaceae	*Oxalis latifolia* Kunth	Broadleaf woodsorrel
Papaveraceae	*Papaver somniferum* L.	Opium poppy
Passifloraceae	*Passiflora tarminiana* Coppens & V.E. Barney	Banana passionfruit
	Passiflora tripartita (Juss.) Poir. var. *mollissima* (Kunth) Holm-Niesen & P.M. Jerg.	Banana passionfruit
Pinaceae	*Pinus halepensis* Mill.	Aleppo pine
	Pinus pinea L.	Italian stone pine
Pittosporaceae	*Pittosporum tobira* (Thunb.) W.T. Aiton	Mock orange, Japanese cheesewood
	Pittosporum undulatum Vent.	Sweet pittosporum, Victorian box
Poaceae	*Eragrostis curvula* (Schrader) Nees	Weeping lovegrass
	Pennisetum ciliare (L.) Link	Buffelgrass
Polygalaceae	*Polygala myrtifolia* L.	Myrtle-leaf milkwort
Proteaceae	*Grevillea robusta* A. Cunn. ex R. Br.	Silkoak
Ranunculaceae	*Clematis vitalba* L.	Old-man's-beard
Rosaceae	*Eriobotrya japonica* (Thunb.) Lindl.	Loquat
	Rosa canina L.	Dog rose
	Rosa eglanteria L. (= *Rosa rubiginosa* L.)	Sweetbriar rose
Salicaceae	*Populus nigra* L. var. *italica* DuRoi.	Black poplar, Lombardy popular
Solanaceae	*Datura inoxia* P. Mill.	Pricklyburr
Tamaricaceae	*Tamarix chinensis* Lour.	Five-stamen tamarisk
Ulmaceae	*Ulmus parvifolia* Jacq.	Chinese elm
	Ulmus pumila L.	Siberian elm
Verbenaceae	*Lantana camara* L.	Lantana

* These may be considered for removal from the trade through discussions with the horticulture industry and also watched for further spread into wildlands.

Species introduced as ornamentals or forage species that have escaped cultivation in California include, *left*, Mexican daisy (*Erigeron karvinskianus*), Japanese honeysuckle (*Lonicera japonica*), buffelgrass (*Pennisetum ciliare*) and African daisy (*Osteospermum ecklonis*). While these species are not yet major problems in the state, some have become more serious invasive plants in other regions of the country.

full prescreening risk assessment before introduction to the state. Plants that are not naturalized in California but that are sold here (table 2) should be reviewed by the nursery industry to reduce their sale and also watched for any spread into wildlands. In addition, noninvasive ornamentals that serve the same purpose in a landscape (same plant shape, same color flowers, etc.) should be promoted as alternative options. Species that are naturalized but not yet sold in California (table 3) should be restricted from sale, and land managers should watch for their further spread. Finally, species that are both naturalized and also sold in California (table 4) may be considered for removal from the trade and also watched by land managers for further spread into wildlands.

This list provides a good starting point for identifying plants, especially ornamental species, that are invasive in regions with similar climates to California and could become problematic here. However, additional steps are required to further understand the potential risk of invasion. In particular, a more detailed risk assessment should be conducted for each of the species we identified as being at high risk for future invasion. Several risk assessment protocols (e.g., DiTomaso et al. 2012; Koop et al. 2012; Reichard and Hamilton 1997) are available to prioritize the greatest potential threats to wildland systems. Implementing these preventative approaches and establishing an early detection program to eradicate incipient populations of these targeted species are far less costly than attempting to manage or contain large well-established populations of invasive plants.

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100 ways UCCE changed California

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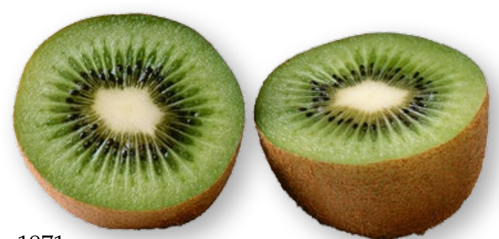
The Rise of the Kiwifruit

In the 1970s, California farmers became interested in a new exotic crop — kiwifruit. The fruit, native to China, was first grown commercially in New Zealand and named the Chinese gooseberry. In the 1950s, when New Zealand first began exporting the fruit commercially, its name was changed to kiwifruit due to its slight resemblance to the country's national bird, the brown, rotund and spiky-feathered kiwi.

Kiwifruit was very well received in the United States, and its popularity began growing rapidly. California growers began to experiment with the unfamiliar fruit, and the state's first commercial production began in the mid-1960s. By 1971, nearly 100 acres of kiwifruit had been planted, mostly in Butte and Kern counties. But many growers were unsuccessful with these early kiwifruit endeavors, as little was known about growing, processing or marketing the fruit here in California. Recognizing the need for more information, UC Cooperative Extension (UCCE) pomology specialist Jim Beutel began researching the new crop, acknowledging in one 1977 article that "the kiwifruit's external appearance is not particularly attractive." But, he added, "the flesh is an attractive emerald green color and has numerous small, jet-black, edible seeds."



A kiwifruit vineyard at the Kearney Agricultural Research and Extension Center.

By the 1980s, kiwifruit production in California had skyrocketed, with the industry increasing 667% to keep up with the growing demand. Beutel was instrumental in supporting the industry's expansion, doing research, publishing information, providing one-on-one consultations to growers all over the state and helping other UCCE farm advisors put on kiwifruit short courses in their communities.

Today, thanks to the work of Beutel, kiwifruit is a mature industry in the state. California kiwifruits are exported all over the world and make up 98% of the kiwifruit industry in the United States. The fruit also provides an important alternative crop for growers who specialize in tree fruits or table grapes.

—Marissa Palin Stein