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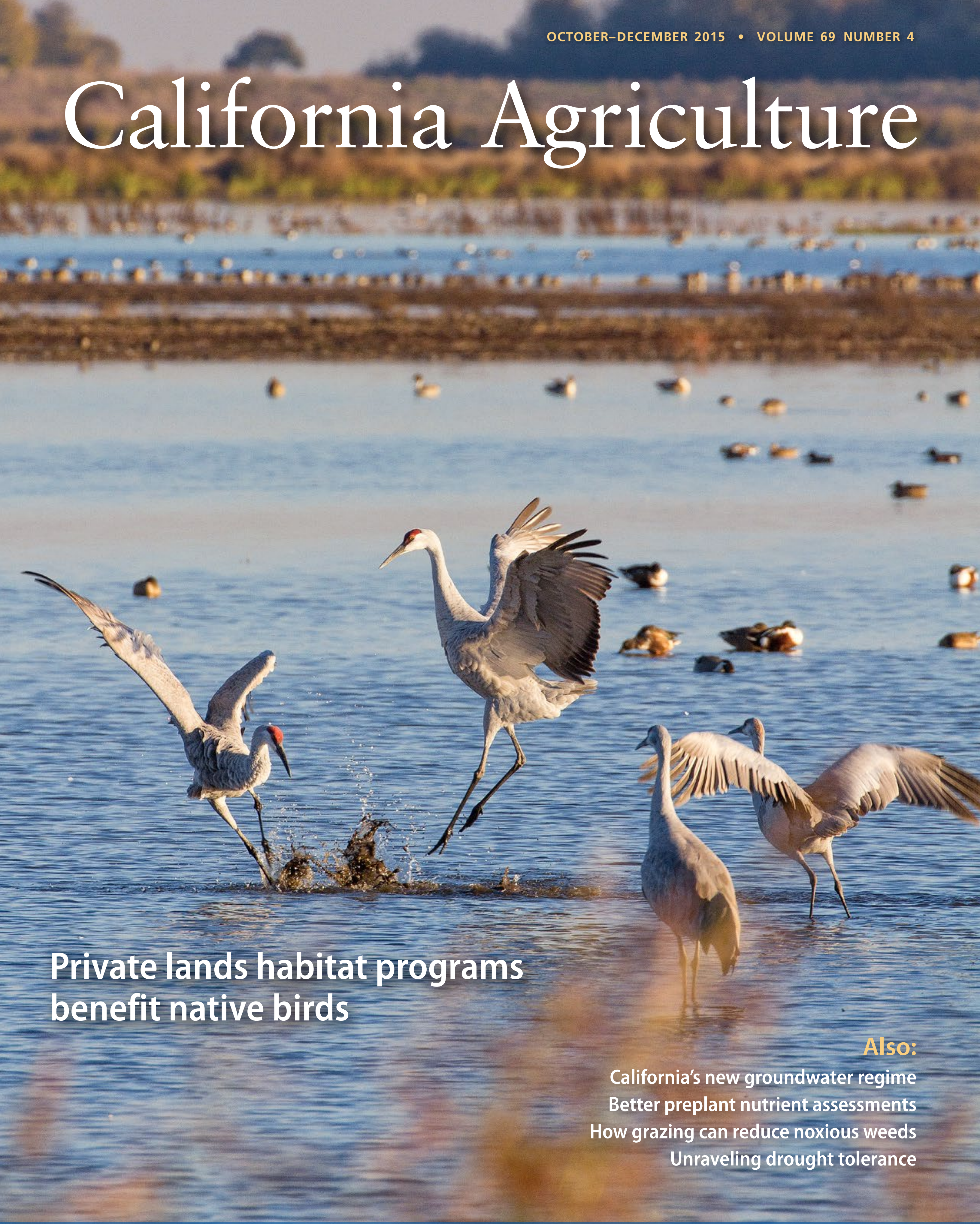
California Agriculture



Private lands habitat programs benefit native birds

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About *California Agriculture*

California Agriculture is a quarterly, peer-reviewed journal reporting research and reviews, published by the University of California Agriculture and Natural Resources (ANR). The first issue appeared in 1946, making *California Agriculture* one of the oldest, continuously published, land-grant university research journals in the country. There are about 11,000 print subscribers.

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COVER: Sandhill cranes (*Grus canadensis*) on Staten Island in the Sacramento-San Joaquin Delta. The birds are in a wheat field that is flooded seasonally to provide habitat. A 5-year study of California's North Coast and Central Valley found that private wetlands and croplands enrolled in habitat conservation programs support a wide range of birds, including many species designated as threatened or endangered (page 210). *Photo by Will Suckow.*

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Will Suckow

UC ANR: The original incubator

In August, Glenda Humiston started as the new vice president of UC Agriculture and Natural Resources (UC ANR). As the head of UC ANR, Humiston oversees UC Cooperative Extension (UCCE), the Agricultural Experiment Station and the division's many statewide programs, from 4-H to UC IPM to the UC Master Gardener Program. Humiston came to UC ANR from the U.S. Department of Agriculture, where she was California state director for rural development from 2009 to 2015. Previously, she was deputy undersecretary for natural resources and environment at USDA from 1998 to 2001. She holds a doctorate in environmental science, policy and management from UC Berkeley, a master's degree in international agricultural development from UC Davis and a bachelor's degree in animal science from Colorado State University.

Glenda Humiston
Vice President
UC Agriculture and Natural Resources

There's a lot of excitement in California today about how connecting people and businesses with resources, information and each other can help to generate new ideas and fuel economic growth.

Across the state, governments, universities, philanthropic organizations and the private sector are establishing business incubators and economic development clusters to capitalize on the power of networks and partnerships. The Shared Value Initiative (sharedvalue.org), a fast-growing movement in the business world, argues that some of the best opportunities for innovation and new markets are to be found in identifying and addressing unmet social needs.

As an organization with a traditionally rural focus and roots in the 19th century, UC ANR might appear stuck on the sidelines of these trends.

But I'd argue that we have a central role in turning ideas into successful, socially beneficial enterprises — and that we've been at it for a long, long time.

For a century, farmers, ranchers and natural resource managers have relied on research and new technologies disseminated through UCCE. With UC ANR's help, growers have increased yields, improved water-use efficiency, reduced pesticide loads, made food safer, expanded export markets and become more environmentally and economically sustainable. California communities and the economy have benefited from successful new industries, healthy ecosystems and sustainably managed landscapes.

If UC ANR isn't an incubator, I don't know what is. Furthermore, I would argue that the partnership of our land-grant university system with Cooperative Extension is the original and most productive incubator that the world has ever seen.

UC ANR works on the most critical issues of our time: food production, environmental sustainability, health and youth development. Providing leadership and helping to drive progress in these areas requires UC ANR to leverage its assets with a wide array of external partners, projects and resources and increase public awareness of how well-managed agricultural and natural resources contribute to California's well-being. There is no one-size-fits-all approach; each region or sector needs tools and strategies to meet its particular goals and needs. As California seeks accord among diverse interests and competing goals, UC ANR must provide knowledge to improve the quality of decisions as well as leadership to help communities find consensus on difficult issues.

As the new vice president of UC ANR, perhaps my most important responsibility is to build collaborations with communities, businesses, organizations and individuals around the state and the nation. This collaborative mission has guided my professional career.

UC ANR has many opportunities to enhance how it serves its mission, supports its clientele and expands the reach of its programs. Capitalizing on these opportunities will require new collaborations — and perhaps unlikely-looking allies. Some partnerships may involve a single UC institution; but I have found that, in most cases, connecting multiple institutions and interdisciplinary resources proves to be much more powerful.

Here's a small taste of the types of partnerships and opportunities I'm talking about:

- **Building Healthy Communities**. Foundations and other philanthropic organizations not only fund but, increasingly, engage directly in community

Eléna Zhukova


JBT FoodTech

This beverage unit installed by AgPLUS partner JBT FoodTech can process up to 600 containers per minute.

development initiatives. One example is the California Endowment's "Building Healthy Communities" initiative. The program funds projects to improve access to food, health care, land use, education, small business development and community leadership. UCCE, UC Master Gardeners and 4-H programs can offer much to ensure the success of such initiatives while UC ANR researchers could support analysis of results and offer innovations in program delivery and extension to additional sites.

- **UC Davis and Seed Central.** Established in 2010, Seed Central is an initiative of the Seed Biotechnology Center at UC Davis and SeedQuest that has been joined by a growing number of companies and organizations in the global seed and food industry. Some 100 seed and seed-related companies are located near UC Davis and benefit greatly from its proximity. Seed Central facilitates communication and research collaboration between the seed industry and UC Davis in order to bring science more quickly to market, creating a globally influential research and development cluster.
- **UC Merced's Blum Center for Developing Economies (BCDE) and Tuolumne County Economic Development Authority (TCEDA).** These institutions are connecting researchers and students to innovators, entrepreneurs and makers throughout Central California to apply science, technology, engineering and mathematics skills and creativity to solve real-world challenges via the "InnovationLab." The lab offers 24/7 space and access to tools like 3-D printers, application-development equipment, an electronics lab, wood shop, computer and social media technology, and conferencing capability for interactions with the UC campus.
- **Central Valley AgPLUS.** Food and beverage processing is California's third-largest manufacturing sector, with 3,421 firms providing 760,000 full- and part-time jobs and producing $82 billion (as of 2012) of direct added value annually. Central Valley AgPLUS is an unprecedented effort to grow this sector through a strategic partnership between the Office of Community and Economic Development at Fresno State, the Center of Economic Development at Chico State, Valley Vision, Innovate NorthState, and the Central Sierra Economic Development District. Participating in this collaboration allows UC ANR to greatly expand partnerships and support key initiatives in climate change, the bioeconomy and advanced manufacturing.

These examples highlight how research, UCCE activities and other resources generated by UC ANR help to improve California's triple bottom line: people, planet and prosperity.

As a graduate of three outstanding land-grant universities, a long-time participant in 4-H, and a frequent partner with UCCE on a wide array of projects throughout California, I have personally experienced how UC ANR addresses many of the key issues of our age. It is a mission that I embrace deeply on a personal and professional level, and I look forward to working with you, UC ANR's stakeholders, on partnerships that can help us to reach our shared goals. CA


Elēna Zhukova

Starting with this issue, *California Agriculture* will publish a regular feature on projects at UC ANR's Research and Extension Centers

Kearney and West Side RECs:
Studies of sorghum's adaptation to drought push the frontiers of crop improvement

With the climate changing and demands on water resources growing, crops that can survive drought are near the top of the global agricultural wish list.

But drought tolerance has so far confounded plant researchers. One problem is that it involves many complex relationships: a host of genes that activate when a plant is short of water; soil microbes that interact with plant roots. Another difficulty has been that plants respond differently to water stress when they are grown outdoors rather than indoors, meaning that greenhouse-based findings haven't translated well to the field.

Two new research projects involving the Kearney and West Side Research and Extension Centers (RECs) are taking on these challenges, using a multifaceted, field-based approach with sorghum as their subject. The knowledge gained could lead eventually to the ability to control the mechanisms of drought tolerance and the development of improved varieties of sorghum and other crops.

West Side REC director Bob Hutmacher collects a soil sample next to a sorghum plant to evaluate the microbial population around sorghum roots.

"We may be able to find ways to manipulate those characteristics to enable drought tolerance and water use efficiency," said Kearney REC director Jeff Dahlberg. "That's the ultimate pie-in-the-sky goal."

The projects are funded by recent grants from the U.S. Department of Energy (DOE) — one from the Biological and Environmental Research (BER) Program and the other from the Advanced Research Project Agency-Energy (ARPA-E). The two DOE programs support the study of microbes and plants for sustainable biofuel production.

Sorghum, in addition to being a staple food grain in much of the world, is promising as a bioenergy crop and as a substitute for corn silage in livestock rations. It is a good candidate for improved drought tolerance in part because it already handles water stress better than many other crops, including its close relative, corn. The grain emerged as a food crop in drought-prone areas of Africa, and existing varieties exhibit a range of traits that help the crop endure periods of scarce water.

Peggy Lemaux, a UC ANR Cooperative Extension specialist based at UC Berkeley, is the principal investigator on the 5-year, $12.3 million BER-funded project awarded in September. Using field plots of sorghum at Kearney and West Side RECs, the project will investigate what's known as the epigenetics of drought tolerance — the ways in which certain genes are activated in response to water stress, Lemaux said. These mechanisms, which allow rapid adjustments to stresses, can change the plant's physiology to better cope with reduced moisture.

The project also will investigate how microbes in the soil may interact with sorghum to enhance its drought tolerance. Compounds produced by microbes may act as signals, touching off epigenetic or other responses that help sorghum plants survive a long dry stretch, Lemaux said. Microbial populations also might enhance delivery of water and nutrients to a sorghum plant's roots and trigger them to produce enzymes and plant hormones that influence its growth and yield.

Lemaux noted that the BER project takes advantage of UC ANR's institutional structure, partnering campus-based Agricultural Experiment Station (AES) faculty and Cooperative Extension specialists with researchers based at the RECs. The project's collaborators also include a UC Berkeley faculty member in statistics and DOE researchers based at the Joint Genome Institute and the Pacific Northwest National Laboratory (PNNL). It's a powerful combination of laboratory and field expertise and resources, Lemaux said.

"We couldn't do it without them, and they couldn't do it without us," Lemaux said of the collaboration between campus- and REC-based researchers.

The ARPA-E grant, for $3.3 million, is headed by PNNL researchers and will include significant work at the Kearney and West Side RECs, led by Dahlberg and West Side REC director Bob Hutmacher. The project will use aerial drones to gather high-resolution imaging data on test plots of multiple varieties of sorghum subjected to varying levels of drought stress.

The drone-based imaging should yield higher-quality data, in less time, on the test plants' physical characteristics, or phenotypes. Unlike many of the other processes in genetic research, which have been dramatically accelerated by automation, documenting plant phenotypes still involves a great deal of manual work. Faster phenotyping would expand the number of field tests and the amount of data that a research team can generate and analyze.

These two major projects build on a Kearney-based study begun in 2012 on the potential for wider-scale cultivation of sorghum in California as a food, feed and fuel crop. That work, led by Dahlberg and involving seven other UC ANR researchers, including Hutmacher and Lemaux, was funded by a $596,000 grant from UC ANR.

Dahlberg became interested in sorghum in the early 1980s as a Peace Corps volunteer in Niger, where the crop is generally grown without irrigation. He chose to study sorghum for his dissertation research at Texas A&M and has been working on it ever since, bringing his interest in the crop to the Kearney REC when he joined as director in 2011.

Globally, sorghum is the fifth most widely produced grain, behind corn, rice, wheat and barley. It is currently a minor crop in California, grown on fewer than 100,000 acres, but there's reason to believe it will have a larger role in the future. It can be grown to yield grain or for biomass or silage production, and it is quite hardy, tolerating extremes of heat as well as waterlogging and drought. Such versatility is well suited to the sorts of extreme weather conditions that continued climate change is expected to bring. CA

Peggy Lemaux

UC Berkeley researchers Devin Coleman-Derr and John Taylor collect soil samples to evaluate microbial populations in an undisturbed field.

Jeff Dahlberg

Test plots at California State University Fresno contrast sorghum plants that have received 50% of their evapotranspiration demand (foreground) and those that have received 100% (right and background). While sorghum is highly drought tolerant, it still needs water. Both the timing and the amount of water applied influence the plant's development.

Research Article

Private lands habitat programs benefit California's native birds

by Ryan T. DiGaudio, Kimberly E. Kreitinger, Catherine M. Hickey, Nathaniel E. Seavy *and* Thomas Gardali

To address the loss of wetlands and riparian forests in California, private lands habitat programs are available through U.S. federal and state government agencies to help growers, ranchers and other private landowners create and enhance wildlife habitat. The programs provide financial and technical assistance for implementing conservation practices. To evaluate the benefits of these programs for wildlife, we examined bird use of private wetlands, postharvest flooded croplands and riparian forests enrolled in habitat programs in the Central Valley and North Coast regions of California. We found that private Central Valley wetlands supported 181 bird species during the breeding season. During fall migration, postharvest flooded croplands supported wetland-dependent species and a higher density of shorebirds than did semipermanent wetlands. At the riparian sites, bird species richness increased after restoration. These results demonstrated that the programs provided habitat for the species they were designed to protect; a variety of resident and migratory bird species used the habitats, and many special status species were recorded at the sites.

There is considerable interest in understanding how private lands in California can contribute to providing habitat for wildlife (Duffy and Kahara 2011; Elphick and Oring 2003; Morrisette 2001). California supports an exceptionally rich mosaic of natural communities — it ranks first out of the 50 states in diversity and endemism of native plant and animal species (Stein 2002). However, the Mediterranean climate, diverse soil types and extensive water resources that contribute to California's biological diversity also foster agricultural productivity, which can conflict with the conservation of wildlife habitat in the state's freshwater wetlands and riparian forests. The Central Valley alone has lost an estimated 95% of its historic wetlands and 98% of its riparian forests, primarily due to conversion to agriculture (Dahl 1990; Dawdy 1989; Frayer et al. 1989; Katibah 1984; Kempka et al. 1991). This extensive habitat loss has led to a growing list of threatened and endangered species in California, accompanied by burdensome regulations on landowners designed to protect these at-risk species. Programs that support private landowners for conserving natural habitat resources have the potential to protect ecosystems and reduce regulatory burdens on the landowners.

In California, habitat programs designed to enhance wetland and riparian ecosystems have included the Natural Resources Conservation Service's (NRCS) Wetlands Reserve Program and U.S. Fish and Wildlife Service's (USFWS) Partners for Fish and Wildlife Program, which restore, enhance and protect habitat through voluntary easement agreements;

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Private lands habitat programs help producers restore and manage wetlands and other important bird habitats on their farmland.

Ryan T. DiGaudio

Riparian habitat in the arid West is considered the single most important habitat type for neotropical migratory landbirds.

and the California Department of Fish and Wildlife's (CDFW) California Waterfowl Habitat Program and its Landowner Incentive Program, which provide financial and technical support for habitat management. The latter two management-based programs were explicitly designed to maximize the habitat value of private lands already enrolled in conservation easement programs, such as the former two programs. These state and federal programs provide incentives and assistance for land management that contribute to regional conservation objectives for birds (CVJV 2006; Hickey et al. 2003; RHJV 2004). However, the outcomes of these programs have not been extensively studied for birds (except see Kahara et al. 2012).

In partnership with state and federal agencies, we initiated a study in the Central Valley (2004 to 2008) and North Coast (Marin and Sonoma counties, 2001 to 2009) regions of California to evaluate bird response to private lands habitat programs on managed wetlands, postharvest flooded croplands and restored riparian vegetation. Our objectives were to (1) determine if wetland habitat supported by habitat programs benefits local, breeding, wetland-dependent birds, (2) test whether the practice of postharvest flooding of croplands can effectively provide surrogate wetland habitat for migratory and breeding waterbirds and (3) determine if riparian restoration projects on private land lead to an increase in the number of riparian bird species.

To achieve our objectives, we conducted bird surveys at sites where habitat conservation, management and restoration practices have been implemented and used species tallies, comparisons of bird densities between treatments, and counts of numbers of bird species over time to evaluate success. We defined success as the use of these sites by the species for which the programs were designed to provide habitat, and by the occurrence of many special status species at the sites.

Bird survey methods

We surveyed birds on properties enrolled in at least one of the state and federal habitat programs mentioned above: the Wetlands Reserve Program, the Partners for Fish and Wildlife Program, the California Waterfowl Habitat Program and Landowner Incentive Program. Most of the sites were enrolled in multiple programs; however, we did not attempt to evaluate individual programs or specific program combinations. Study site selection was not random; we surveyed sites identified for us by the funding agencies and partners.

Wetland breeding survey. To summarize bird use, we tallied which bird species used participating private wetlands across the Central Valley during the spring and summer breeding season. We surveyed birds from April to July (repeating the survey approximately every 3 weeks) in seasonal, semipermanent and permanent wetlands supported by multiple state and federal habitat programs.

Seasonal wetlands were flooded during the winter and drained during the spring; semipermanent wetlands were flooded from winter or early spring through summer (often until July 15) and permanent wetlands had water year-round. These wetlands varied in size from 2 to 260 acres.

We surveyed birds for 5 years (2004 to 2008) in four geographic subregions of the Central Valley, conducting a total of 2,246 surveys at 221 wetland sites. Each site represented a distinct wetland management unit or pond. The wetlands were located in the Delta (n = 8), Sacramento Valley (n = 108), the San Joaquin Basin (northern San Joaquin Valley; n = 62) and

Encouraging producers to flood their croplands after harvest can help provide important stopover habitat for migrating waterfowl, waterbirds and shorebirds such as these long-billed dowitchers (*Limnodromus scolopaceus*). This practice is particularly beneficial for wetland-dependent birds in the Tulare Basin, where much of the region's natural wetlands have been lost.

the Tulare Basin (southern San Joaquin Valley; $n = 43$).

To survey birds, we used a scan-sampling survey method, which entailed scanning each wetland using binoculars and/or spotting scopes from various vantage points along the wetland's perimeter (Reed et al. 1997). Surveys were conducted during daylight hours, and duration of surveys varied from roughly 5 minutes to 2 hours, depending on the number of birds and size of the wetland. We assumed that relatively few birds entered or left during the survey period, and that the length of the survey did not influence the number of birds counted. Species were confirmed breeding if we observed nests, dependent fledglings, precocial young, nesting material carries, food carries, fecal sac carries, copulation or distraction displays (e.g., killdeer, *Charadrius vociferous*, broken wing display).

In restored riparian habitat at North Coast sites, the authors documented 88 bird species and confirmed breeding for 42 species, including warbling vireo (*Vireo gilvus*).

To summarize the bird use of the wetlands, we grouped survey data from all wetland types (seasonal, semipermanent and permanent) and tallied the total number of species (separating waterbird and landbird species), the number of species breeding and the number of species with special conservation status. We defined special conservation status species as species that are designated as either state or federally threatened or endangered (CDFW 2015), CDFW Bird Species of Special Concern (Shuford and Gardali 2008) or USFWS Bird Species of Conservation Concern (USFWS 2008).

Wetland fall migration survey. In the Tulare Basin of southern San Joaquin Valley, we surveyed birds on 16 postharvest, flooded cropland fields and 23 semipermanent wetlands supported by the Landowner Incentive Program. We conducted surveys every 2 weeks in August and September during the fall migratory period from 2005 to 2008.

Cropland fields were flooded in August and September, and water was held through October or later, up to December, depending on the year. The semipermanent wetlands were flooded in April and remained flooded through the August and September survey period. We employed the same bird survey methodology as described above. To summarize bird use of these flooded fields and semipermanent wetlands, we tallied the total number of species (separating waterbird and landbird species) and the number of species with special conservation status.

We also compared the bird use of flooded fields and semipermanent wetlands. We measured the area of each field or wetland and then, on each survey, calculated the density (birds per acre) of shorebirds, ducks and large wading birds (herons, egrets, ibis and cranes). We averaged the density for each field or wetland across the 119 surveys during the study. We then compared mean bird density (expressed as birds per 10 acres) between postharvest flooded croplands and semipermanent wetlands.

Since the data were not normally distributed, we conducted one-way Monte-Carlo permutation tests (9999 permutations) to determine if there were significant differences in density between flooded croplands and semipermanent wetlands. All tests were done in R version 2.8.1 (R Development Core Team 2008) using the Coin package (Hothorn et al. 2008).

Riparian habitat survey. In the Central Valley (18 sites) and the North Coast (15 sites), we surveyed birds at sites where riparian restoration was supported by multiple state and federal incentive programs. The restoration of these areas included fencing out livestock and planting native riparian vegetation. Restoration ages of the areas ranged from 0 to 14 years at the Central Valley sites and 0 to 20 years at the North Coast sites. We conducted bird surveys from April to June to evaluate the breeding bird community, primarily songbirds (Passeriformes).

In the Central Valley, we conducted point count surveys described by Ralph et al. (1993). We established 152 point count stations approximately 200 meters apart across the 18 riparian restoration sites (2 to 25 points per site, depending on the size of the site). Stations were surveyed twice during the breeding season from 2004 through 2008. During 5-minute counts (beginning at dawn and continuing for the first 4 hours of the morning), we recorded all birds seen or heard and the estimated distance (< 50 or > 50 meters) to the bird. For analysis, we used only those birds noted within 50 meters of the observer and assumed that detection probabilities were similar within this distance among habitat types and years. Furthermore, we excluded nonterritorial species and species with large territories (e.g., waterfowl, shorebirds, raptors and swallows), since point count methods were not designed for these types of species.

At the North Coast sites, we used the area search method to survey the breeding bird community at the 15 restoration sites over a period of 9 years (2001 to 2002, 2004 to 2005, and again in 2009). We used this method instead of point counts at the North Coast sites because they were generally too small to fit multiple independent point counts. All sites were surveyed two or three times ≥ 10 days apart following standardized protocols (Ralph et al. 1993). Area search plots varied in size from ⅓ to 10 acres and followed the course of the creek. The plot boundaries remained static over time. Each area search survey period was constrained to 20 minutes.

For Central Valley point count data, we calculated mean species richness (total number of species detected) per point per site for each year. For North Coast area search data, we calculated species richness for each area search plot for each year. We used linear regression to test for significant trends in species richness over years since restoration for both regions. For this analysis, we assumed that the increase in species richness over the course of the study was linear, that temporal autocorrelation was not significant and that

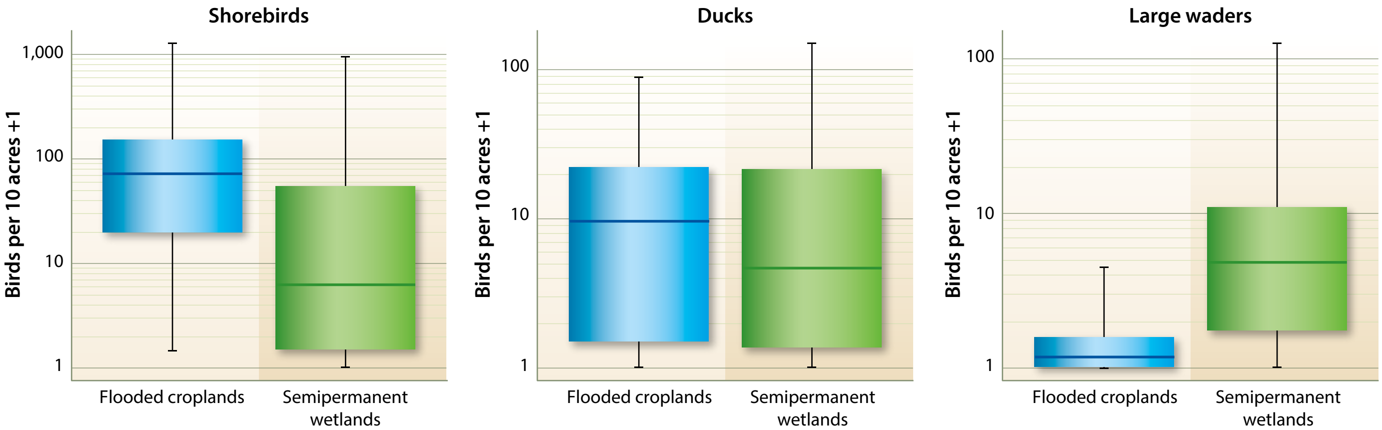

Fig. 1. Modified boxplots depicting log (density + 1) (birds per 10 acres) of shorebirds, ducks and large waders at postharvest flooded croplands and semipermanent wetlands. The shaded box indicates the central 50% of the data points (also called the interquartile range), and the horizontal line within the box indicates the median.

the residuals were normally distributed. Analyses were performed in R version 2.8.1 (R Development Core Team 2008).

Bird counts

Wetland breeding sites. In seasonal, semipermanent and permanent wetlands during the breeding season, we detected a total of 181 species (75 waterbird species and 106 landbird species), including 30 of the possible 43 special conservation status bird species known to occur in Central Valley wetlands (table 1). Of the special status species, 3 were designated as state endangered, 2 as state threatened and 1 as federally threatened (table 1). We also confirmed breeding for 78 species of birds, 12 of which were special status.

Wetland fall migration sites. In August and September, we found 63 species on flooded croplands and 88 species in wetlands. The number of different species was 107 in total, 59 waterbirds and 48 landbirds. We detected 15 special status species using flooded croplands and semipermanent wetlands in the Tulare Basin, including peregrine falcon (*Falco peregrines*), a species of conservation concern (table 1).

Density of birds varied among guilds between flooded croplands and semipermanent wetlands (fig. 1). We found a near-significant ($Z = 1.77$, $p = 0.07$) trend toward greater shorebird density in flooded croplands than in semipermanent wetlands. Large waders, however, were significantly more dense in semipermanent wetlands ($Z = -3.15$, $p = 0.001$). There was no significant difference in duck density between flooded croplands and semipermanent wetlands ($Z = 0.28$, $p = 0.78$).

Riparian sites. At the Central Valley riparian restoration sites, we detected a total of 132 bird species, including 1 state endangered, 2 state threatened and 18 other special status species (table 1). We confirmed breeding for 47 species in the Central Valley, including 5 special status species (table 1). At the North Coast sites, we detected 88 species, including 8 special status species. We confirmed breeding for 42 species at the North Coast sites, including 3 special status species (table 1).

In both the Central Valley and North Coast regions, bird species richness increased significantly as restoration sites matured ($p < 0.001$, $r^2 = 0.353$ and $p < 0.001$, $r^2 = 0.165$, respectively), suggesting a positive trajectory in recovering native riparian bird communities (fig. 2). In the Central Valley, the number of species detected during point counts increased by 0.41 species in each year after the restoration (95% confidence interval = 0.28 to 0.54). At the North Coast restoration sites, the number of species detected on area searches increased by 0.50 species each year after the restoration (95% confidence interval = 0.31 to 0.69).

Evaluation of benefits

Our results show that private lands that have been restored, enhanced and managed through habitat programs are being used by a diversity of bird species, including special status species targeted for conservation by habitat programs. Given the extensive loss of wetlands and riparian vegetation across California, particularly in the Central Valley (Dahl 1990; Dawdy 1989; Frayer et al. 1989; Katibah 1984; Kempka et al. 1991), these results suggest important conservation outcomes.

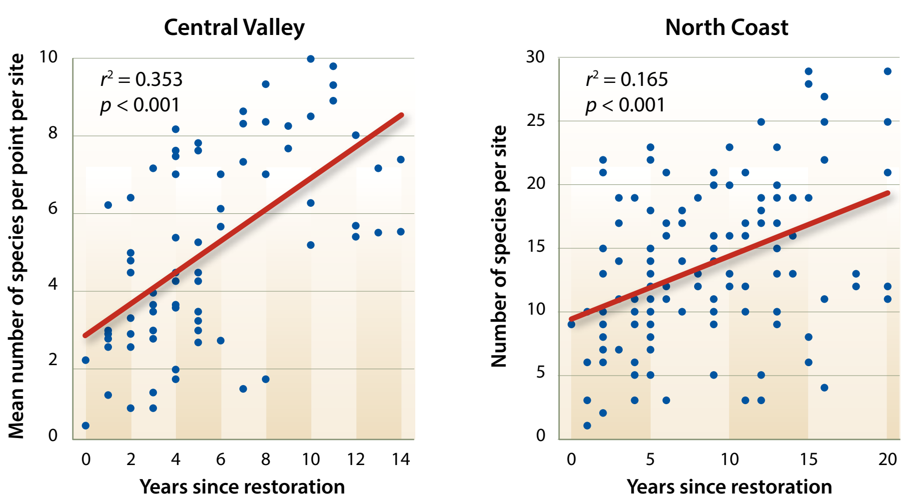

Fig. 2. Bird species richness plotted against restoration age in restored riparian habitat in the North Coast and Central Valley regions.

TABLE 1. Waterbird and landbird species detected at privately owned wetlands, flooded croplands and riparian restoration sites supported by private lands habitat programs

	Wetlands (spring–summer*)	Wetlands (fall†)	Flooded croplands (fall)	Riparian: Central Valley	Riparian: North Coast	Conservation status‡
WATERBIRDS						
Fulvous whistling-duck *Dendrocygna bicolor*	■					BSSC
Greater white-fronted goose *Anser albifrons*	■					
Snow goose *Chen caerulescens*	■			■		
Ross's goose *Chen rossii*	■					
Cackling goose *Branta hutchinsii*	■					
Canada goose *Branta canadensis*	●§			■		
Mute swan *Cygnus olor*	■					
Wood duck *Aix sponsa*	●	■		●		
Gadwall *Anas strepera*	●	■	■	■		
American wigeon *Anas americana*	■	■	■			
Mallard *Anas platyrhynchos*	●	■	■	●	●	
Blue-winged teal *Anas discors*	●					
Cinnamon teal *Anas cyanoptera*	●	■	■	■	■	
Northern shoveler *Anas clypeata*	●	■	■	■		
Northern pintail *Anas acuta*	●	■	■	■		
Green-winged teal *Anas crecca*	●	■	■			
Canvasback *Aythya valisineria*	■		■			
Redhead *Aythya americana*	●		■			BSSC
Ring-necked duck *Aythya collaris*	■					
Lesser scaup *Aythya affinis*	■					
Bufflehead *Bucephala albeola*	■					
Common goldeneye *Bucephala clangula*	■					
Hooded merganser *Lophodytes cucullatus*	■			●		
Common merganser *Mergus merganser*					●	
Ruddy duck *Oxyura jamaicensis*	●	■	■			
Pied-billed grebe *Podilymbus podiceps*	●	■	■	●		
Horned grebe *Podiceps auritus*	■	■				
Eared grebe *Podiceps nigricollis*	●	■	■			
Western grebe *Aechmophorus occidentalis*	●		■		■	
Clark's grebe *Aechmophorus clarkii*	●		■			
American white pelican *Pelecanus erythrorhynchos*	■	■	■	■		BSSC
Double-crested cormorant *Phalacrocorax auritus*	■	■	■	■		
American bittern *Botaurus lentiginosus*	●	■		■		
Least bittern *Ixobrychus exilis*	●					BSSC
Great blue heron *Ardea herodias*	●	■	■	■	■	
Great egret *Ardea alba*	●	■	■	■		
Snowy egret *Egretta thula*	■	■	■	■		
Cattle egret *Bubulcus ibis*	■	■	■	■		
Green heron *Butorides virescens*	■	■		■	●	
Black-crowned night-heron *Nycticorax nycticorax*	●	■	■	■	■	
White-faced ibis *Plegadis chihi*	●	■	■	■		
Virginia rail *Rallus limicola*	●	■		■		
Sora *Porzana carolina*	■	■		■		
Common gallinule *Gallinula galeata*	●	■		●		
American coot *Fulica americana*	●	■	■	■		
Sandhill crane *Grus canadensis*		■				ST (greater sandhill crane only), BSSC
Black-bellied plover *Pluvialis squatarola*	■	■	■			

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* Wetlands surveyed in the spring and summer (April to July) included seasonal, semipermanent and permanent ponds.

† Fall wetlands surveys (August and September) included only semipermanent wetlands.

‡ FT = federally threatened, SE = state endangered, ST = state threatened, BSSC = California bird species of special concern, BCC = USFWS bird species of conservation concern.

§ A circle symbol ● denotes confirmed breeding.

The Modesto song sparrow (*Melospiza melodia mailliardi*), a California bird species of special concern, is one of the 30 species with special conservation status the authors documented in Central Valley private wetlands.

In wetland habitat during the breeding season, we recorded 181 bird species, including 30 special status species. Our record included all 7 shorebird species known to breed in the Central Valley and confirmed breeding for 4 of those 7. The Central Valley Joint Venture (CVJV), a partnership of agencies and nongovernmental organizations that implements bird conservation within the Central Valley, established conservation objectives in 2006 for 7 waterbird focal species that breed within the Central Valley; we recorded 6 out of 7 of these species (CVJV 2006), 3 of which were confirmed breeding. That a significant proportion of the species identified in the CVJV Implementation Plan were breeding on these sites suggests that these habitat programs are effective at providing habitat for the species they are designed to support.

In fall, we found that shorebird and duck densities were similar between wetlands and flooded croplands, suggesting that flooding cropland can provide surrogate wetland habitat for these species during migration. Herons and egrets, however, were more dense in wetlands than in flooded croplands during the fall, perhaps because of the greater food availability for the long-legged waders in wetlands.

At riparian restoration sites on private lands at Central Valley and North Coast sites combined, we found 143 species, including 22 special status species and 5 out of the 7 CVJV riparian focal species (CVJV 2006). California Partners in Flight, a voluntary consortium of conservation groups, government agencies, academic institutions and individuals dedicated to reversing population declines of landbirds, has identified 17 riparian focal species as indicators of healthy riparian habitat; we found 14 out of these 17 riparian focal species (RHJV 2004). We found that bird species richness increased with age of restoration, and though we did not test the relationship between species richness and vegetation structure, we suggest that vegetation growth is primarily responsible for this trend. Landowners could expect to see early successional riparian birds (e.g., song sparrow, *Melospiza melodia*) recruit to restoration sites within the first few years after restoration, whereas late successional species such as cavity nesters (e.g., wren species) may not recruit for 5 to 10 years (Gardali et al. 2006).

At the end of the study, we provided every participating landowner with a letter that described the type of habitat they had made and included a list of the birds we had observed there. These letters also provided additional steps that they could take to enhance the habitat. The letters often led to conversations with landowners that provided an opportunity to discuss other habitat enhancement opportunities on their land.

For wetlands and flooded fields in the Central Valley, the most critical habitat element, and often limiting factor, is water. Water availability is an ever present

Cinnamon teal (*Anas cyanoptera*) was one of the 181 bird species the authors documented using private wetlands in the Central Valley during the breeding season.

Herons and egrets were more dense in wetlands than in flooded croplands during the fall, perhaps as a result of greater food availability in wetlands.

issue for managing wetland habitat in California, even during normal rainfall years. However, the severe and historic drought currently impacting the West has recently left much of the state's wetlands and traditionally flooded fields dry, thus making incentives to provide wetland habitat more important now than ever for the conservation of waterfowl, shorebirds and waterbirds. The availability and cost of pumping water or purchasing water from local irrigation districts during the summer can deter landowners from maintaining permanent or semipermanent wetlands through the breeding season. By providing financial assistance to landowners, private lands habitat programs can offset costs and thereby help landowners provide additional flooded acreage. Without these incentive programs, along with clean, reliable water supplies, these wetlands and flooded agricultural fields may be dry during crucial bird breeding, wintering and migration periods.

Without these incentive programs . . . these wetlands and flooded agricultural fields may be dry during crucial bird breeding, wintering and migration periods.

In addition to providing benefits to bird populations, flooding croplands after summer harvest in the Tulare Lake Basin can have agronomic benefits — it has been used by growers to remove accumulated salts, control black root rot (*Thielaviopsis basicola*) and increase soil moisture for the next crop planting (Moss et al. 2009). The practice, however, has become increasingly cost prohibitive, which further demonstrates the importance of incentive programs. Similarly, the restoration of riparian vegetation has benefits that extend beyond songbird habitat. Healthy riparian corridors can improve water quality, reduce erosion, provide resources for fish and other wildlife and prepare for climate change (Lennox et al. 2011; Seavy et al. 2009).

The presence of special status species can present a challenge for private landowners. If threatened or endangered species use the habitat created by incentive programs, landowners may become subject to regulatory burdens (e.g., limits on their ability to modify habitat on their property or restrictions on activities that could result in a "take" of a threatened or endangered species under the Endangered Species Act). To address this situation, a number of approaches to protecting landowners are being developed. One example is safe harbor agreement, a voluntary agreement between a private landowner and USFWS under which the landowner undertakes conservation activities, such as habitat restoration, intended to enhance the survival of threatened or endangered species. In exchange, USFWS agrees to not require additional or different land management activities to protect threatened or endangered species that may be attracted to the property by the improved habitat (Trainor et al. 2013). In the long run, the habitat programs may decrease the likelihood that species are added to the state and federal threatened and endangered lists, thereby reducing the need for the regulations.

Habitat programs provide a successful model of wildlife agencies, the agricultural community, nongovernmental organizations and private landowners voluntarily working together to help achieve conservation goals. Habitat programs are a win-win strategy; they support private landowners in maintaining productive farms and ranches, while promoting wildlife conservation. The future success of habitat programs will depend on maintaining the engagement of private landowners and the funding resources that provide landowners with financial and technical assistance. CA

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This project would not have been possible without the cooperation of the private landowners and managers, and we thank them for allowing us access to their properties and for their dedication to providing wildlife habitat. Funding for this project was provided by USDA NRCS Wetlands Reserve Program, USFWS Partners for Fish and Wildlife Program, USFWS Federal Assistance Program/CDFW Landowner Incentive Program, CDFW Comprehensive Wetland Habitat Program, S.D. Bechtel, Jr. Foundation, Central Valley Joint Venture, Altria Group, Richard Grand Foundation, Marin and Southern Sonoma Resource Conservation Districts and The Bay Institute. This manuscript benefited from feedback provided by Dean Kwasny, Craig Isola and Jessica Groves.

TABLE 1 (continued). Waterbird and landbird species detected at privately owned wetlands, flooded croplands and riparian restoration sites supported by private lands habitat programs

	Wetlands (spring–summer*)	Wetlands (fall†)	Flooded croplands (fall)	Riparian: Central Valley	Riparian: North Coast	Conservation status‡
WATERBIRDS						
Snowy plover *Charadrius nivosus*	●					BSSC, BCC
Semipalmated plover *Charadrius semipalmatus*	■	■	■			
Killdeer *Charadrius vociferus*	●	■	■	●	●	
Black-necked stilt *Himantopus mexicanus*	●	■	■	■		
American avocet *Recurvirostra americana*	●	■	■	■		
Spotted sandpiper *Actitis macularius*	■	■		■		
Solitary sandpiper *Tringa solitaria*	■	■				
Greater yellowlegs *Tringa melanoleuca*	■	■	■	■		
Willet *Tringa semipalmata*	■					
Lesser yellowlegs *Tringa flavipes*	■	■	■			
Whimbrel *Numenius phaeopus*	■		■	■		BCC
Long-billed curlew *Numenius americanus*	■	■	■	■		BCC
Marbled godwit *Limosa fedoa*	■	■	■			BCC
Sanderling *Calidris alba*	■					
Western sandpiper *Calidris mauri*	■	■	■			
Least sandpiper *Calidris minutilla*	■	■	■			
Baird's sandpiper *Calidris bairdii*			■			
Pectoral sandpiper *Calidris melanotos*		■				
Dunlin *Calidris alpina*	■		■			
Stilt sandpiper *Calidris himantopus*	■	■				
Ruff *Philomachus pugnax*	■					
Short-billed dowitcher *Limnodromus griseus*	■					BCC
Long-billed dowitcher *Limnodromus scolopaceus*	■	■	■	■		
Wilson's snipe *Gallinago delicata*	■	■				
Wilson's phalarope *Phalaropus tricolor*	■	■	■			
Red-necked phalarope *Phalaropus lobatus*	■	■	■			
Franklin's gull *Leucophaeus pipixcan*			■			
Ring-billed gull *Larus delawarensis*	■		■	■		
California gull *Larus californicus*	■		■			
Caspian tern *Hydroprogne caspia*	■	■	■	■		
Black tern *Chlidonias niger*	■		■	■		BSSC
Forster's tern *Sterna forsteri*	●	■	■			
Black swan *Cygnus atratus*	■			■		
LANDBIRDS						
California quail *Callipepla californica*	●			●	●	
Ring-necked pheasant *Phasianus colchicus*	●	■		●		
Wild turkey *Meleagris gallopavo*	●			■	■	
Turkey vulture *Cathartes aura*	■		■	■	■	
Osprey *Pandion haliaetus*	■	■		■		
White-tailed kite *Elanus leucurus*	■	■		■	■	
Bald eagle *Haliaeetus leucocephalus*	■					SE, BCC
Northern harrier *Circus cyaneus*	●	■	■	●		BSSC
Cooper's hawk *Accipiter cooperii*	●			■	■	
Red-shouldered hawk *Buteo lineatus*	■			■	■	
Swainson's hawk *Buteo swainsoni*	●	■		●		ST, BCC
Red-tailed hawk *Buteo jamaicensis*	●	■		●	■	
Golden eagle *Aquila chrysaetos*	■					
American kestrel *Falco sparverius*	■	■		●	■	
Merlin *Falco columbarius*	■		■			
Peregrine falcon *Falco peregrinus*	■		■	■		BCC

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* Wetlands surveyed in the spring and summer (April to July) included seasonal, semipermanent and permanent ponds.

† Fall wetlands surveys (August and September) included only semipermanent wetlands.

‡ FT = federally threatened, SE = state endangered, ST = state threatened, BSSC = California bird species of special concern, BCC = USFWS bird species of conservation concern.

§ A circle symbol ● denotes confirmed breeding.

TABLE 1 (continued). Waterbird and landbird species detected at privately owned wetlands, flooded croplands and riparian restoration sites supported by private lands habitat programs

	Wetlands (spring–summer*)	Wetlands (fall†)	Flooded croplands (fall)	Riparian		Conservation status‡
				Central Valley	North Coast	
LANDBIRDS						
Prairie falcon *Falco mexicanus*			■			
Rock pigeon *Columba livia*				■		
Eurasian collared-dove *Streptopelia decaocto*				■	■	
Mourning dove *Zenaida macroura*	●	■		●	■	
Western yellow-billed cuckoo *Coccyzus americanus*	■					FT, SE, BCC
Greater roadrunner *Geococcyx californianus*	■	■				
Barn owl *Tyto alba*	●	■			■	
Great horned owl *Bubo virginianus*	●			■	■	
Burrowing owl *Athene cunicularia*	■					BSSC, BCC
Short-eared owl *Asio flammeus*	■					BSSC, BCC
Lesser nighthawk *Chordeiles acutipennis*	■					
Vaux's swift *Chaetura vauxi*	■					
White-throated swift *Aeronautes saxatalis*	■					
Black-chinned hummingbird *Archilochus alexandri*	■			■		
Anna's hummingbird *Calypte anna*	■			■	■	
Rufous hummingbird *Selasphorus rufus*					■	BCC
Allen's hummingbird *Selasphorus sasin*					●	BCC
Belted kingfisher *Megaceryle alcyon*	■			●	■	
Acorn woodpecker *Melanerpes formicivorus*				■		
Nuttall's woodpecker *Picoides nuttallii*	●			■	●	BCC
Downy woodpecker *Picoides pubescens*	●			■	●	
Hairy woodpecker *Picoides villosus*					■	
Northern flicker *Colaptes auratus*	■			■	■	
Olive-sided flycatcher *Contopus cooperi*	■			■	■	BCC
Western wood-pewee *Contopus sordidulus*	●	■		●	■	
Willow flycatcher *Empidonax traillii*	■			■		SE, BCC
Dusky flycatcher *Empidonax oberholseri*	■					
Pacific-slope flycatcher *Empidonax difficilis*	■			■	■	
Black phoebe *Sayornis nigricans*	●	■		●	●	
Ash-throated flycatcher *Myiarchus cinerascens*	●			●	●	
Western kingbird *Tyrannus verticalis*	●	■		●	●	
Loggerhead shrike *Lanius ludovicianus*	●	■		■		BSSC, BCC
Cassin's vireo *Vireo cassinii*				■		
Hutton's vireo *Vireo huttoni*					■	
Warbling vireo *Vireo gilvus*	■			■	●	
Steller's jay *Cyanocitta stelleri*					■	
Western scrub-jay *Aphelocoma californica*	●			●	●	
Yellow-billed magpie *Pica nuttalli*	●			●		BCC
American crow *Corvus brachyrhynchos*	■	■	■	■	■	
Common raven *Corvus corax*	●		■	■	■	
Horned lark *Eremophila alpestris*	■	■	■	■	■	
Tree swallow *Tachycineta bicolor*	●	■	■	●	■	
Violet-green swallow *Tachycineta thalassina*	■		■		●	
Northern rough-winged swallow *Stelgidopteryx serripennis*	■	■		●	■	
Bank swallow *Riparia riparia*	■			■		ST
Cliff swallow *Petrochelidon pyrrhonota*	■	■	■	●	●	
Barn swallow *Hirundo rustica*	●	■	■	■	●	
Chestnut-backed chickadee *Poecile rufescens*					●	

* Wetlands surveyed in the spring and summer (April to July) included seasonal, semipermanent and permanent ponds.

† Fall wetlands surveys (August and September) included only semipermanent wetlands.

‡ FT = federally threatened, SE = state endangered, ST = state threatened, BSSC = California bird species of special concern, BCC = USFWS bird species of conservation concern.

§ A circle symbol ● denotes confirmed breeding.

TABLE 1 (continued). Waterbird and landbird species detected at privately owned wetlands, flooded croplands and riparian restoration sites supported by private lands habitat programs

	Wetlands (spring–summer*)	Wetlands (fall†)	Flooded croplands (fall)	Riparian Central Valley	Riparian North Coast	Conservation status‡
LANDBIRDS						
Oak titmouse *Baeolophus inornatus*	■			●	■	BCC
Bushtit *Psaltriparus minimus*	●			●	●	
White-breasted nuthatch *Sitta carolinensis*	■			■	■	
Brown creeper *Certhia americana*					■	
Rock wren *Salpinctes obsoletus*			■			
Bewick's wren *Thryomanes bewickii*	●			●	●	
House wren *Troglodytes aedon*	●			●	■	
Pacific wren *Troglodytes pacificus*					■	
Marsh wren *Cistothorus palustris*	●	■		●		
Ruby-crowned kinglet *Regulus calendula*	■			■		
Western bluebird *Sialia mexicana*	■			●	●	
Swainson's thrush *Catharus ustulatus*	■			■	●	
Hermit thrush *Catharus guttatus*	■			■		
American robin *Turdus migratorius*	●			●	●	
Wrentit *Chamaea fasciata*	■			■	■	
Northern mockingbird *Mimus polyglottos*	●			●		
European starling *Sturnus vulgaris*	●			●	●	
American pipit *Anthus rubescens*	■		■	■		
Cedar waxwing *Bombycilla cedrorum*	■			■	■	
Orange-crowned warbler *Oreothlypis celata*	■	■		■	●	
Nashville warbler *Oreothlypis ruficapilla*	■					
Yellow warbler *Setophaga petechia*	■	■		●	■	BSSC, BCC
Yellow-rumped warbler *Setophaga coronata*	■			■	■	
Townsend's warbler *Setophaga townsendi*	■			■		
Hermit warbler *Setophaga occidentalis*	■					
LANDBIRDS						
Black-and-white warbler *Mniotilta varia*				■		
MacGillivray's warbler *Geothlypis tolmiei*				■		
Common yellowthroat *Geothlypis trichas*	●	■		●	■	
Wilson's warbler *Cardellina pusilla*	■			■	●	
Yellow-breasted chat *Icteria virens*	■					BSSC
Spotted towhee *Pipilo maculatus*	●			●	●	
California towhee *Melozone crissalis*	●			●	●	
Rufous-crowned sparrow *Aimophila ruficeps*					■	
Brewer's sparrow *Spizella breweri*				■		BCC
Vesper sparrow *Pooecetes gramineus*	■	■				BSSC, BCC
Lark sparrow *Chondestes grammacus*	●			■	■	
Sage sparrow *Amphispiza belli*	■					
Savannah sparrow *Passerculus sandwichensis*	■	■	■	■	●	
Grasshopper sparrow *Ammodramus savannarum*	●			■	■	BSSC
Fox sparrow *Passerella iliaca*		■				
Song sparrow *Melospiza melodia*	●	■		●	●	Subspecies in the Sacramento Valley is BSSC (*M.m. mailliardi*)
Lincoln's sparrow *Melospiza lincolnii*	■	■		■		
White-crowned sparrow *Zonotrichia leucophrys*	■	■		■	■	
Golden-crowned sparrow *Zonotrichia atricapilla*	■			■	■	
Oregon junco *Junco hyemalis oregonus*	■			■	●	

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† Fall wetlands surveys (August and September) included only semipermanent wetlands.

‡ FT = federally threatened, SE = state endangered, ST = state threatened, BSSC = California bird species of special concern, BCC = USFWS bird species of conservation concern.

§ A circle symbol ● denotes confirmed breeding.

TABLE 1 (continued). Waterbird and landbird species detected at privately owned wetlands, flooded croplands and riparian restoration sites supported by private lands habitat programs

	Wetlands (spring–summer*)	Wetlands (fall†)	Flooded croplands (fall)	Riparian Central Valley	Riparian North Coast	Conservation status‡
LANDBIRDS						
Western tanager *Piranga ludoviciana*	■			■		
Black-headed grosbeak *Pheucticus melanocephalus*	●			●	●	
Blue grosbeak *Passerina caerulea*	●			■		
Lazuli bunting *Passerina amoena*	●	■		●	●	
Red-winged blackbird *Agelaius phoeniceus*	●	■	■	●	●	
Tricolored blackbird *Agelaius tricolor*	●	■		■	●	BSSC, BCC
Western meadowlark *Sturnella neglecta*	●	■		●	●	
Yellow-headed blackbird *Xanthocephalus xanthocephalus*	●	■		■		BSSC
Brewer's blackbird *Euphagus cyanocephalus*	●	■	■	●	●	
Great-tailed grackle *Quiscalus mexicanus*	●	■		■		
Brown-headed cowbird *Molothrus ater*	●	■		●	●	
Bullock's oriole *Icterus bullockii*	●			●	●	
Purple finch *Carpodacus purpureus*					■	
House finch *Carpodacus mexicanus*	●	■		●	●	
Lesser goldfinch *Spinus psaltria*	●			●	●	
Lawrence's goldfinch *Spinus lawrencei*				■		BCC
American goldfinch *Spinus tristis*	●	■		●	●	
House sparrow *Passer domesticus*	■			■	●	

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† Fall wetlands surveys (August and September) included only semipermanent wetlands.

‡ FT = federally threatened, SE = state endangered, ST = state threatened, BSSC = California bird species of special concern, BCC = USFWS bird species of conservation concern.

§ A circle symbol ● denotes confirmed breeding.

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California's agricultural regions gear up to actively manage groundwater use and protection

by Thomas Harter

New regulations are emerging in response to historic groundwater depletion and widespread groundwater quality degradation in California. They aim at long-term preservation of groundwater resources for use in agriculture, in urban areas and for the support of ecosystems in streams dependent on groundwater. The regulations are driving a historic shift in the way the agriculture sector is engaged in managing and protecting groundwater resources in California. A review and synthesis of these recent regulatory developments — the Sustainable Groundwater Management Act and new policies under the California Porter-Cologne Water Quality Control Act — clarifies key challenges for farmers, scientists and regulators and points to the need for continuing innovation in agricultural practices as well as in planning and policy.

Groundwater is a critical resource for California water management. Stored in aquifers, water from rainy seasons can be used during dry and hot summers and supports water users through droughts if it is replenished in wet years. Aquifers also help move water from areas of recharge (often on the edge of the valley floor near the foothills) to areas dominated by extraction that are miles or — in very large aquifers — a few tens of miles away. Unfortunately, in many areas of California we have not been replenishing this account sufficiently during wet years. Groundwater resources across California's agricultural regions have been more stressed during the current drought than at any other time in history (CDWR 2014a).

In most wells, depth to groundwater has exceeded that of the same or nearby wells in the 2007–2009 drought, and exceeds the depths recorded in the mid-20th century, prior to local, state and federal water projects (reservoirs and canals) coming on-line. The demand for groundwater has been increasing due to the increased acreage of intensively grown crops, large-scale conversion of rangeland and field crops to permanent crops and uncertainty about water deliveries from the Sacramento-San Joaquin Delta, the heart of California's elaborate surface water conveyance system (CDWR 2014b).

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The Kings River flows across a coarse gravel bed near the Sierra Nevada foothills, recharging groundwater.

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California Gov. Jerry Brown signed the new groundwater legislation into law in September 2014.

Lower groundwater levels have significantly increased pumping costs and increased the need for constructing deeper wells where existing wells were not sufficiently deep to access falling water levels (Howitt et al. 2014; Medellín-Azuara et al. 2015). Greater reliance on groundwater during the drought has caused land subsidence on a large scale in the Central Valley (in some cases more than 12 inches of subsidence in 2014 alone), coastal basins and Southern California; it has also exacerbated seawater intrusion where pumping occurs in aquifers near the coast (CDWR 2014c). As pumping lowers the water table, water quality is sometimes compromised by saline water or other naturally occurring contaminants (e.g., Jurgens et al. 2010). Rapidly falling water tables also lead to more-contaminated shallow groundwater entering drinking water wells.

Agricultural regions in California are challenged not only by dwindling groundwater supplies — a critical drought insurance for California — but also by significant groundwater quality degradation, in particular from nitrate and salt pollution. Pollutants may come from urban sources (such as wastewater treatment and food processing plants), domestic household sources (such as septic systems) or agricultural sources (such as fertilizer, animal manure and irrigation water).

A number of studies have shown a high incidence of nitrate, above drinking water standards, in domestic and public drinking water supply wells; in some counties, more than 40% of domestic wells exceed the nitrate limit for safe drinking water (Harter et al. 2012; Lockhart et al. 2013; LWA 2013; SWRCB 2013). Salt accumulation in streams and groundwater has also been found to be significant (LWA 2013), with potentially punitive economic consequences: By 2030, the combined impact of surface water and groundwater salinization to agriculture and the California economy, if current conditions continue and no preventative action is taken, is estimated at $6 to $10 billion annually in lost production costs, job losses and other impacts (Howitt et al. 2009).

The problems of groundwater overdraft and water quality degradation have been recognized for some time. Increasing public concern over the past two decades has raised the level of local, state and federal government engagement and of actions by policy- and decision-makers. Groundwater users and wastewater dischargers in the urban and the agricultural sectors face new regulatory requirements. While urban governments have a long history of dealing with limited water resources, the agricultural community is experiencing significant and historic changes in its involvement with managing groundwater extraction and protecting groundwater resources for the future.

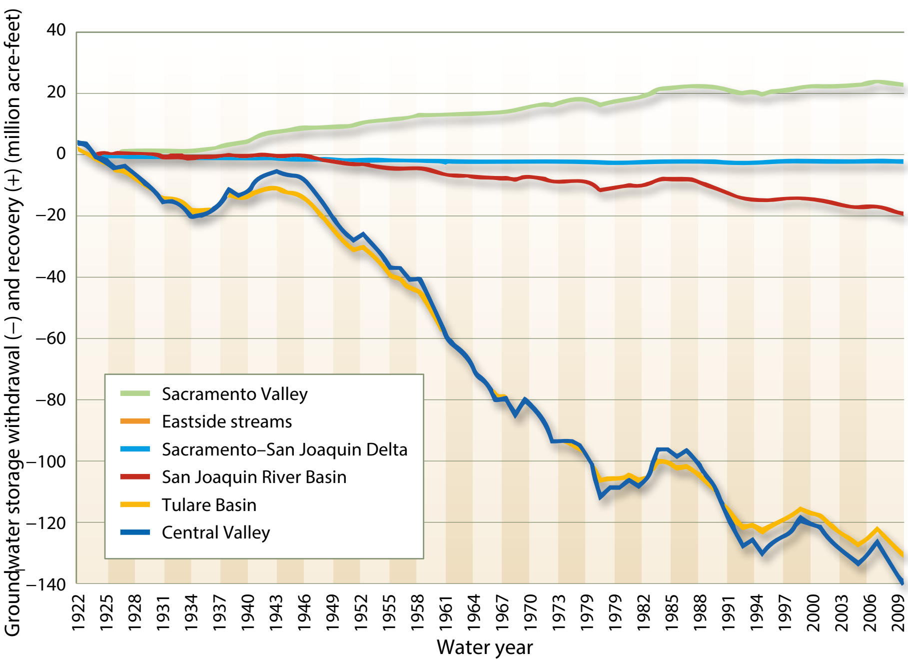

Fig. 1. Changes in groundwater storage in the California Central Valley (dark blue) and its subregions from 1922 to 2009 (adapted from Brush 2014). The largest depletions have occurred in the Tulare Lake Basin, which includes the southern part of the Central Valley from Fresno to Bakersfield.

Groundwater supply management

On September 16, 2014, Gov. Jerry Brown signed the Sustainable Groundwater Management Act (SGMA), California's first comprehensive groundwater management legislation. It focused on managing groundwater supplies as part of an integrated hydrologic system for the benefit of current and future generations of Californians.

The legislation and the governor's water action plan (California Natural Resources Agency 2014) recognize the importance of groundwater for California's livelihood and its central role in California water management. The legislation seeks to put a process in place that ends decades of unsustainable groundwater use and management in some California regions and prevents future unsustainable groundwater use in other regions. For example, an estimated 140 million acre-feet were depleted from the Central Valley aquifer system (mostly in the Tulare Lake Basin) between 1922 and 2010 (fig. 1). And seawater intrusion due to groundwater pumping has migrated 8 miles into the Salinas Valley aquifer system (fig. 2).

While other Western states have statewide water rights management systems that include groundwater, California has lacked an administrative approach to managing groundwater rights. Conflicts that have arisen among groundwater users, for example in some areas in urban Southern California, have been addressed through expensive and lengthy judicial proceedings called groundwater basin adjudications.

The core principles that guided the development of the new legislation include the following:

- A vision that groundwater is best managed and controlled at the local or regional level; the state would only step in if local efforts are not successful or are not moving forward in accordance with the law.
- A broad definition of groundwater sustainability and a specific outline of what undesired effects must be avoided. The latter include continuous water level drawdown, subsidence, seawater intrusion, water quality degradation and continued (or new) impacts to groundwater-dependent ecosystems and streams after Jan. 1, 2015, when the legislation took effect.
- The state's role is focused on providing clear guidelines on requirements for local groundwater management, to be developed in 2015 and 2016 by the Department of Water Resources, as well as providing technical and financial support.
- Existing water rights will continue to be protected.

The agricultural community is experiencing significant and historic changes in its involvement with managing groundwater extraction and protecting groundwater resources.

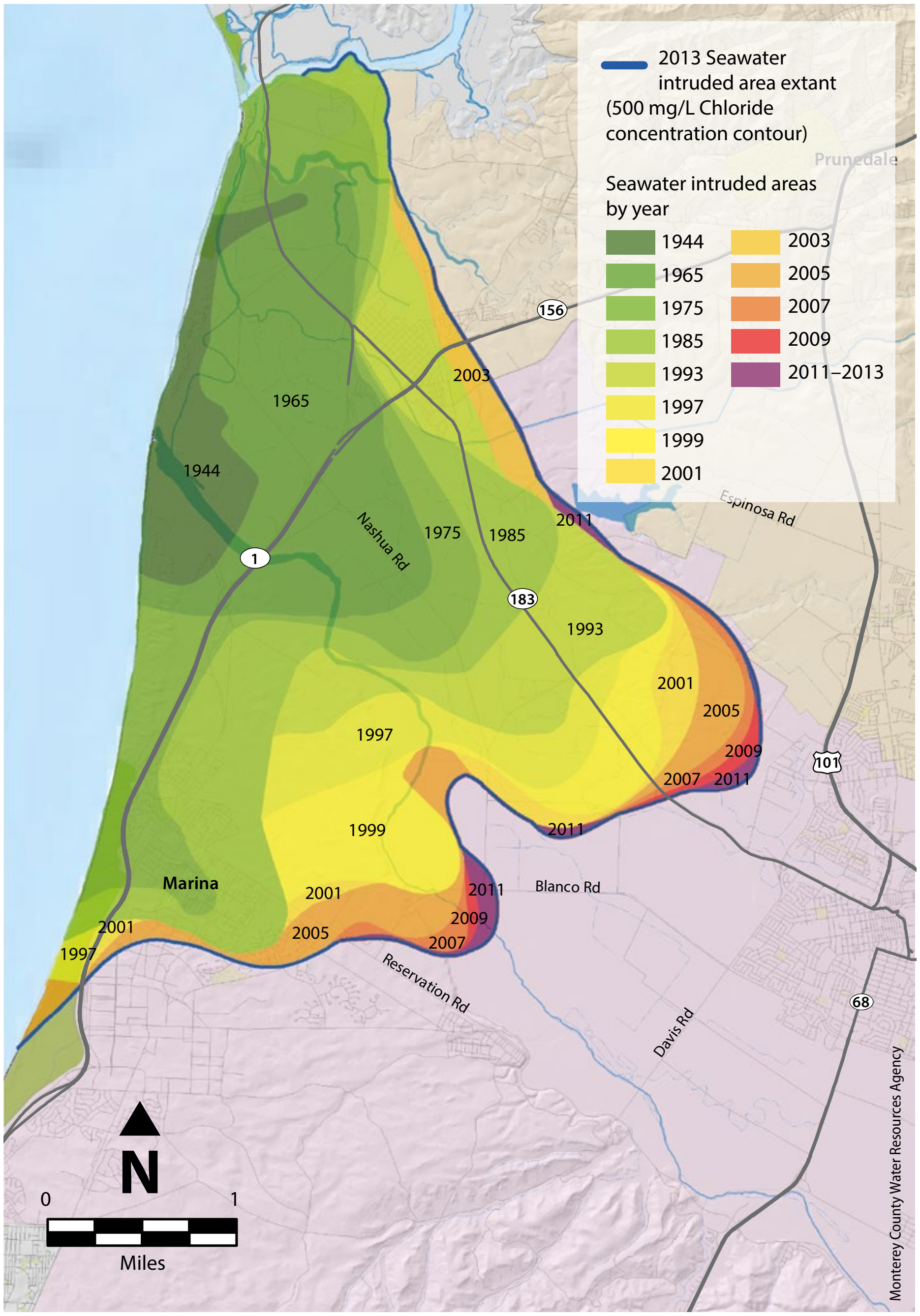

Fig. 2. History of seawater intrusion in the Salinas Valley (Brown and Caldwell 2015).

Based on these principles, the legislation lays out a framework for the entire state to manage its groundwater. In 127 medium- and high-priority groundwater basins (representing about 96% of groundwater extraction), groundwater sustainability agencies (GSAs) will have to be formed no later than June 2017. These GSAs will be responsible for developing and implementing a groundwater sustainability plan (GSP) that has specific objectives and meets specified sustainability targets consistent with the core principles of the SGMA. GSAs have 3 to 5 years to develop and begin implementing their GSP (by 2022, or in critically overdrafted basins by 2020). GSAs must show significant progress in implementing their plan and achieve sustainability no later than 2042.

Between 2015 and 2017, the focus of the implementation of the SGMA will be multipronged:

- GSAs will be formed that together govern all of the 127 medium- and high-priority groundwater basins, not just partially but in their entirety. This process will only be possible with significant local stakeholder involvement and will require significant outreach, facilitation and local leadership.
- The Department of Water Resources will be in charge of identifying critically overdrafted basins, developing minimum regulations for a GSP, new rules for adjusting basin boundaries and implementing basin coordination among GSAs, and regulations for determining medium- and high-priority basins that have significant groundwater-dependent ecosystems or stream flow but are not already included in the current group of 127 medium- and high-priority basins.
- Technical guidelines and financial support will be developed throughout the state.

While farmers and landowners may not see immediate impacts from the legislation, their involvement in the formation of the GSAs and in the development of the GSPs provides opportunities to shape the political process in ways typically not possible in the court-driven adjudication process. GSAs can be formed by local public agencies, such as cities, counties, water and irrigation districts, or other special acts districts (e.g., water replenishment districts).

The SGMA provides flexibility and allows for either a single agency or multiple agencies to run a GSA. A GSA in turn may govern an entire groundwater basin or just a portion of a groundwater basin. Where multiple GSAs govern a groundwater basin, GSAs have to coordinate their efforts. A basin may have a single GSP implemented by one or multiple GSAs, or a GSA may have multiple GSPs. Importantly, the GSAs must consider the interests of the wide range of groundwater uses and users, including agricultural pumpers. Given the broad authorities given by the SGMA to GSAs in managing recharge and extraction, groundwater users have strong motivation to be engaged early in the formation of GSAs to ensure political representation in the decision-making process when GSPs are developed and implemented. GSPs will rank around four key programmatic areas:

- data collection, monitoring, modeling, evaluation, assessment and reporting (on a continuous basis)
- stakeholder engagement, communication, outreach and facilitation of stakeholder-informed policy development
- development of groundwater supply projects to increase recharge as needed (e.g., intentional recharge, groundwater banking, increased recycled water use, storm water capture, surface water imports)
- reducing groundwater extraction as needed (e.g., water conservation programs, land purchases for agricultural land retirement, setting extraction limits, extraction fees)

Funding for GSP activities will likely come from a combination of state and local funding sources.

In overdrafted basins, adjudications may continue to be an alternative process to achieve sustainability, despite the high cost and often years-long legal proceedings involved. As of this writing, the Legislature is actively considering multiple bills that would create an alternative, streamlined adjudication process.

In the intermediate and long run, the main impact from this legislation will be that new recharge and groundwater storage options will be pursued, and, where needed, pumpers may see restrictions in pumping or well drilling. Where additional recharge is available, pumpers may be asked to pay additional costs to secure the recharge needed in return for their right to continue pumping. Basin boundaries may be adjusted and may include fractured rock aquifers currently not recognized as groundwater basins by the Department of Water Resources although they are subject to significant groundwater extraction in some areas.

Litigation and state intervention may be inevitable in some cases, but it remains to be seen how frequently that route will be chosen over mediation or facilitated GSP development and implementation. In either case, the new groundwater legislation marks a turning point in California water management by no longer allowing for continued depletion of groundwater resources and by requiring an active, well-informed groundwater management system that is better integrated with surface water management, water quality management and land use decisions to maintain a balance that best serves competing human, economic and environmental health interests.

Groundwater quality regulation

The federal Clean Water Act addresses only surface water quality. By contrast, California's water quality law, the Porter-Cologne Water Quality Control Act of 1969 (Porter-Cologne Act), includes the protection of groundwater quality. The California Legislature designated the State Water Resources Control Board (SWRCB) and nine newly created regional water boards (RWBs) to implement the Porter-Cologne Act.

The primary function of the RWBs is to establish a basin plan that identifies water quality goals and to develop regulatory programs to achieve those goals. Nonpoint sources of potential groundwater pollution (urban storm water, agriculture) were long exempted from direct oversight through unconditional waste discharge waivers. However, those waivers were discontinued by the Legislature in 2002, which led to new regulatory requirements for agricultural and other nonpoint source water dischargers (Dowd et al. 2008). Focused on surface water quality in the first decade after 2002, these regulatory efforts now increasingly address groundwater quality. They require demonstrable source control and documentation of groundwater nitrate and salt discharges and also provide state and federal funds to improve the drinking water supplies of communities affected by poor groundwater quality.

The nine RWBs use different approaches to assess and control agricultural discharges. The Central Valley RWB and Central Coast RWB regions are home to large areas of California's most intensive agricultural operations and have therefore developed the most extensive regulations. But all RWBs are obligated to consider discharges from nonpoint sources to groundwater and to develop basin plan amendments for nutrient and salt management (SWRCB 2009).

In the Central Valley, three major programs have been or are being developed to control salt and nutrient discharges to groundwater and surface water: the Central Valley Dairy Order, the Irrigated Lands Regulatory Program (ILRP) and the Central Valley Salinity Alternatives for Long-Term Sustainability (CV-SALTS) program. The Central Coast has developed its own version of the ILRP, referred to as the Central Coast Agricultural Order.

With respect to groundwater protection, all of the above programs have in common that they require

- assessment of sources, groundwater pathways (hydrogeology, water quality) and potential groundwater quality impacts
- source management plans
- source management certification and reporting
- direct or indirect (proxy) groundwater discharge monitoring
- development of management practices that are protective of groundwater quality
- groundwater monitoring at the regional level

Central Valley Dairy Order. The 2007 Dairy Order was the first comprehensive California groundwater quality permitting program applicable specifically to farms. It sets the framework for permitting dairy discharges of nutrients and salts to surface water and groundwater. The dairy order requires dairies to prepare nutrient and waste management plans, annually report nutrient budgets for individual fields, tonnage of manure exports and water quality of on-site wells. Targeted shallow groundwater monitoring and efforts to develop improved management practices that demonstrably improve groundwater quality are implemented through the Central Valley Dairy Representative Monitoring Program. This program is led by a coalition of dairy producers that is working closely with the RWB; it offers an efficient alternative to individual dairy groundwater monitoring plans.

Central Valley Irrigated Lands Regulatory Program. Upon its inception in the early 2000s, the Central Valley ILRP (like a similar program in the Central Coast region) focused on surface water and watershed protection through farmer education, certification and coalition-led stream water quality monitoring and management. But since 2010, the Central Valley RWB has been expanding the ILRP to add elements that also protect and improve groundwater quality, primarily nitrate, pesticide and salt contamination, through source management on irrigated lands.

In the Central Valley, the ILRP covers about 7 million irrigated acres with several tens of thousands of individual farms. Permits (waste discharge orders) are given either to individual farms or to regional ILRP coalitions, organizations that farms can join to represent them collectively with the RWB. ILRP coalitions representing large groups of farmers include the Sacramento River Watershed, Rice Farmers, Eastern San Joaquin Watershed, San Joaquin County and Delta, Western San Joaquin Watershed, Tulare Lake Basin Area, and Western Tulare Lake Basin Area coalitions. Each coalition is subject to a separate RWB order.

Under the expanded ILRP, the first step is a Groundwater Assessment Report (GAR), which is currently being developed or has been developed by each of the coalitions. The assessment identifies

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Water well drilling rig on the UC Davis campus.

historic and current groundwater quality conditions and identifies vulnerable groundwater regions. The assessment provides the rationale for the monitoring and reporting requirements, which may differ within and between regions, and allows for a tiered program of monitoring and reporting requirements for subregions to reflect the diverse potential impacts to groundwater.

In a next step, beginning in 2015, field-specific nutrient management planning forms will need to be completed by all farmers for the first time. Generally, farmers will now be required to implement management practices, keep appropriate records (for random audits) and report some of the information collected to their coalition. The coalitions are further responsible for performing groundwater monitoring, typically in a network of domestic and monitoring wells. As in the dairy program, the coalitions are also responsible for developing management practices that demonstrably improve and protect groundwater quality. A significant focus will be on documenting field nitrogen inputs and outputs and on improving nitrogen-use efficiency.

Central Coast Agricultural Order. In 2012, the Central Coast RWB adopted an update to the ILRP, called the Agricultural Order (or Agricultural Regulatory Program). The program covers about 4,000 farms on about 400,000 acres. Based on its own groundwater assessment work, the RWB created three tiers of farms depending on the potential risk they pose to groundwater quality. The tiers are determined by pesticide use, farm size, nitrate occurrence in nearby public supply and farm wells, and by crop type. About one in seven farms are in the highest tier, tier three (posing the greatest risk), about half of the farms, mostly vineyards, fall in the lowest tier (posing the least risk), and the remainder are in tier two.

As in the Central Valley, farms in all tiers are required to perform proper nutrient, pesticide and irrigation management, documented in their farm plans (although the specific forms may differ from those in the Central Valley). Backflow prevention and proper well abandonment are also required on all farms. Unlike in the Central Valley ILRP, all farms need to sample groundwater from existing wells twice during the first year. Subsequent groundwater sampling frequency is greater for farms in tier three than in tier two or one. Farms can choose to implement the groundwater sampling program individually or join a coalition that has been created specifically to perform groundwater monitoring and to support farmers with the implementation of the Agricultural Regulatory Program.

Central Valley SALTS program. Operating at an even larger scale and affecting stakeholders beyond agriculture (e.g., wastewater treatment plants, food processing plants, urban storm water systems) is the Central Valley Salinity Alternatives for Long-Term Sustainability (CV-SALTS) program. In coordination with the RWB, it was created in 2009 by stakeholders to develop a comprehensive salt and nutrient basin plan amendment for the Central Valley that complies with the state's recycled water policy (SWRCB 2009). The development of the basin plan amendment includes a wide range of assessments by CV-SALTS: nitrate and salt source loading from agricultural, urban and industrial sources, extensive review of surface water and groundwater quality data, and development of potential management practice and infrastructure solutions.

The CV-SALTS program builds upon and is coordinated with the Central Valley Dairy Order and ILRP efforts. It focuses in particular on avoiding future salinization of the Central Valley aquifer system under SWRCB's overarching antidegradation policy. Stakeholders are organized within the Central Valley Salinity Coalition (CVSC), which is scheduled to provide its final salt and nutrient management plan (SNMP) to the RWB in 2016. As part of these efforts, a recent Strategic Salt Accumulation and Transport Study (SSALTS) compared historic water quality data to an assessment of current salt and nutrient loading in the Central Valley; it determined that approximately 1.2 million acre-feet of Central Valley groundwater needs to be desalinized annually to meet long-term irrigation and drinking water standards.

SSALTS suggests various alternatives for water treatment, including desalination and evaporation ponds. Implementation costs are estimated to be roughly $70 billion over the next 30 years, of which $20 billion can be raised by selling approximately 1.1 million acre-feet of ultraclean treated water annually to urban areas. These costs include some saline water being disposed of by deep injection and some being stored in salt accumulation areas on the Tulare Lake Bed (CDM Smith 2014).

Challenging transitions for agriculture, science and the regulatory community

These efforts to manage groundwater supply and groundwater quality make the agricultural community subject to an evolving set of new requirements for documentation of key farm activities, training, practice improvement, monitoring and reporting. This will be a significant and in some cases expensive shift in farming practices. It is without parallel in California's agricultural history. As was the case with the development and implementation of water quality regulatory programs in the 1970s through 1990s that targeted and significantly changed practices in industrial and urban land uses, the transition period will be challenging for this newly regulated community and likely take a generation to be fully effective.

To the degree that a more centralized, region-wide effort — rather than a farm-by-farm approach — can direct the goals of these new programs, the ILRP coalitions will have a key role in providing services to help member farmers comply, at an annual cost currently ranging from about $3 to $7 per acre (including regulatory fees assessed by the RWBs). Similar coordination and funding approaches may evolve within the GSAs that implement the new sustainable groundwater management legislation, with some additional funding available also through state and federal grants. But in addition to paying monitoring and compliance fees, farmers and their employees will also participate in training and continuing education, provided through the ILRP coalitions, local GSAs, UC ANR Cooperative Extension, National Resources Conservation Service, Resource Conservation Districts and others; and on many farms, significant infrastructure improvements are needed to address groundwater quality and quantity concerns, at significant cost to the farm operation (Medellin-Azuara et al. 2013).

This is not a transition period only for farmers; it is also a transition period for scientists and educators who develop and provide innovative management practices and training to protect groundwater quality and better understand the groundwater–agriculture interface. Agronomic and crop scientists have rarely taken into account losses of contaminants to groundwater when developing best management practices and farm recommendations. Existing recommendations for fertilizer applications, for example, are in urgent need of revision to account for potential unwanted losses of nutrients to groundwater (Gold et al. 2013; Rosenstock et al. 2014). Another challenge for scientists is the design of groundwater monitoring networks. Existing groundwater research has developed many approaches to monitoring distinct contaminant plumes, typically a few acres in size (e.g., Einarson and Mackay 2001), but recommendations for the design of nonpoint source monitoring networks are currently lacking (Belitz et al. 2010).

Furthermore, this is a transition period for regulatory agencies, which for the first time are regulating nonpoint sources of groundwater pollution that involve large tracts of land with numerous individual landowners who are adjacent to each other and a wide range of crops, soils and management practices. For agencies, this is a situation that requires innovative strategies and a significant rethinking of existing programs that have been focused on point sources or surface water quality.

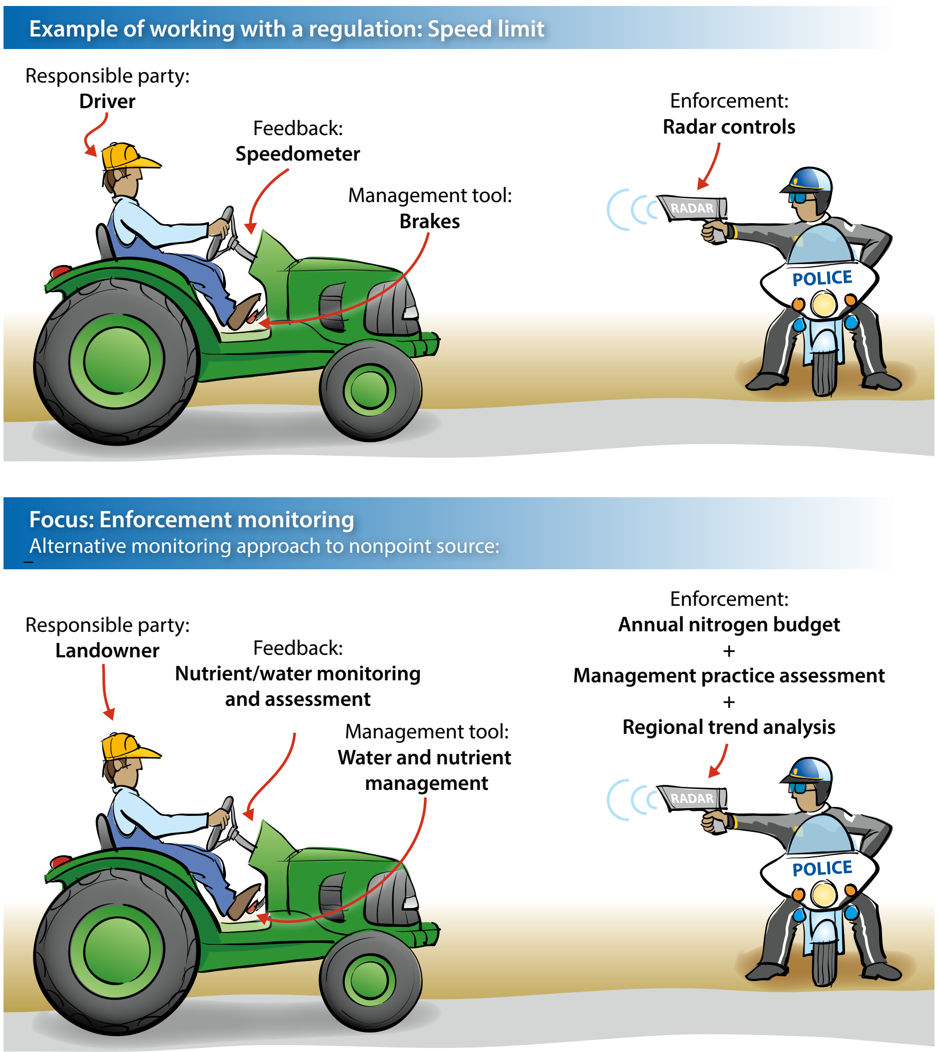

Fig. 3. Implementation of new nonpoint source monitoring programs to evaluate discharge to groundwater. A well-known enforcement program is the speed limit, which involves the driver as the responsible party, a speedometer that provides instantaneous feedback on speed, brakes and accelerator to adjust the speed, and police radar controls for enforcement. The equivalent in nonpoint source regulatory programs is the landowner as responsible party, the nutrient and water budgets as feedbacks to the landowner, nutrient and water management as the tool to adjust discharge and a three-tracked monitoring program for enforcement (see text).

For example, regulatory agencies have long focused on shallow groundwater monitoring wells as a key tool for monitoring potential waste discharges into groundwater and to detect inadvertent contaminant plumes from point sources, such as from underground gasoline storage tanks. Underground storage tanks are discrete point sources, and leaks from them can be detected by using down-gradient monitoring wells (Day et al. 2001). Agricultural irrigation, in contrast, leaks by design across broad landscapes, to flush salts from the root zone. Agricultural irrigation has therefore also been a significant source of groundwater recharge, especially irrigation from older non-efficient systems.

New monitoring approaches

Regulatory agencies have come to recognize that traditional site monitoring well networks are not the most effective tool for farm discharge monitoring. In the Central Valley Dairy Order, Central Valley ILRP and Central Coast Agricultural Order, an alternative is emerging that employs a loosely integrated three-tracked monitoring approach (fig. 3):

1. Proxy monitoring, e.g., nutrient budgets: Nitrogen budgets at the field and farm scale are used to estimate potential groundwater nitrate losses, instead of groundwater monitoring wells that would more directly observe discharge of nitrate.

2. Management practice assessments: Because discharge is not measured directly, research is needed to show the relationship between the nitrogen budget (the proxy waste discharge monitoring tool), agricultural management practices and impact to groundwater quality. In the Central Valley ILRP, this step is referred to as the management practice evaluation program.

3. Regional trend monitoring: As an insurance that the first two tracks are successful, regional long-term dynamics in groundwater quality are monitored through trend monitoring programs, implemented by farm coalitions or through a regulatory agency (e.g., California Department of Pesticide Regulation domestic well monitoring program).

Two monitoring wells (short white casings) adjacent to an irrigated, manure-treated field as part of a dairy monitoring program.

The specific monitoring requirements under each of the three tracks are a function of groundwater conditions, potential pollution sources, proximity to public and private water supply wells and existing contamination. The role of the groundwater assessments described above is to better understand these aquifer conditions as a basis for developing these three-tracked monitoring programs effectively, efficiently and commensurate with groundwater vulnerability.

Future directions

New agricultural practices to manage groundwater quantity and quality. Managing groundwater quantity in California's diverse agricultural landscape is intricately linked to protecting groundwater quality and vice versa. New practices in the agricultural landscape to recharge clean water into aquifers while maintaining high irrigation efficiencies and while also controlling nutrient and pesticide leaching will address both groundwater overdraft and groundwater quality.

Dzurella et al. (2012) and others have outlined numerous ways to improve nutrient management in California's diverse cropping systems, following largely the concept of the Four Rs: Right amount, Right time, Right place, Right form (CAWSI 2015). Significant educational efforts by universities, state and federal agencies, and industry groups will need to continue and intensify to support agriculture in moving forward with practices that better protect groundwater. There is one key complication around managing nutrients: while high nutrient-use efficiency reduces nitrate and pesticide loading, it also is typically achieved only with high water-use efficiency. In situations where irrigation water is imported to the groundwater basin rather than pumped from local aquifers, higher water-use efficiency translates into significant reductions in groundwater recharge, impacting long-term water supplies and raising the need for additional recharge of clean water.

New agricultural practices, yet to be developed, also promise to play an important role in simultaneously addressing groundwater quality and groundwater quantity issues: the agricultural landscape potentially provides a wide range of opportunities for using floodwaters and other surplus surface water to recharge groundwater, whether with recharge basins, field flooding, targeted clean recharge irrigations or other methods (e.g., Bachand et al. 2014; Harter and Dahlke 2014). The significant potential for innovation and field testing in this arena could lead to water being intentionally recharged in the agricultural landscape without degrading water quality, possibly even improving water quality. For example, in areas recharging groundwater for public supply wells ("source areas"), some nitrogen-intensive crops may be replaced with crops that are known to be relatively protective of groundwater quality. This has been shown to be an economically promising option to address long-term drinking water quality issues, especially in the source area of drinking water supplies for small, often disadvantaged communities (Mayzelle et al. 2014; Rudolph et al. 2015). More research and pilot testing are needed.

Integrating groundwater management with surface water management and with land-use planning. Groundwater management cannot be done without managing surface water resources. The future of groundwater use, protection and management in California's agricultural landscape will be an increasingly integrated approach to managing the quality and quantity of both surface water and groundwater. Land-use planners must also be more involved in and informed by water planning and assessment activities. New regulations for groundwater sustainability and groundwater quality protection have emphasized the engagement of landowners and local stakeholders in the planning and implementation of new regulations, providing stakeholders, including farmers, with opportunities for engagement, dialogue and education. Integration of the new groundwater regulations with existing programs in integrated regional water management (IRWM) planning and urban water management planning will be needed. This integrated strategy will employ a diverse portfolio of approaches reflecting local needs, local technical and economic capacity, and the diversity of local stakeholders and of their engagement in these efforts.

Sharing the costs. The new groundwater management and groundwater quality regulations and improvements involve additional costs and efforts for farmers and other local and state stakeholders and taxpayers, but they will provide long-term benefits to water users, including agriculture. Disagreements and lawsuits over how to share costs will likely continue to be part of the agricultural groundwater landscape as well.

The global long-term view. Despite the growing pains, sustainable management of groundwater supplies and protection and improvement of groundwater quality in California agricultural regions are a necessary and vital foundation for continued economic and ecosystem prosperity in these regions. If California continues to lead, nationally, this broad sustainability effort and if that leadership is demonstrable and transparent to the public, California agriculture may some day enjoy a significant economic advantage: sustainable agricultural produce is expected to be in demand among increasingly discerning consumers, including large food service providers (for instance, Menus of Change).

Finally, and most importantly, California is not alone in this challenge. Irrigated agricultural regions around the world produce 40% of global agricultural products. Many of these regions are struggling with overuse and water quality degradation of their groundwater resources, posing significant risks to global food security and political stability (Brabeck-Letmathe and Ganter 2015; University of California 2015). Meeting the sustainable groundwater challenge with forward thinking and integrated agricultural, scientific and policy programs has become a global endeavor. CA

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Research Article

Soil sampling protocol reliably estimates preplant NO_3^- in SDI tomatoes

by Cristina Lazcano, Jordon Wade, William R. Horwath *and* Martin Burger

Subsurface drip irrigation (SDI), because it can precisely deliver nutrients close to plant roots, could lead to carefully determined applications of fertilizer to meet crop needs and less risk of nitrate (NO_3^-) leaching to groundwater. Appropriate fertilizer applications, however, depend on an accurate assessment of the spatial distribution of the main plant macronutrients (N, P and K) in the soil profile before planting. To develop nutrient sampling guidelines, we determined the spatial distributions of preplant nitrate (NO_3^-), bicarbonate extractable phosphorus (Olsen-P) and exchangeable potassium (K) in the top 20 inches (50 centimeters) of subsurface drip irrigated processing tomato fields in three of the main growing regions in the Central Valley of California. Nutrient distribution varied with depth (P and K), distance from the center of the bed (NO_3^-) and growing region (NO_3^- and K). No depletion of NO_3^-, Olsen-P or K in the root feeding areas close to the drip tape was detected. Preplant NO_3^- ranged considerably, from 45 to 438 pounds N per acre (50 to 491 kilograms/hectare), the higher levels in fields with consecutive crops of tomatoes. A sampling protocol that growers could use, developed from analysis of the distribution results, provided reliable estimates of preplant NO_3^- as well as P and K in all surveyed fields.

Subsurface drip irrigation (SDI) allows for a precise delivery of water and nutrients close to plant roots, making it possible for growers to increase water and nutrient use efficiency and crop yields.

Efficient use of nitrogen (N) is gaining importance in terms of lowering the risk of nitrate (NO_3^-) leaching into groundwater during the rainy and irrigation seasons. Avoiding a buildup of large surpluses of residual N is feasible under SDI if the available N at preplant can be reliably quantified. Our primary goal in this study was to develop guidelines on how to reliably, efficiently and economically sample for preplant NO_3^- in processing tomato fields under SDI.

A recent survey among tomato growers showed that soil NO_3^- is determined in only a limited number of fields every year at preplant (Geisseler et al. 2015).

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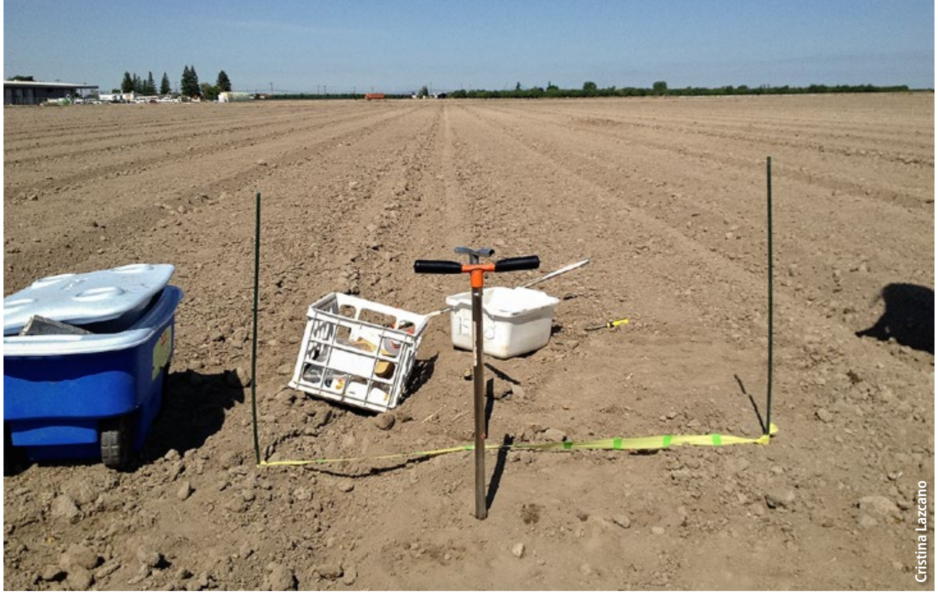
Although subsurface drip irrigation is widely used in California to produce processing tomatoes, knowledge of nutrient distribution at preplant is limited. To address this, UC researchers developed a sampling protocol that can be used to estimate preplant levels of nitrate, phosphorus and potassium.

Martin Burger



Preplant soil samples were collected at 5-inch intervals from the center of the bed towards the center of the furrow.

Currently, N fertilizer rates for processing tomatoes of about 178 pounds per acre (lb/ac) (200 kilograms per hectare [kg/ha]) are recommended under SDI (Hartz and Bottoms 2009; Tei et al. 2002). Tomato plants take up an average of 263 lb/ac (296 kg/ha), with 71% of the N allocated to the fruit by harvest (Hartz and Bottoms 2009). N concentration in fruit at optimum fertilization rates has been reported as 4.47 pounds per U.S. ton (lb/US tn) (2.24 kilograms per megagram [kg/Mg]) marketable fruit (Tei et al. 2002).

Mineral fertilizer is considered the main source of N in conventionally managed tomato systems, but other sources such as soil residual, or carryover, NO_3^-, mineralization of soil organic matter, and NO_3^- in irrigation water contribute to the supply of crop-available N. The latter sources are often not considered in fertilizer rate calculations, and as a result, N inputs can be in excess of crop need.

There are several difficulties in estimating preplant NO_3^- levels, a concern mentioned in Dzurella et al. (2012): (1) NO_3^- is one of the plant nutrients with the highest mobility, and therefore highest spatial variability, in soils, which makes it difficult to estimate total available N. (2) Under SDI, NO_3^- may accumulate at the periphery of the wetted soil volume and be depleted where roots proliferate at high density, such as near the drip tape emitter (Lecompte et al. 2008). As a consequence, NO_3^- concentration in furrows can be up to 16 times higher than in the center of the bed (Lecompte et al. 2008). (3) NO_3^- concentration and spatial distribution might be affected by ratios of atmospheric precipitation to evapotranspiration (ET).

The extent and distribution of precipitation determines NO_3^- leaching potential, especially under Mediterranean climate conditions (Poch-Massegú et al. 2014), with greater downward movement of NO_3^- occurring seasonally; whereas atmospheric variables, such as temperature, affect NO_3^- movement through their influence on evapotranspiration rates. Both irrigation management and weather conditions affect NO_3^- levels and spatial distribution. Therefore, measurements under varied climatic conditions are necessary to assess the extent such factors have on NO_3^- distribution in drip-irrigated processing tomato fields.

Unlike NO_3^-, phosphorous (P) and potassium (K) are less mobile in the soil profile. While less mobility reduces the loss of these nutrients through leaching, it also limits diffusion from enriched soil patches outside of the root growth zone. As a result, fields with several years of SDI cultivation might present a characteristic depletion within the root zone, where nutrient uptake is most intense (Hartz and Hanson 2009).

In spite of the widespread use of SDI in processing tomatoes, there is a lack of knowledge of the spatial distribution of the main plant macronutrients (N, P and K) at preplant. Complicating this further, management practices (i.e., rotations, continuous SDI cultivation) and climatic factors (i.e., precipitation and evapotranspiration) influence the spatial distribution of these nutrients.

We carried out a survey to address the lack of knowledge in this area: we assessed preplant distribution of NO_3^-, extractable P and exchangeable K in relation to the SDI line in commercial processing tomato fields. Crop N uptake and nitrogen use efficiency were evaluated in relation to preplant inorganic N levels and

Weighing of the vine biomass, *left*, and fruit biomass, *right*, collected at each location within a field. Vine biomass, which is incorporated into the soil after harvest, contributed an average N input of 109 lb/ac.

fertilizer N inputs in order to evaluate the performance of current practices of SDI processing tomato production. The main goal, as mentioned above, was to develop guidelines on the simplest way to reliably assess preplant NO_3^-.

Sampling sites, procedures

A total of 16 commercial processing tomato production fields were selected for the study. Fields were located along a transect of a decreasing ratio of precipitation to potential evapotranspiration (ET_o), with six fields in Yolo County (ET_o = 1.01), four in San Joaquin County (ET_o = 0.54) and six in Fresno County (ET_o = 0.31), three of the growing regions with the largest production of processing tomatoes in the state.

The selected fields had been cultivated under SDI for a minimum of 2 and a maximum of 9 years. Fields comprised a range of different management conditions typical of processing tomato production in California, including different bed sizes (60 versus 80 inches [in], or 1.5 versus 2 meters [m]), the number of consecutive years in tomato production and the planting of fall/winter crops in the fields (table 1).

Preplant soil sampling was carried out in all 16 fields from late February to mid-May, depending on the planting schedule and before the application of any fertilizers. In each field, five random locations were selected and a systematic sampling was carried out using a soil probe at regular (5 in, or 13 centimeter [cm]) intervals from the center of the bed to the center of the furrow. At each sampling point, two sets of soil from 0 to 10, and 10 to 20 inches (0 to 25, and 25 and 50 cm) in depth were taken and composited per depth. The exact position of the five sampling locations (± 9.8 feet, or 3 m) was recorded using GPS latitude-longitude coordinates in order to collect plant and soil samples from the same locations at harvest. Harvest NO_3^- concentrations were measured before the incorporation of vine residue by taking one core 10 inches from the center of the bed to a depth of 20 inches at each of the five locations per field.

Analysis of soil samples

The soil samples were stored in plastic bags, transported to the laboratory and stored at 4°C. Gravimetric soil moisture content was determined immediately after collection by drying a subsample at 221°F (105°C). In addition, a 10-gram subsample was immediately extracted with 2M potassium chloride (KCl) solution for the colorimetric analysis of NO_3^- concentration (Doane and Horwath

TABLE 1. Main characteristics and management practices of the 16 fields sampled

County	Field ID	Soil series	Soil texture* % Sand	Soil texture* % Clay	Drips/ bed	Years under drip	Consecutive years with tomatoes†	Bed size (in)	Drip depth (in)	Cover/ winter crop	Fertilizer inputs Preplant	Fertilizer inputs In-season	Fertilizer inputs Fall/ winter
Yolo	Y1	Yolo silt loam	11.3	21.0	1	2	1	80	na	No	8-24-5-0.5 (Zn)	UN-32	None
	Y2	Sycamore silt loam	11.3	21.0	1			60	na	No	8-24-5-0.5 (Zn)	UN-32	None
	Y3	Marvin silty clay loam	34.0	23.0	1	2	1	60	12	Triticale	8-24-5-0.5 (Zn)	28-0-0-5 (S)	Gypsum
	Y4	Tehama loam	34.0	23.0	1	4	2	60	12	Triticale	8-24-5-0.5 (Zn)	28-0-0-5 (S)	Gypsum
	Y5	Capay silty clay	5.5	47.5	1	9	0	60	10	Triticale	8-24-6	UN-32, 0-0-14, HPhos32	Manure
	Y6	Brentwood silty clay	5.5	47.5	1	2	0	60	10	Triticale	8-24-6	UN-32, 0-0-14, HPhos32	Manure
San Joaquin	SJ1	Stockton clay	13.7	50.0	2	5	0	80	12	No	10-34-0	UN-32, CAN17, KCl	None
	SJ2	Jacktone clay	22.1	50.0	2	5	1	80	12	No	10-34-0	CAN17, KCl	None
	SJ3	Capay clay	29.5	39.2	1	4	4	60	na	Triticale	8-24-6-3 (Zn)	UN-32	None
	SJ4	Stomar clay loam	22.1	50.0	1	3	4	60	na	Triticale	8-24-6-3 (Zn)	1-3-10	None
Fresno	F1	Westhaven loam	33.0	29.5	1	4	2	60	12	Grain crop	Transplant supreme	15-15-0, CAN17	None
	F2	Calflax clay loam	27.5	35.0	1	4	4	60	12	Grain crop	Transplant supreme	15-15-0, CAN17	None
	F3	Fresno fine sandy loam	52.0	21.2	1	5	5	60	12	No	4-10-10	UN-32	None
	F4	Fresno fine sandy loam	52.0	21.2	1	4	4	60	12	No	4-10-10	UN-32	None
	F5	Westhaven loam	34.0	21.0	1	3	2	80	15	No	6-21-0	UN-32, 22-5.9-0.6 (S)	None
	F6	Westhaven loam	34.0	21.0	1	3	2	80	15	No	6-21-0	UN-32, 22-5.9-0.6 (S)	None

* At 0–20 inches.
† Before the study.

2003). Available Olsen-P was analyzed colorimetrically after extraction with sodium bicarbonate ($NaHCO_3$) (Kuo 1996). Exchangeable K was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) on an air-dried and ground preplant soil subsample after extraction with ammonium acetate (Thomas 1982).

N uptake and use efficiency

Crop N uptake was determined by hand-harvest at the preplant sampling locations. Briefly, we sampled a length of 1 meter along the bed and all plants within this meter were counted and cut at soil level. Fruit and vines were separated, weighed and a subsample of both components selected for further determination of dry mass and percentage N (% N) through dry combustion on a C and N analyzer (Costech Analytical Technologies Inc., Valencia, CA) (Dumas 1848).

Vine and fruit biomass and % N per plant were calculated and then extrapolated to the rest of the field using plant density of the area harvested. Apparent nitrogen use efficiency of the tomato crop (NUE_C) was calculated as the ratio between N uptake by the tomato crop, including fruit and vine sampled at each field, and the available N, taking into account both the preplant soil NO_3^- and the fertilizer inputs reported by the growers.

Nitrogen outputs were calculated based on the marketable yields reported by the growers and the average N content of the fruit sampled from the hand-harvest plots. Apparent nitrogen use efficiency of the harvested fruit (NUE_F) was calculated as the ratio between N outputs in the harvested fruit and the available N, including preplant soil NO_3^- and fertilizer inputs.

P levels and distribution

Twelve of the 16 fields showed significantly higher Olsen-P concentration in the upper layer of soil than the deeper layer (fig. 1). Concentrations were homogeneous across the beds, with only two fields showing significant differences between sampling points (data not shown). Significant differences in extractable P between sampling distances from the center of the bed were observed in the Yolo growing region, with higher concentrations closer to the center of the bed (fig. 1).

No significant differences between growing regions were detected ($p = 0.77$), although average concentrations in the 0 to 20 inches soil layer tended to be highest in the Fresno (13.7 ± 3.1 parts per million, ppm) area, followed by the Yolo and San Joaquin areas (12 ± 1.7 and 10.6 ± 2.9 ppm, respectively).

Our study showed that Olsen-P was not lower within the root growth area than outside of it. This finding was in contrast to the earlier suggestion that the amount of available P can substantially decline close to the drip tape because of concentrated root feeding (Hartz and Hanson 2009). In fact, in this study, within the Yolo County area, Olsen-P concentrations were higher closer to the center of the bed and decreased toward the furrows.

The majority of the fields in this study showed average P concentrations lower than 15 ppm in both layers (table 2), within the threshold value of 12 to 20 ppm, where there is potential for a yield response to a P application. Generally, fields with < 15 ppm of available P would

TABLE 2. Preplant concentration of Olsen-P and exchangeable K in the 16 fields sampled

		Preplant PO_4^--P (ppm)			Preplant K (meq/100 grams)		
County	Field ID	Average	0–10 inch depth	10–20 inch depth	Average	0–10 inch depth	10–20 inch depth
Yolo	Y1	7.6	11.4	3.8	0.6	0.7	0.5
	Y2	13.5	17.2	9.7	0.6	0.7	0.6
	Y3	18.1	21.1	15.1	0.8	0.8	0.8
	Y4	7.2	9.8	4.7	0.6	0.6	0.6
	Y5	14.6	12.0	17.2	1.2	1.0	1.3
	Y6	11.2	11.9	10.6	0.7	0.7	0.7
San Joaquin	SJ1	4.5	4.6	4.4	1.2	1.2	1.2
	SJ2	8.4	8.3	8.5	0.6	0.6	0.6
	SJ3	18.6	25.6	11.7	1.1	1.3	0.9
	SJ4	10.9	12.5	9.4	0.9	0.9	0.8
Fresno	F1	13.9	16.8	10.9	1.1	1.2	1.0
	F2	9.5	11.9	7.1	1.4	1.6	1.2
	F3	28.0	35.5	20.5	1.5	1.7	1.2
	F4	15.3	21.6	9.1	0.7	0.7	0.5
	F5	6.7	7.9	5.6	1.2	1.1	1.2
	F6	8.7	10.2	7.2	1.42	1.68	1.15

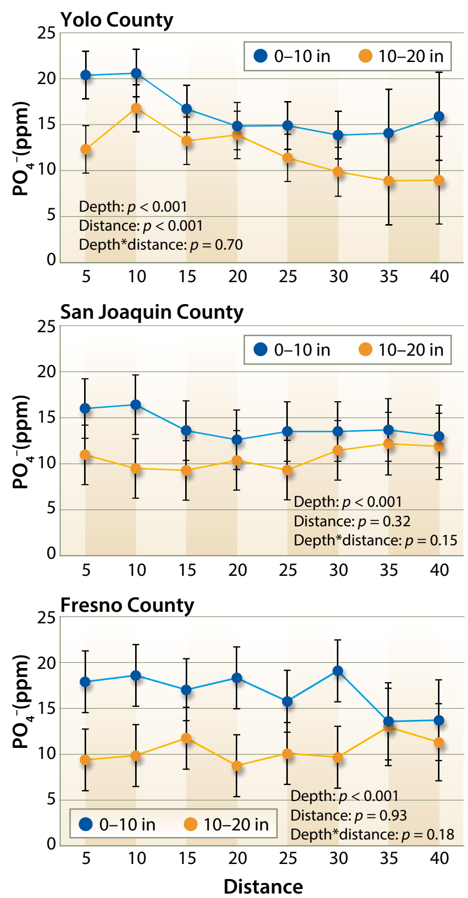


Fig. 1. Change in PO_4^- content of the soil at different distances from the center of the bed and at two depth intervals (0 to 10, and 10 to 20 inches) in Yolo, San Joaquin and Fresno counties. Statistical significance of the depth, distance and the interaction between them (depth*distance) is shown at each of the three growing regions.

respond to a P application, whereas fields with more than 25 ppm would be unlikely to do so (Hartz 2008). In this study, only one of the fields had extractable P higher than 25 ppm. These results show that some of the fields could benefit from additional P fertilization, yet current fertilization practices are effective in avoiding P depletion in the root-feeding zone.

K levels and distribution

Soil exchangeable K content was mostly homogeneous within the beds, and no depletion was observed close to the drip tape in any of the three growing areas (fig. 2). The lack of K depletion in the root zone may be because potassium can easily be supplied through fertigation, with the advantage of little potential for fixation before the plants take it up since K fixation in interlayer sites of soil minerals mainly takes place during drying following water additions (Cassman et al. 1990). As shown in table 2, average field exchangeable K concentrations were generally high and well above 130 to 150 ppm (0.33 to 0.38 meq/100 g [grams]), which has been defined as the threshold for yield responses in furrow-irrigated processing tomato in California (Hartz 2002; Hartz and Hanson 2009; Miyao 2002).

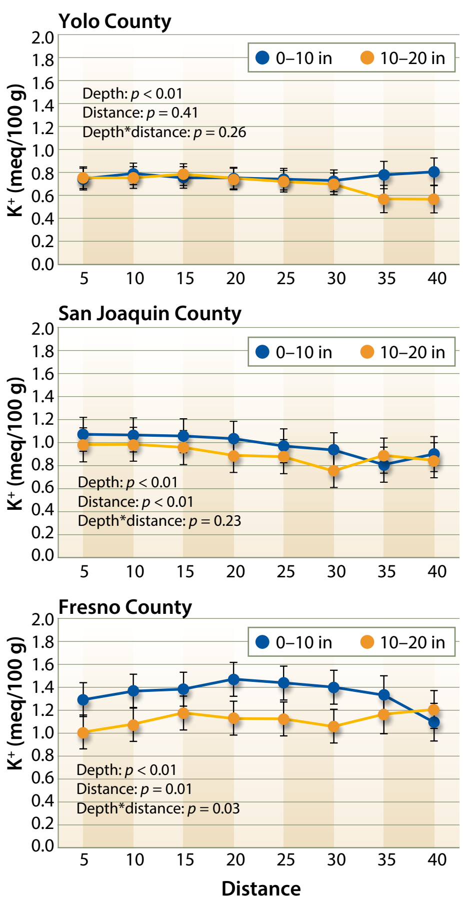


Fig. 2. Exchangeable K content of the soil at different distances from the center of the bed and at two depth intervals (0 to 10, and 10 to 20 inches) in Yolo, San Joaquin and Fresno counties. Statistical significance of the depth, distance and the interaction between them (depth*distance) is shown at each of the three growing regions.

Preplant NO_3^--N in the depth interval of 0 to 20 inches (0 to 50 cm) ranged from 45 to 438 lb/ac (50 to 491 kg/ha).

For drip irrigation, yield thresholds have been estimated to be higher at 200 to 300 ppm (0.51 to 0.77 meq/100 g), although there is still limited information available in this respect (Hartz and Hanson 2009). All fields were above 200 ppm (0.51 meq/100 g), meaning that yield increases resulting from K additions could not be expected; however, K applications benefit fruit quality even at levels that are not yield limiting (Hartz et al. 2005).

High exchangeable K is not rare in processing tomato soils; concentrations ranging from 187 to 331 ppm (0.48 to 0.85 meq/100 g) have been previously reported for the Yolo growing region (Hartz et al. 2005). Concentrations reported in our survey are, however, well over these values, particularly in Fresno County (1.20 ± 0.12 meq/100 g) followed by San Joaquin (0.95 ± 0.14 meq/100 g) and Yolo counties (0.75 ± 0.12 meq/100 g), with significant differences between the three growing areas ($p < 0.01$). Exchangeable K was similar at the two depths in Yolo County (fig. 2), whereas K concentrations were higher in the upper soil layer in Fresno and San Joaquin counties ($p < 0.01$ and $p < 0.05$, respectively). In the fields in San Joaquin County, K concentration tended to decrease from the center of the bed toward the furrow.

NO_3^- levels and NUE

Preplant NO_3^--N in the depth interval of 0 to 20 inches (0 to 50 cm) ranged from 45 to 438 lb/ac (50 to 491 kg/ha) among all the fields. The average NO_3^--N content in this layer was significantly higher in San Joaquin and Fresno counties (232 ± 31 and 216 ± 54 lb/ac, or 261 ± 34 and 243 ± 61 tn/ha, respectively) than in Yolo County (70 ± 8 lb/ac, or 79 ± 9 tn/ha) ($p < 0.001$).

The growers reported seasonal fertilizer N inputs ranging from 115 to 320 lb/ac (129 to 360 kg/ha), bringing total available N (preplant NO_3^- and fertilizer N) to range from 209 to 758 lb/ac (235 to 852 kg/ha) (table 3). According to the hand-harvest data, average whole plant N uptake was 274 lb/ac (308 kg/ha), with a range of 150 to 401 lb/ac (167 to 451 kg/ha) among all the fields. The results of our survey suggest that N fertilization could be decreased without yield penalty in some of the fields, especially those in Fresno and San Joaquin counties.

Preplant NO_3^- concentrations were positively correlated with the number of consecutive years that the fields were cropped with processing tomatoes ($R^2 = 0.67$; $p < 0.01$). In Yolo County, the number of years of consecutive tomato was between 0 and 2, whereas in San Joaquin and Fresno counties it was between 0 and 5 (table 1). These differences in years of consecutive tomato production may, in part, explain the differences in preplant NO_3^- levels observed among the processing tomato growing areas. Another likely reason for the higher preplant NO_3^- levels in Fresno County may be the lower rainfall in this area. Lower precipitation and higher evaporation rates in Fresno may lower leaching and promote buildup of NO_3^- closer to the soil surface, whereas in Yolo County, which receives more rainfall, some of the residual NO_3^- may have been leached below 20 inches (50 cm) during the rainy season.

Crop marketable yield reported by the growers in the different fields ranged from 39.9 to 63.1 tn/ac (90.7 to 143.3 Mg/ha) (table 3), being higher in the Fresno (57.1 ± 2.9 tn/ac, or 130 ± 6.5 Mg/ha) than the San Joaquin and Yolo growing regions (51.9 ± 4 tn/ac , and 49.9 ± 2.6 tn/ac or 116.7 ± 9 Mg/ha and 112.3 ± 5.85 Mg/ha, respectively). Similar crop yields have been reported by Hartz and Bottoms (2009) for Yolo County.

Tomato plants took up between 150 and 401 lb/ac of N (table 3), of which they allocated between 82 and 251 lb/ac to fruit production, representing between 55% and 63% of total plant N. Fruit N allocation was, in most cases, lower than that reported by Hartz and Bottoms (2009) for processing tomatoes with adequate N fertilization. Across the 16 fields studied, the apparent NUE_C was highly variable, ranging between 1.25 and 0.52 (table 3), and being higher for Yolo County (0.92 ± 0.11) than for Fresno and San Joaquin counties (0.80 ± 0.08 and 0.78 ± 0.10, respectively). Nitrogen outputs in the harvested crop ranged from 93 to 174 lb/ac (105 to 196 kg/ha; table 3), and the apparent N use efficiency of the harvested fruit (NUE_F) was between 0.15 and 0.64 (table 3).

NUE_C values close to or above 1 show that soil sources other than fertilizer or preplant N contributed to plant uptake. In-season soil mineralized N and NO_3^- in irrigation water can be substantial sources of N for the tomato plants in addition to fertilizer or preplant N. To estimate potential mineralizable N, subsamples of 10 grams of air-dried soil from the surface layer, 0 to 10 inches (0 to 25 cm), of the 16 fields were incubated in the laboratory under aerobic conditions at 55% water holding capacity. After 105 days, mineralization of organic N sources provided an average of 53 lb/ac (60 kg/ha) as NH_4^+ and NO_3^-, with some fields producing as much as 82 lb/ac (91 kg/ha) (table 3). Earlier, Krusekopf et al. (2002), following a similar procedure, arrived at the same average estimate of mineralized N of 53.4 lb/ac (60 kg/ha) in a study involving 10 tomato fields in the Sacramento and San Joaquin valleys.

Vine biomass, which is incorporated into the soil after harvest, contributed an average input of 109 lb/ac (122 kg/ha) (table 3) and could represent a large part of this potentially mineralizable N pool. In addition to the N that becomes available during crop growth, NO_3^- in the irrigation water can also be a substantial source of N. No data was collected in this study regarding the NO_3^- content of irrigation water at the different fields. One of the growers reported that an average of 21 lb/ac (24 kg/ha) was supplied to the crop in the irrigation water. If these two N inputs (i.e., mineralization and irrigation water) are taken into account, then the actual crop NUE is lower than reported here.

In the present study, postharvest, or residual, NO_3^- concentrations measured to a depth of 20 inches ranged from 43 to 392 lb/ac NO_3^--N (48 to 441 kg/ha), with an average of 141 lb/ac NO_3^--N (159 kg/ha) (table 3). This survey showed high residual levels of NO_3^- in some tomato fields. Fields exhibiting low NUE and high levels of residual NO_3^- have a greater leaching potential during the irrigation season and/or during winter. These fields would benefit from fertilizer applications that are adjusted according to preplant soil NO_3^- concentrations.

Nutrient distribution

No general pattern in NO_3^--N distribution around the drip tape was observed across the 16 fields, although significant differences in NO_3^--N concentration between sampling distances from the center of the bed were observed for the majority of the 16 fields (data not shown). When the data was averaged across each growing region, fields from Fresno County showed a higher NO_3^--N concentration at 15 and 20 inches (38 and 51 cm) than 5 inches (13 cm) from the center of the bed, particularly in the upper layer, 0 to 10 inches (0 to 25 cm), of soil; whereas in Yolo County, NO_3^--N concentrations decreased with increasing distance from the drip tape (fig. 3).

TABLE 3. Preplant N levels, N inputs, N uptake in the crop and residual soil N in the 16 fields of the study

		Preplant NO_3^--N (lb/ac)							Crop N (lb/ac)*						
County	Field ID	0–20″ depth	0–10″ depth	10–20″ depth	Fertilizer N (lb/ac)	Total available N (lb/ac)	Marketable yield (tn/ac)	N output† (lb/ac)	Vine	Fruit	Whole plant	NUEC*	NUEF†	Min N (lb/ac)	Residual soil N (lb/ac)
Yolo	Y1	78.2	38.5	39.8	175	253	58.2	148	145	172	317	1.25	0.58	46.0	53
	Y2	106.1	71.2	52.6	177	283	58.3	n.d.‡	n.d.	n.d.	n.d.	n.d.	n.d.	55.3	n.d.
	Y3	62.0	29.7	25.4	147	209	48.9	134	65	112	177	0.85	0.64	60.9	83
	Y4	62.6	21.0	21.9	146	209	49.9	120	66	157	223	1.07	0.57	58.7	107
	Y5	45.0	20.6	24.4	213	258	40.7	93	68	82	150	0.58	0.36	50.2	70
	Y6	64.7	30.1	34.5	187	252	51.9	123	84	133	217	0.86	0.49	n.d.	125
San Joaquin	SJ1	199.4	87.1	109.6	115	314	57.0	111	99	180	279	0.89	0.38	38.9	152
	SJ2	159.2	73.6	88.3	135	294	55.0	118	110	179	289	0.98	0.38	61.3	123
	SJ3	293.0	159.6	133.5	220	513	55.7	156	168	198	366	0.71	0.30	55.2	392
	SJ4	275.1	142.7	132.4	220	495	39.9	124	121	136	257	0.52	0.25	58.8	339
Fresno	F1	115.7	82.6	70.1	205	321	60.8	172	107	183	290	0.90	0.54	49.8	132
	F2	171.7	75.1	104.1	205	377	61.7	174	116	216	332	0.88	0.46	44.8	111
	F3	437.7	244.1	193.6	320	758	45.5	110	150	251	401	0.53	0.15	70.8	43
	F4	318.0	200.9	117.0	320	638	53.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	81.7	n.d.
	F5	113.4	55.1	58.3	187	300	57.9	150	139	143	282	0.94	0.50	31.8	89
	F6	142.6	76.3	66.3	208	351	63.1	147	82	180	262	0.75	0.42	28.0	151

* Based on hand-harvest at five locations in each field.
† Based on marketable yields reported by growers.
‡ n.d. = Not determined.

TABLE 4. Average NO_3^--N content of the whole field and of samples taken at different distances from the center of the bed across 80-inch beds

		Average NO_3^--N content *lb/ac*									
Field ID	Whole field	5″ (12.7 cm)	10″ (25.4 cm)	15″ (38.1 cm)	20″ (50.8 cm)	25″ (63.5 cm)	30″ (76.2 cm)	35″ (88.9 cm)	40″ (101.6 cm)	15″ + 30″ (38.1 + 76.2 cm)	20″ + 25″ (50.8 + 63.5 cm)
Y1	78.2	106.9	92.1	93.4	72.3	78.7	72.0	52.0	58.4	82.7	75.5
SJ1	159.2	167.0	162.7	138.3	136.8	186.2	180.0	167.1	135.1	159.1	161.5
SJ2	199.4	206.5	182.0	169.4	237.9	187.8	196.6	210.6	204.0	183.0	212.9
F5	113.4	111.7	175.1	123.7	125.8	102.1	96.3	88.5	84.1	110.0	113.9
F6	148.8	187.9	198.9	150.0	152.5	151.8	132.5	123.4	65.6	141.2	152.2
Relative error (%)*		**14.6**	**23.4**	**11.5**	**10.9**	**7.1**	**9.7**	**16.7**	**24.9**	**4.4**	**2.9**

* Relative error from the field average of the different sampling distances and best combination of sampling distances is according to the Minimax analysis.

Concentrations of NO_3^--N at the two sampling depth intervals (0 to 10 and 10 to 20 in) were generally similar. Significant differences were only observed in Fresno County ($p < 0.01$, fig. 3), supporting the hypothesis that in areas with lower precipitation, more NO_3^- may accumulate in the upper layer, whereas NO_3^- in the soil surface layer is leached to lower layers in areas receiving more precipitation, homogenizing NO_3^--N concentration in the soil profile.

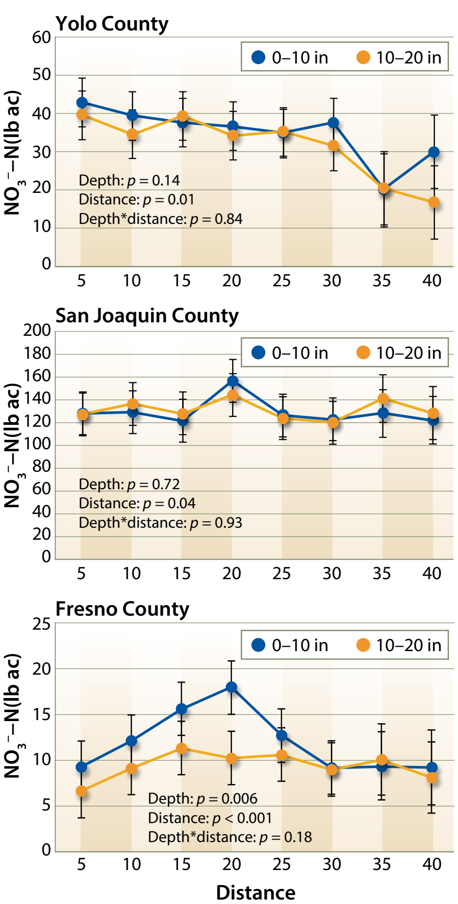


Fig. 3. NO_3^- content of the soil at different distances from the center of the bed and at two depth intervals (0 to 10, and 10 to 20 inches). Average NO_3^- content and standard errors by county for each layer and 5-inch lateral distance are shown. Statistical significance of the depth, distance and the interaction between them (depth*distance) is shown at each of the three growing regions.

NO_3^- sampling protocol

With the information on preplant spatial distribution of nutrient concentrations, we elaborated a sampling protocol that accurately estimates the amount of NO_3^--N in the top 20 inches (50 cm) of SDI processing tomato fields. The protocol was based on a Minimax analysis by selecting the minimum number of samples within the field and locations within the bed (i.e., distances from the drip tape) that best estimated soil NO_3^--N based on the criterion of the minimum relative error from the field average. Briefly, for all the fields, the amounts of NO_3^--N in the two soil layers were summed for each sampling distance from the center. Subsequently, the averages of all possible combinations of sample locations within the bed or within the field were compared to the field average of all the measurements in a given field, and the relative errors were obtained according to the following formula:

$$\text{Relative error} = (|\bar{\bar{X}}_D - \bar{X}_F|/\bar{X}_F)$$

where $\bar{\bar{X}}_D$ is the average NO_3^--N concentration for the given combination of 1, 2, 3, 4 or 5 sampling distances within the bed, and $\bar{X}_F$ is the average NO_3^--N concentration of the field.

The combination of samples with the lowest relative error across all fields (< 5% from the field mean) and the lowest number of samples taken was selected as the best sampling procedure to estimate average soil NO_3^--N. Calculations were made separately for fields with 80-inch and 60-inch beds, with SAS version 9.1 statistical software.

We found that in fields with 80-inch (2 m) beds taking two cores at 15 and 30 inches (38 and 76 cm) or at 20 and 25 inches (51 and 64 cm) from the bed center reduced the sampling error to 4% and 3%, respectively (table 4). For 60-inch (1.5 m) beds, taking three cores at 5, 10 and 20 inches (13, 25 and 51 cm) or at 5, 20 and 25 inches (13, 51 and 64 cm) reduced the sampling error to 4% of the field average (table 5). In addition, the Minimax analysis showed that these samples should be taken in at least four different locations within the field in 80-inch (2 m) beds, and in at least three locations in fields with 60-inch (1.5 m) beds.

This sampling method also guarantees the collection of representative samples for Olsen-P and exchangeable K. In the case of P, in the fields with 80-inch (2 m) beds, collecting two soil samples at 15 and 30 inches or at 20 and 25 inches from the bed center would result in a sampling error of 11% and 12%, respectively. In fields with 60-inch (1.5 m) beds, collecting three soil samples at 5, 10 and 20 inches or 5, 20 and 25 inches would yield a sampling error of 10% and 5%, respectively. In the case of exchangeable K, the sampling error would be significantly lower because of the higher homogeneity of this nutrient's distribution across the beds. In fields with 80-inch (2 m) beds, we observed a sampling error of 3% in either of the combination of sampling distances (15 and 30 inches or 20 and 25 inches) and in 60-inch (1.5 m) beds of 2% and 1%.

TABLE 5. Average NO_3^--N content of the whole field and of samples taken at different distances from the center of the bed across 60-inch beds

		Average NO_3^--N content *lb/ac*							
Field ID	**Whole field**	**5″ (12.7 cm)**	**10″ (25.4 cm)**	**15″ (38.1 cm)**	**20″ (50.8 cm)**	**25″ (63.5 cm)**	**30″ (76.2 cm)**	**5″ + 10″ + 20″ (12.7 + 25.4 + 50.8 cm)**	**5″ + 20″ + 25″ (12.7 + 50.8 + 63.5 cm)**
Y2	123.8	157.7	159.2	142.8	115.7	90.9	76.4	126.1	121.4
Y3	63.6	66.2	43.4	52.3	70.8	65.3	83.5	59.7	67.5
Y4	64.2	40.6	42.6	55.5	56.0	89.1	101.6	66.6	61.9
Y5	45.0	56.3	47.2	59.0	40.6	34.1	33.1	46.4	43.7
Y6	64.7	68.0	60.5	60.1	71.1	62.4	66.1	62.2	67.2
SJ3	293.0	277.5	361.0	298.3	349.4	247.0	225.2	294.8	291.3
SJ4	275.1	258.2	244.6	256.2	367.5	267.5	256.7	252.5	297.7
F1	115.7	161.7	103.7	137.2	110.3	88.1	93.3	111.4	120.0
F2	318.0	153.7	257.2	327.8	445.6	427.8	295.9	293.6	342.4
F3	171.7	142.8	150.8	191.5	191.9	205.7	147.4	163.2	180.2
F4	437.7	226.2	408.2	647.3	619.0	401.6	323.7	459.7	415.6
Relative error (%)		**24.2**	**17.1**	**15.9**	**18.3**	**18.3**	**23.0**	**4.4**	**4.4**

* Relative error from the field average of the different sampling distances and best combination of sampling distances is according to the Minimax analysis.

The data collected in this study provides a snapshot of current management practices and soil nutrient status for SDI processing tomatoes in California. It shows considerable buildup of residual NO_3^- in soils, particularly after several years of consecutive processing tomato cultivation. Regular preplant soil sampling using the protocol developed in this study would enable growers to adjust fertilizer rates, reduce the occurrence of excessive NO_3^- levels and detect suboptimal nutrient levels in their fields. Yet, how much of the pre-plant NO_3^- available can be accessed by the roots is contingent on the SDI wetting pattern, which may vary among fields depending on soil hydraulic properties. CA

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Introducing cattle grazing to a noxious weed-dominated rangeland shifts plant communities

by Josh S. Davy, Leslie M. Roche, Alexis V. Robertson, Dennis E. Nay *and* Kenneth W. Tate

Invasive weed species in California's rangelands can reduce herbaceous diversity, forage quality and wildlife habitat. Small-scale studies (5 acres or fewer) have shown reductions of medusahead and yellow starthistle using prescribed grazing on rangelands, but little is published on the effects of pasture-scale (greater than 80 acres) prescribed grazing on weed control and plant community responses. We report the results of a 6-year collaborative study of manager-applied prescribed grazing implemented on rangeland that had not been grazed for 4 years. Grazing reduced medusahead but did not alter yellow starthistle cover. Medusahead reductions were only seen in years that did not have significant late spring rainfall, suggesting that it is able to recover from heavy grazing if soil moisture is present. Later season grazing appears to have the potential to suppress medusahead in all years. In practice, however, such grazing is constrained by livestock drinking water availability and forage quality, which were limited even in years with late spring rainfall. Thus, we expect that grazing treatments under real-world constraints would reduce medusahead only in years with little late spring rainfall. After 10 years of grazing exclusion, the ungrazed plant communities began to shift, replacing medusahead with species that have little value, such as ripgut and red brome.

Across California, annual rangelands cover approximately 16 million acres and are among the most species-rich ecosystems in the state, supporting thousands of plant and animal species (Allen-Diaz et al. 2007; Barrett 1980; Garrison and Standiford 1996). California's modern-day rangelands are largely dominated by nonnative annuals, which some believe replaced previously diverse native forb and grass communities (Bartolome 1987; Schiffman 2007). These naturalized annuals now provide a majority of the state's livestock forage base. Currently, several noxious weed species are driving another transformation of California's rangelands and pose a continued and growing threat to rangeland ecosystem functions and services (D'Antonio et al. 2007; DiTomaso 2000; Kyser et al. 2007; Young 1992).

The spread of invasive weeds changes plant community composition and can lead to shifts in soil moisture and nutrient availability as well as the suppression of both native plants and other desirable and more palatable nonnatives, thereby reducing herbaceous diversity, wildlife habitat, forage quality and agricultural productivity (DiTomaso 2000; Eviner et al. 2010; George 1992). Across California's annual rangelands, noxious weeds have been estimated to reduce livestock carrying capacity by as much as 50% to 80% (DiTomaso 2000; George 1992; Hironaka 1961; Major et al. 1960).

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Cattle in a prescribed grazing paddock in the spring. Prescribed grazing reduced medusahead cover in years that did not have significant late spring rainfall.

Josh S. Davy

Medusahead and yellow starthistle

Two of the most prominent invasive species of concern are medusahead (*Elymus caput-medusae* L., synonym: *Taeniatherum caput-medusae* L. Nevski) and yellow starthistle (*Centaurea solstitialis* L.). Together, these rapidly expanding species cover more than 15 million acres throughout California (DiTomaso and Healy 2007; DiTomaso et al. 2008; Pitcairn et al. 1998; Young 1992).

The phenological development of medusahead and yellow starthistle is in part what makes these invaders so successful. Medusahead, and particularly yellow starthistle, mature late in the annual growing season (November to May). These species germinate after the first fall rains, with smaller germination events sometimes occurring later in the wet season (Benefield et al. 2001). Although germination timing is similar to that of the surrounding grassland community, medusahead does not produce seed heads until late April or May, after most naturalized annuals have completed their life cycle (Dahl and Tisdale 1975; DiTomaso et al. 2008; Young et al. 1970). Yellow starthistle commonly produces seed heads in May and June; it begins flowering in June and can continue beyond October (DiTomaso et al. 2000; DiTomaso et al. 2008). In fact, many of yellow starthistle's developmental stages (seedling, vegetative, flowering, seed formation and maturation) generally extend well into the summer dormant period distinctive to Mediterranean climates (Maddox 1981). The later development periods enable medusahead and yellow starthistle to take advantage of late spring and early summer rains when they occur. When late-season moisture is present, medusahead and yellow starthistle will continue to grow after potential competitors have stopped, allowing them to dominate and dramatically alter the vegetation structure (DiTomaso et al. 2000; Kyser et al. 2007; Young 1992).

Managing weeds with grazing

Prescribed livestock grazing is commonly proposed as a low-cost, if not profitable, option to manage weedy species on rangelands. Prescribed grazing is the controlled implementation of the timing, frequency and intensity of grazing to achieve specific goal(s), such as weed control. Small-scale grazing studies (5 acres or fewer) have examined the effects of livestock type (cattle, sheep, goats), grazing intensity (animals per acre) and grazing season (winter, early spring, late spring) on individual weed species (e.g., DiTomaso et al. 2007; DiTomaso et. al 2008; George et al. 1989, Lusk et al. 1961; Thomsen et al. 1993). These studies have consistently demonstrated that properly timed (late-spring, post-bolting/pre-flowering phenological stages — that is, immediately prior to seed head production) and intensive (high animal density resulting in high pressure on vegetation) grazing can reduce medusahead cover by 30% to 100% and yellow starthistle flower heads by 75% to 90% (DiTomaso et al. 2008; Thomsen et al. 1993). Experimentally manipulated livestock grazing has also been shown to enhance herbaceous diversity and native plant richness in vernal pools, interior annual grasslands and coastal grassland sites (DiTomaso et al. 2008; Hayes and Holl 2003; Marty et al. 2005). However, there is little published work examining pasture-scale (greater than 80 acres) implementation of prescribed grazing to manage invasive weeds.

Pasture-scale prescribed grazing

Across California, rangeland managers have reported that livestock grazing can be managed to control medusahead and yellow starthistle (Huntsinger et al. 2007). These findings are *experiential* rather than *experimental* — that is, based on direct implementation, observation and site-specific fine-tuning of intensity, season and frequency of livestock grazing to achieve specific goals. A recent scientific review of conservation effectiveness of rangeland management practices (including prescribed grazing) highlighted a critical need for the monitoring and reporting of practice effectiveness at the pasture scale (Briske et al. 2011). Collaborative, on-the-ground management implementation and monitoring will enable managers and researchers to better assess effectiveness and practicality of conservation practices such as prescribed grazing to control invasive weeds. Our objective was to assess the effect of a "real" prescribed grazing regime implemented by ranch personnel (rather than researchers) on medusahead and yellow starthistle populations on a Bureau of Land Management (BLM) grazing allotment known as the Bear Creek Unit of the Cache Creek Natural Area.

Study site: Bear Creek Unit

The Bear Creek Unit, located in Northern California's interior coast range in Colusa County, is an 11,090-acre (with 7,360 acres suitable for grazing) BLM-managed land that consists of a patch-mosaic of annual grasslands, blue oak woodlands and serpentine chaparral plant communities. The climate is

***Right*, yellow starthistle (*Centaurea solstitialis*) flowers at full bloom and seed dispersal stages.**

***Below*, medusahead (*Taeniatherum caput-medusae*) inflorescence with mature fruit.**

Researchers targeted annual grasslands and blue oak woodlands for prescribed grazing in the Bear Creek Unit of the Cache Creek Natural Area in Colusa County.

Josh S. Davy

Mediterranean, with hot, dry summers and mild, wet winters. Mean annual precipitation is 24 inches, and mean annual air temperature is 61°F (PRISM 2011). Sites examined in this study ranged from approximately 1,200 to 1,600 feet in elevation.

For this study, we targeted the annual grassland and blue oak (*Quercus douglasii* Hook. & Arn.) woodland plant communities, as they provided the majority of forage on the management unit, and were dominated by the target weeds. In the study area, soils were largely formed from residuum of sandstone and shale (Alfisols), with a small inclusion of soils formed from alluvium (Mollisols) (Soil Survey Staff 2012). Common nonnative annual grasses include soft chess (*Bromus hordeaceus* L.), slender oat (*Avena barbata* Link) and ripgut brome (*B. diandrus* Roth). This area also supports various native forbs, including miniature lupine (*Lupinus bicolor* Lindl.), Ithuriel's spear (*Triteleia laxa* Benth.), owl's clover (*Castilleja attenuata* (A. Gray) Chuang & Heckard), mariposa lily (*Calochortus* spp.) and tidytips (*Layia* spp.). Native grasses are widely scattered in the area, with purple needlegrass (*Stipa pulchra* Hitchc.) being the most prominent native perennial grass. Medusahead and yellow starthistle are common across the landscape, with an emerging population of barb goatgrass (*Aegilops triuncialis* L.) also present.

Grazing strategy

Until August of 2001, the Bear Creek Unit was continuously grazed throughout the growing season under grazing leases. The BLM, which acquired the Bear Creek Unit in 1999, terminated grazing in 2001 in an attempt to enhance native plant cover. In the 4 years following cessation of grazing, BLM monitoring teams reported increased invasive weed cover and high accumulations and persistence of vegetative litter, or thatch (USDI 2004). In fall of 2006, average residual dry matter (RDM, the previous year's vegetative thatch) across the unit was estimated to be 4,200 pounds per acre. In working toward invasive weed control — one of BLM's top management priorities (USDI 2004; USDI 2011) — the BLM collaborated with local stakeholders to reintroduce grazing on the Bear Creek Unit in 2006.

To target medusahead and yellow starthistle, we implemented a moderately stocked, rotational cattle grazing system across 11 paddocks, ranging from 80 to 600 acres in size. Paddocks were generally grazed January through May using cows calving between January and March — cattle on and off dates, stocking densities and paddock rotations (table 1) were made at the discretion of the site manager based on factors such as drinking water availability, forage availability and cattle conditions (i.e., body condition score, weight gain). From 2006 to 2011, cattle numbers ranged from 318 to 520, averaging 392 total cows during the study

TABLE 1. Late spring (May-Jun) and total (Oct. 1–Sep. 30, the water year) precipitation (ppt) as percent of average, and cattle grazing information for the sampling period 2006 to 2011

	2006	2007	2008	2009	2010	2011
Late spring % of average ppt	73	26	3	124	121	327
Total % of average ppt	156	40	55	52	81	92
Animal unit months*	4,276	2,190	2,187	2,223	1,911	2,158
Cattle on-date	7-Jan	2-Jan	16-Jan	19-Nov	19-Dec	22-Nov
Cattle off-date	11-Jun	27-May	22-May	23-May	2-Jun	25-May

* An animal unit month represents one cow grazed for one month.

period. Grazing event duration ranged from several days up to 2 weeks, with two grazing events per paddock: one grazing from late November to February to reduce weed thatch, and allow alternative species to establish (George et al. 1989); and one grazing event from March to June to target late-flowering invasives (DiTomaso et al. 2008; Thomsen et al. 1993). By October of 2009, we estimated average RDM across the unit to be 1,400 pounds per acre, or approximately one-third the RDM observed under initial ungrazed conditions.

Livestock-proof grazing exclosure at the Bear Creek Unit.

Kenneth W. Tate

Plant community analysis

Prior to reintroduction of cattle grazing, we established permanent paired plots (one cattle grazed plot and one ungrazed exclosure; ITT 1996) in each of the 11 paddocks. Permanent plots were chosen in a random stratified manner to ensure sample sites were representative for each pasture. Exclosure plots measured 8 feet by 8 feet and were livestock proof. To examine shifts in plant species cover and abundance over the course of the study, we began monitoring plant community composition in June of 2006. At each set of permanent grazed and ungrazed paired plots, we estimated percent basal cover by species within a 10-ft^2 hoop. Ocular estimates of herbaceous composition (percent cover by species; ITT 1996) were collected after peak standing crop for both grazed and ungrazed plots in June of 2006, 2009 and 2011. This resulted in a total of 22 observations for each year, and 66 total observations for the study period.

To determine if grazing management at the Bear Creek Unit significantly impacted medusahead and yellow starthistle over the course of the study, we used linear mixed effects regression to examine trends in cover of these species between grazed and ungrazed treatments. The dependent variables observed were percent medusahead and yellow starthistle cover, and the independent variables were treatment (grazed, ungrazed), year (2006, 2009, 2011) and the interaction between treatment and year. Within each treatment, we also examined changes in cover between the baseline (2006) and final (2011) evaluations for the most commonly occurring species: medusahead, yellow starthistle, soft chess, filaree (*Erodium* spp.), red brome (*Bromus madritensis* L.), ripgut brome, slender oat and a composite functional group composed of several thatch-loving species including red brome, ripgut brome and slender oat. We used linear and generalized linear mixed effects regression models to test for differences in percent observed species cover between 2006 and 2011. For all analyses, site identity was included as a random term to account for repeated measurements (Pinheiro and Bates 2000). Standard diagnostic tests were used to check assumptions of linearity, normality and constant variance. Analyses were performed using STATA/SE 13.0 statistical software (StataCorp 2013).

To examine changes in overall plant community composition, we used nonmetric multidimensional scaling (NMDS). NMDS is an ordination technique widely used to examine patterns in multidimensional data (e.g., plant community data) and, unlike other ordination methods, makes few assumptions about the data. Species cover values were log-transformed, and NMDS scores were calculated based on a Bray-Curtis dissimilarity matrix (McCune and Grace 2002). Analysis was conducted in the R software environment using the metaMDS routine from the vegan package (Oksanen et al. 2007; R Development Core Team 2010). The metaMDS function selects several random start positions to find a global solution, so that it does not become trapped at local optima. The final configuration is rotated via principal components so that the first dimension explains the greatest amount of variance. NMDS was run for 2 through 6 dimensions, with the optimal number of dimensions selected via examination of a scree plot, which displays stress versus dimensionality for each solution (McCune and Grace 2002).

To examine whether overall plant community composition significantly differed between grazed and ungrazed treatments, we used blocked (i.e., for paired plots) multiresponse permutation procedures (MRBP). MRBP provides a nonparametric test of multivariate differences between pre-defined groups, such as “grazed” and “ungrazed” plots (McCune and Grace 2002). Observations were blocked by plot pair identification number, and species cover data were log-transformed. MRBP was based on Euclidean distance measures and median alignment within blocks (McCune and Grace 2002).

Yellow starthistle response

Our analyses showed that prescribed grazing applied to Bear Creek Unit did not impact yellow starthistle cover. Trends in basal cover of yellow starthistle did not significantly differ between grazed and ungrazed treatments (fig. 1), with no significant changes in yellow starthistle cover for either treatment between baseline and final evaluations (fig. 2).

The lack of response to grazing may be due to a mismatch in the timing of grazing and the post-bolting/pre-flowering phenological stages of yellow starthistle. Since yellow starthistle matures and produces seeds later than other species, including medusahead, grazing late in the annual growing season (after May 1) is particularly important for effective suppression (DiTomaso at al. 2006). In addition, yellow starthistle populations commonly exhibit multiple life forms

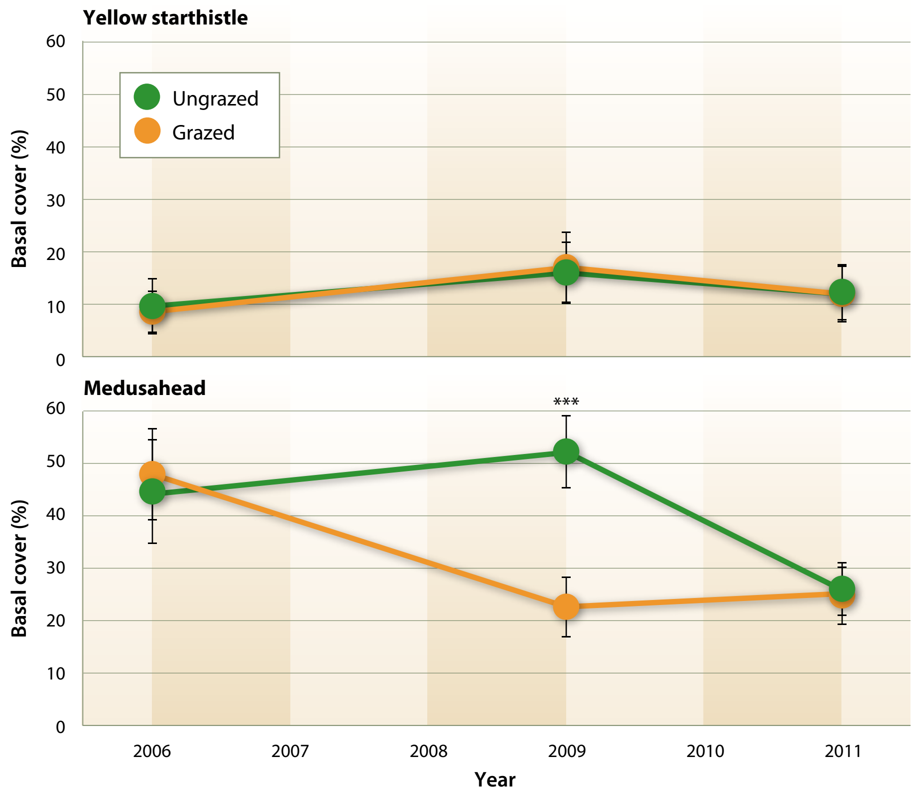

Fig 1. Change in percent basal cover of target herbaceous plant species from 2006 to 2011. * indicates *P* < 0.01.**

(seedlings, rosettes, flowering adults, annual, biennial) simultaneously (DiTomaso 2000; Kyser et al. 2007). This diversity creates an additional obstacle to suppression, because individual plants are not all susceptible to grazing at the same time.

During this study, timing of cattle removal was dictated by real management considerations such as availability of water and desirable forage for livestock, which were both limited by May in most years. As a result, cattle were likely not present during the post-bolting/pre-flowering phenological stages when grazing can reduce yellow starthistle cover and seed production (DiTomaso et al. 2006; Thomsen et al. 1993).

Medusahead response

Following baseline (2006) botanical evaluations, medusahead cover within grazed treatment plots fell by roughly half in 2009. Additionally, in 2009, medusahead cover in the grazed treatment was significantly lower (*P* < 0.01) than that observed in the ungrazed treatment (fig. 1). However, by the final evaluation (2011), medusahead cover for both grazed and ungrazed treatments converged to similar levels.

As with yellow starthistle, research has shown that grazing late in the growing season (late April and May) is critical to successful medusahead control (DiTomaso et al. 2008). However, medusahead develops earlier in the spring than yellow starthistle and does not exhibit yellow starthistle's diversity of life forms. Medusahead's earlier maturing phenology narrows the window for grazing to achieve suppression. Although managerial constraints in this study made it impossible to graze late enough into the season to impact yellow starthistle, medusahead populations were impacted in several years. The differential reduction of medusahead cover in the grazed

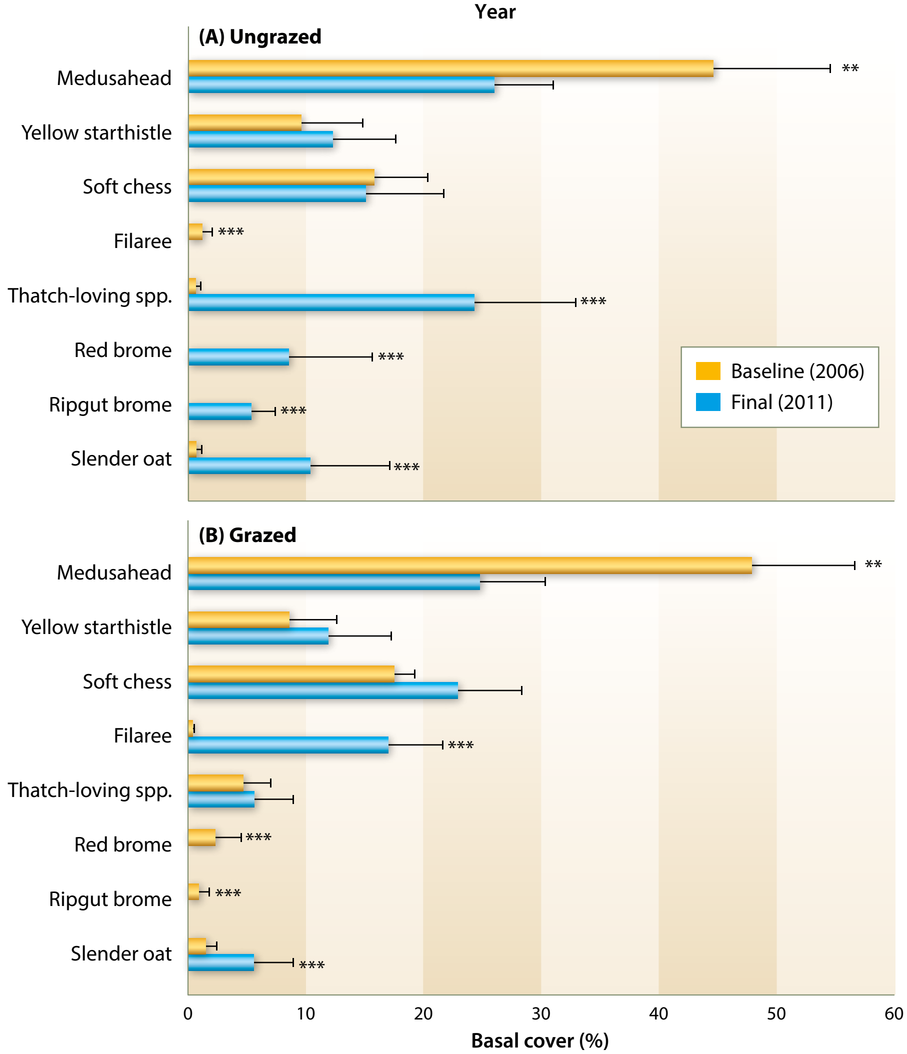

Fig. 2. Changes in cover of the most commonly occurring species between baseline (2006) and final sampling events (2011) for ungrazed (A) and grazed (B) treatments. Cover values for thatch-loving species were calculated as the sum of ripgut, red brome and slender oat basal cover. * indicates *P* < 0.1; ** indicates *P* < 0.05; and * indicates *P* < 0.01.**

Kenneth W. Tate

Authors Alexis Robertson (left) and Josh Davy (right) monitoring plots after a spring grazing. By 2011, there was a significant increase in desirable forage species in the grazed plots.

treatment between the periods 2006 through 2009 and 2009 through 2011 is potentially explained by three interacting factors: (1) timing and amount of rainfall; (2) timing of cattle removal each spring; and (3) ability of medusahead to recover from grazing and produce seed.

During the period 2006 through 2009, when medusahead cover was significantly reduced in the grazed treatment (fig. 1), late spring (May-June) and/or total annual rainfall were substantially lower than reported long-term averages in 2007 and 2008. Lack of late season (periods after May 1) precipitation created dry soil moisture conditions at the end of the grazing season, which potentially diminished the ability of medusahead to recover from grazing and produce new seed heads (DiTomaso et al. 2008), which is why the plant reduction created in 2008 is apparent in 2009. With the exception of 2006 and 2010, cattle were removed from the management unit between May 22 and 27. The lower late season rainfall, and resulting depleted soil moisture levels, may have created a multi-year window of opportunity in which the timing of grazing overlapped with the most susceptible phenological stages of medusahead development.

In contrast, late spring rainfall (May-June) during the period 2009 through 2011 was well above the reported long-term average, which potentially enhanced the ability of medusahead to respond to post-grazing conditions. Although the timing of cattle removal was similar to that of the 2006–2009 period (table 1), this late season rainfall enabled medusahead plants to recover from grazing disturbances (and any transitory losses in cover) and produce new inflorescences.

During consecutive years with lack of late season soil moisture, this fixed end-point grazing strategy appears to have reduced medusahead cover, while in consecutive years with late season soil moisture it did not. These findings suggest that adapting the timing of cattle removal based on late season rainfall patterns would increase the overall effectiveness of grazing for medusahead suppression. However, basing cattle management decisions solely on late spring rainfall may not be feasible from a livestock production perspective, particularly during June when earlier maturing desirable annuals have senesced and no longer provide adequate forage quality. Management and economic considerations such as availability of water and desirable forage, accessibility of sufficient numbers of cattle for late season targeted grazing, and animal performance need to be balanced with weed management goals. Resolving these tradeoffs appears critical to attaining consistent, annual suppression of invasive weeds via grazing management.

Plant community response

In addition to investigating the responses of medusahead and yellow starthistle, we examined plant community changes both within and between grazed and ungrazed treatments. Over the course of the study period, a total of 64 species were observed. One of the most notable changes was the significant ($P < 0.05$) decline of medusahead between 2006 and 2011 in both grazed and ungrazed treatments (fig. 2). In the ungrazed treatments, medusahead was largely replaced by the nonnative annual grasses slender oat, ripgut and red brome (fig. 2A), which have been reported to be tolerant of high

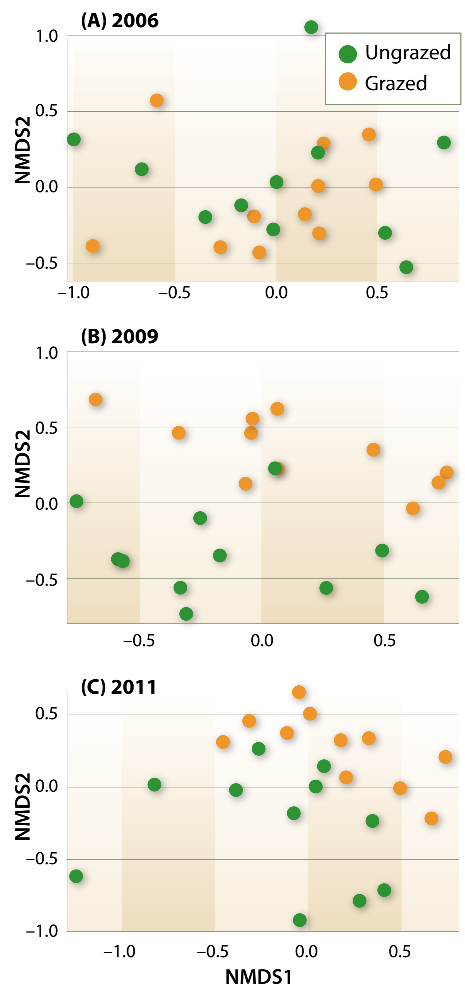

Fig. 3. Overall plant community changes between grazed and ungrazed plots in 2006 (A), 2009 (B) and 2011 (C) based on NMDS ordination. In 2006, no difference in species composition was detected between grazed and ungrazed plots, as indicated by the intermingled dots (A). In 2009 and 2011, the dots diverge, indicating a significant difference in plant species composition between grazed and ungrazed plots after grazing was initiated (B and C). Significance values for differences between grazed and ungrazed plots were $P = 0.68$, $P < 0.01$ and $P < 0.01$ for 2006, 2009 and 2011, respectively.

thatch conditions (Amatangelo et al. 2008; George et al. 2001). Ripgut and red brome are also considered weedy invasives and provide little ecological or forage value (DiTomaso and Healy 2007). For the grazed treatment, there was a significant ($P < 0.01$) increase in filaree and slender oat, which are generally considered desirable forage species, and a significant ($P < 0.01$) decline in ripgut and red brome (fig. 2B).

NMDS analysis confirmed divergence in overall plant community composition between grazed and ungrazed treatments during the study period. Initial plant community composition was not statistically different ($P = 0.68$) between grazed and ungrazed treatment plots in 2006 at the onset of grazing (fig. 3A). By 2009, plant communities significantly ($P < 0.01$) diverged between grazed and ungrazed treatments (fig. 3B), and remained significantly different in 2011 ($P < 0.01$) (fig. 3C).

Management implications

Annually adapting the timing of cattle removal based on seasonal rainfall patterns and phenology of target species may increase the effectiveness of grazing management to control invasive weeds such as medusahead and yellow starthistle. However, it is critical to acknowledge and address key management challenges, including availability and distribution of water and accessibility of sufficient cattle numbers for targeted grazing in late spring and early summer. This study of a prescribed grazing system demonstrates the continuing challenges and tradeoffs in balancing land management and conservation goals with the economic realities of livestock production, and highlights the need to cautiously translate small-scale research results into practical solutions for rangeland management. CA

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Phytophthora ramorum can survive introduction into finished compost

by Steven Swain *and* Matteo Garbelotto

Composted municipal green waste is a potential vehicle for the transmission of Phytophtora ramorum*, the pathogen responsible for the disease known as sudden oak death. To assess the survival rate of the pathogen in compost, we introduced zoospores — a type of infectious propagule — into six composts of varying provenance and maturity. The compost samples represented three production facilities, two production techniques (turned windrow and forced air static pile) and two levels of maturity (fresh, defined as aged for less than 1 week; and mature, aged for more than 4 weeks). Positive re-isolations — indicating survival of the pathogen — were obtained from all composts. The re-isolation rate from the compost from one of the three production facilities was greater than that obtained from an inert substrate (filter paper) inoculated with the pathogen (*$P < 0.01$*), while re-isolation rates from the other two sources were statistically indistinguishable from those obtained from the inert substrate (*$P > 0.01$*). There was no significant difference in re-isolation rate between composts produced by the turned windrow method and composts produced by the forced air static pile technique. Re-isolation rates were greater from mature composts than from fresh composts (*$P < 0.01$*). The results show that* P. ramorum *may be present and infectious if introduced into finished compost, and that variations in compost characteristics appear to influence survival rates.*

Phytophthora ramorum, the causal agent of the disease commonly referred to as sudden oak death (Rizzo et al. 2002), has killed millions of trees on the north coast of California. (Frankel and Palmieri 2014; Meentemeyer et al. 2011). An introduced pathogen both in North America and Europe (Goss et al. 2009), it was discovered in California in 1995. *P. ramorum* often forms lethal bark lesions on oaks (*Quercus* spp.) and the related tanoak (*Notholithocarpus densiflorus*), but it spreads by spores formed on foliar lesions on scores of other plant species, including common landscape plants (Rizzo and Garbelotto 2003). New foliar hosts have been discovered annually since 2002 (USDA-APHIS 2013), and the symptoms can vary substantially from host to host (Garbelotto 2003; Hüberli et al. 2003; Hüberli et al. 2004; Murphy and Rizzo 2003). Furthermore, the disease keeps spreading to new locations through limited-distance natural dispersal, infected nursery stock and perhaps through other yet unknown means (Croucher et al. 2013; Garbelotto et al. 2003; Orlikowski and Szkuta 2002; Werres et al. 2001). To help prevent the spread of the pathogen to new localities, movement of infected plant material is highly regulated (Paswater 2003).

With the host species list and associated symptoms growing at this rate, even conscientious landscape contractors may not be able to keep pace and identify those plants likely to be infected. Debris from infected plants is almost certainly taken to local composting facilities, which are subject to restrictions on shipping product out of the quarantine area if found to be not pathogen-free (Paswater 2003). Leaves of foliar hosts can be extremely infectious (Davidson et al. 2002),

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UC ANR researchers tested composts made from municipal green wastes to determine whether the sudden oak death pathogen could survive in finished compost.

Coast live oaks killed by the sudden oak death pathogen (*Phytophthora ramorum*).

even for extended periods of time. For instance, *P. ramorum* can remain viable on detached leaves of bay laurel (*Umbellularia californica*) for several weeks (Harnik et al. 2004). Survival of *P. ramorum* in dead and down logs and firewood (Shelly et al. 2005) can also last several weeks.

The composting process can eradicate even the toughest resting propagules commonly produced by *P. ramorum* if the process is conducted according to U.S. Environmental Protection Agency (EPA) PFRP guidelines (Swain et al. 2006).

In addition, finished compost has a well-established history of suppressing a variety of plant pathogens when incorporated into potting mixes or planted into soil (Hoitink and Fahy 1986), though these suppressive qualities have primarily been demonstrated once the compost has been incorporated into soil or container media (Bollen 1985; Gorodecki and Hadar 1990; Hoitink and Boehm 1999), and may not be an inherent property of the finished compost itself (Hardy and Sivasithamparam 1991). The survival of *P. ramorum* in finished compost, however, had not previously been evaluated.

It stands to reason that *P. ramorum* would be able survive in finished compost if resting propagules are introduced directly into it, as such propagules have been isolated and germinated from inhospitable substrates including tires and sneaker soles (Davidson et al. 2005).

We use the term *resting propagules* to refer to spores such as chlamydospores and oospores that have thick cell walls resistant to desiccation, microbial degradation and temperature extremes, as might be found in compost piles. Other sources have referred to these structures as *survival propagules* (Erwin and Ribeiro 1996), or *resting spores* (Judelson and Blanco 2005). Resting propagules are comparatively large and heavy, and as such they don't disperse as well as other spore types such as sporangia or zoospores (Judelson and Blanco 2005). We distinguish resting propagules from *dispersal propagules*, which are more delicate spore types such as sporangia and zoospores. Sporangia are light and passively carried by wind and rain, while zoospores actively swim in water films and hunt for suitable hosts to infect.

Our research addressed the question of whether *P. ramorum* may have a high survival rate in finished compost if reached by dispersal propagules that may be transported by wind or water from fresh green waste or infectious plants within or near composting facilities. In other words, we sought to determine whether finished compost allows for survival of *P. ramorum*, assuming: (a) inclusion of resting propagules such as chlamydospores has been avoided and (b) dispersal propagules have reached it. In addition, we investigated whether compost can become infectious — that is, whether re-isolation rates of dispersal propagules from finished composts can be higher than those from any similarly treated inert substrate.

Materials and methods

In order to maximize the differentiation between survival — a process mediated primarily by the survival and germination of resting propagules — and an infectious phase in which secondary sporulation and creation of dispersal propagules may occur in the absence of resting propagules, we developed a water bath inoculation system that would allow for production of dispersal propagules — in this case, zoospores — without significant introduction of resting propagules. Accordingly, the timeline of this experiment was designed to study zoospore driven colonization, as this is the process that is the primary driver behind the "natural" infection process of *P. ramorum* (Garbelotto and Hayden 2012).

California bay laurel (*Umbellularia californica*) infected with *Phytophthora ramorum*.

We used finished composts of varying provenances and curing times, produced both by "turned windrow" and "forced air static pile" techniques. The term "finished" here refers to compost that has completed its thermophilic phase. After the thermophilic phase is completed, most commercial composts are cured for a time ranging from a few days to several months, depending upon the production system used and the characteristics of the desired end product (Wu et al. 2000). During the curing phase, phytotoxic chemicals are degraded and metabolic rates within the compost are given time to stabilize. This process is important to the production of most commercially produced composts (Wu et al. 2000), and composting facilities typically have large piles of curing compost on site. Were *P. ramorum* to be introduced into these piles and to survive, it could be transported to new uninfected locations when the compost is sold.

Inoculation methods and substrates

Using zoospores. Three 1.5-cm diameter disks each of *P. ramorum* isolate Pr52 (CBS110537; ATCC MYA-2436) and Pr102 (ATCC MYA-2949) grown on V-8 agar (Erwin and Ribeiro 1996) were placed into each 90-mm petri dish and flooded with enough deionized water to bring the level just below the surface of the agar disks. The dishes were incubated in the dark at 16°C for 3 days, then chilled to 4°C for half an hour to induce sporulation, and then incubated for 1 hour at room

TABLE 1. Experimental layout

Compost*	Maturity, type	*P. ramorum* recovery rate	$P < 0.01$
W1	Mature, turned pile	0.92	d
FA	Mature, forced air	0.33	a,b
W2	Mature, turned pile	0.42	b,c
W1	Fresh, turned pile	0.67	c,d
FA	Fresh, forced air	0†	a
W2	Fresh, turned pile	0.08	a,b
Control	Inert, filter paper	0.13	a,b

* W(1 or 2) = turned windrow, FA = static forced air.
† Re-isolation successful in a pilot study.

temperature before quantifying zoospores with a hemacytometer (Hausser Scientific, Horsham, PA). Zoospore concentrations were diluted to 5×10^4 zoospores/ml, and 15 ml of the inoculation solution was poured into inoculation cages (see below).

Using colony plugs. Three 1.5-cm diameter disks each of *P. ramorum* isolate Pr52 (CBS110537; ATCC MYA-2436) and Pr102 (ATCC MYA-2949) grown on V-8 agar (Erwin and Ribeiro 1996) were used for inoculation. Such plugs contained hyphae (filaments that make up the body of *P. ramorum*), sporangia and chlamydospores, and were placed directly into the inoculation cages (see below).

Compost. The composts used in these experiments (table 1) were sourced from three different commercial suppliers. Two of the suppliers (which produced composts W1 and W2) used turned windrow method, while the third used forced air static pile composting (compost FA). All three composts were made from municipal green wastes sourced from the northern San Francisco Bay region. Two categories of compost were used: (1) "Fresh" composts, which had just finished their thermophilic phase, and had been curing for less than one week, and (2) "mature" composts, which had been curing for 4 weeks or more. Composts came from commercial facilities where temperatures and time of composting follow EPA guidelines (EPA 2003). Each compost included a control treatment and was tested by pear baiting to ensure it was free of any phytophthora prior to being used in the experiment.

Filter papers. All experiments were replicated using filter paper as an alternative media to compost, in order to separate any compost-specific results from results that could be obtained from any inert media.

Water baths. Each compost or filter paper was placed into a 1-quart ice cream container, and partially flooded with deionized water. A cage, made from a small perforated plastic cup, was then placed into the compost-water mixture, and the inoculum was introduced to the cage (fig. 1). For the hyphal series, whole inoculum grown on agar plugs was placed into the cages. For the zoospore series, approximately 15 ml of zoospores were introduced to each cage. The compost was then flooded the rest of the way, allowing the water to flow into the cup from the outside. The resulting assemblages were then stored in the dark at 12°C for 4 days, after which time the cages were removed with their contents. Finally, the bottoms of the ice cream containers were perforated, allowing the water to drain off. The compost and filter papers were then allowed to dry until each substrate was moist. Half of each filter paper was cut up and plated as outlined in *Direct testing*, below. The remaining half filter papers, and all compost samples, were then transferred into their own 1-gallon plastic bag and pear baited. Negative controls were run where no inoculum was added to each cup. For positive controls, washed, green, unripe D'Anjou pears were added to the ice cream containers in place of compost or filter paper, and the perforated plastic cages were affixed to the sides of the containers with tape. This process was simultaneously replicated four times for each compost origin and age. The entire series was simultaneously replicated twice more, resulting in 12 containers for each compost type, split into three replicates of four.

Pathogen re-isolation and analyses

Pear baiting. A single green, washed, organically grown unripe D'Anjou pear was placed into each 1-gallon plastic bag or 1-quart ice cream container, and enough water was added to the container to cover most of the pear, and/or achieve an approximate water to compost ratio of 4:1 (Tsao 1983). The pears were incubated in the water for 4 days and then placed to dry on paper towels for an additional 4 to 5 days, all at 12°C. The resulting pear lesions, if found, were then plated onto PARP as outlined below in *Direct testing.*

Direct testing. Viability of the pathogen was determined by counting how many filter paper or pear skin sample fragments (about 1 to 4 mm^2 in size) formed colonies when plated on $P_{10}ARP$ (PARP) selective media (Erwin and Ribeiro 1996, modified to 25 µg/ml PCNB). One sample was plated directly onto PARP selective media from the infection margin of each pear lesion; approximately 50 sample fragments from one half of each filter paper were plated onto PARP as well. PARP plates were incubated in the dark at 20°C and scored as either positive or negative at 2 weeks from the time of inoculation. As a positive control, one plate from every batch of PARP medium was infected with Pr52 and Pr102. Any batch of PARP that failed to support the growth of *P. ramorum* was discarded.

Statistics. All formal analysis was done on a pairwise basis using nonparametric Fisher's exact test.

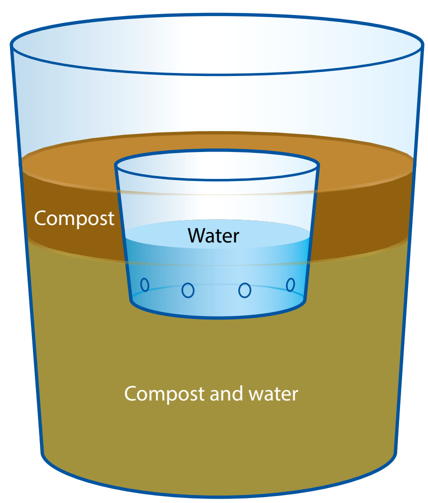

Fig. 1. One-quart ice cream container water bath diagram. For positive controls, pears were placed into containers containing no compost. For negative controls (inert media) filter papers were placed into the bottoms of the containers instead of compost. Perforated cage for zoospores or culture disks is shown sunken in compost and water.

Results

A contingency analysis was performed comparing isolation success of composts inoculated using zoospores and those inoculated using hyphal plugs bearing sporangia. Results show no difference between the two inoculation methods (N = 118, DF = 1, –LogLike = 0.21870008, R^2 = 0.0027; two-tailed Fisher's exact test P = 0.5726) and hence data from the two were pooled together.

It was possible to recover *P. ramorum* from all composts except for fresh compost from site FA (table 1). However, low levels of *P. ramorum* were recovered from fresh site FA compost in a pilot study previously completed (data not shown). Recovery from "mature" composts that had cured for 4 weeks or more (M) was higher than that from "fresh" composts that had cured for less than 1 week (F) ($P < 0.01$).

Substrates were clumped in two groups (labeled "a" and "d" in fig. 2 and table 1) ($P < 0.01$) based on recovery rates: the highest recovery of *P. ramorum* was obtained from both mature and fresh turned pile composts from site W1, while the lowest recovery rates were obtained from the inert substrate and from all other composts except the mature turned windrow pile W2. The mature turned pile compost W2 had an intermediate recovery rate overlapping the two groups. It is also interesting to note that the recovery rate of the fresh forced air compost FA was lower than that of the inert substrate (fig. 2).

Discussion

P. ramorum could be recovered from every compost substrate tested, so it is clear that at least some, and possibly all, finished composts allow for survival, even when the number of dispersal and resting propagules is minimized. The recovery rates for FA and W2 composts were statistically indistinguishable from filter paper, which suggests that these composts are not any better substrates for *P. ramorum* survival than any other material. Interestingly, the recovery rate from fresh forced air compost FA was lower than that from the inert substrate, suggesting this composting technique generates a substrate unfavorable to survival of *P. ramorum* zoospores. It appears that this peculiarity may be lost as the forced air compost matures, suggesting that the low survival rate of the pathogen in fresher compost may be due to a transient presence of inhibiting chemicals or competing thermophilic organisms, or both.

Recovery rates obtained from site W1 were significantly higher than those from inert media and from the other two composts. The higher rates most likely simply reflect a higher survival rate, though another possibility is a higher germination rate after encystment (Erwin and Ribeiro 1996), and while it's unlikely, we cannot exclude the possibility of colonization.

Overall, fresh compost was less favorable to *P. ramorum* recovery than mature compost, suggesting that well-cured compost may represent a greater risk for spreading *P. ramorum* if it is infected. The lower suppressive action of older compost is expected, due to changes in microbial communities and in particular due to a lower representation of highly suppressive thermophilic fungi in older composts (Goyal et al. 2005).

Although we did not test for how long each substrate remained infectious, our main goal here was to determine whether *P. ramorum*, a federally regulated pathogen (USDA 2007), may be present and infectious in a commercially available product, were it to be infested. Our results show that it can, and that there are initial differences among substrates. How long each substrate will remain infectious is relatively less important when dealing with a regulated organism.

At present we cannot explain the source variation found between composting facility W1 and facilities FA and W2. A large number of factors may be involved, including the base materials going into the compost (Hoitink and Boehm 1999), the moisture, carbon availability and fungal diversity of the pile (Soares et al. 1995), and the frequency and efficiency of turning operations (Churchill et al. 1995). The most apparent difference between the two windrow composting facilities is that facility W2 has specially designed windrow turning equipment (Scarab compost turner), while facility W1 uses front-end loaders for turning. Furthermore, compost from site W1 appeared to be composed of materials that were ground more coarsely prior to composting than the other composts, so it appears that finer composts may be more suppressive than coarse ones.

Conclusions

Our study was designed as a proof of concept and the conclusions we can draw from the results are that *P. ramorum* can survive if inoculated using a high

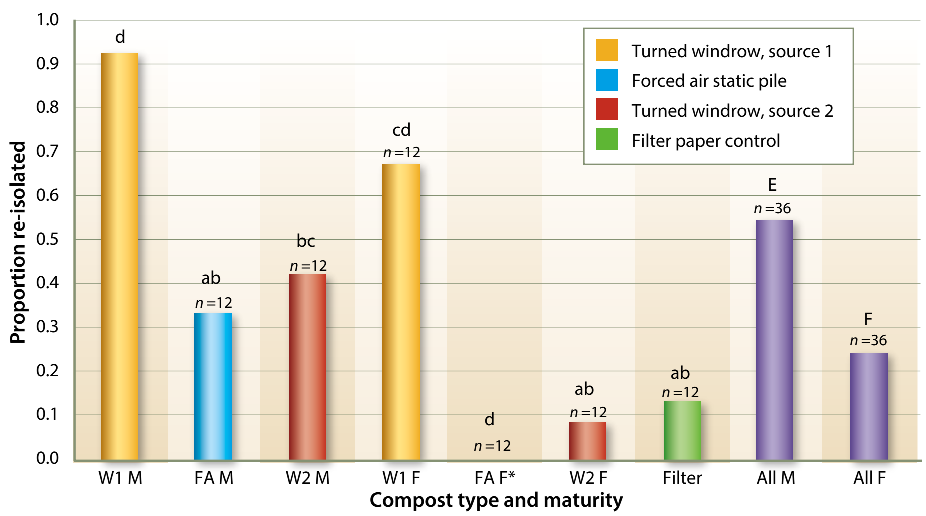

Fig. 2. Percentage comparison of re-isolation success. Column suffix M denotes mature compost (inoculated after it had aged 4 weeks or more), while column suffix F denotes fresh composts aged less than 1 week. Columns labeled "all" combine either mature or fresh compost from all sources, and therefore show average values across all facilities and composting techniques used. Letters denote significance grouping at the ($P < 0.01$) level of confidence. Lowercase letters can be compared to other lowercase letters, while uppercase letters should only be compared to other uppercase letters, as significance was not cross checked across case groupings. Any column not containing a given letter is statistically different at $P < 0.01$ from any column that does, except as stated above. For example, compost pile W2 F (a,b) is similar to any piles marked a or b, but it is statistically distinct from piles marked c or d. * Re-isolation successful in a pilot study.

concentration of inoculum in all finished compost, that older finished composts are less suppressive than fresh finished composts, and that it may be able to grow in some composts. However, our study did not address which traits may make a compost suitable for growth of the pathogen: further research including precise characterization of composts using the U.S. Composting Council Test Method for the Examination of Composting and Compost (TMECC) standards (compostingcouncil.org/tmecc/) is needed to determine which types of composts are most amenable to survival and possibly growth of this serious plant pathogen.

It should be noted that our experiments involved the use of large amounts of inoculum. Under real-world conditions a comparable situation might only occur when large amounts of fresh infected plant material is shipped to the composting facility in cool, rainy conditions, or if compost rows were to be under or near highly infected infectious hosts such as *Rhododendron* spp., California bay laurels or tanoaks.

These findings suggest that in composting facilities that may be shipping material out of the immediate area, measures should be taken to ensure that finished compost is not contaminated by infected green waste. Best management practices for composting facilities should minimize the potential for infected surface water or wind-blown rain from fresh materials to contaminate mature compost. Additionally, known plant hosts for *P. ramorum* should not be located within the immediate vicinity of the composting facility. We encourage monitoring of infectious hosts near composting facilities within the zone of infestation (see sodmap.org), and their removal, if possible, when these plants may be within the facility itself. These measures are essential to ensure the final product does not include any infectious material. CA

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Upcoming UC ANR events in 2016

Eléna Zhukova

San Joaquin Valley Grape Symposium

http://ucanr.edu/?calitem=300020

Date: January 6, 2016
Time: 7:30 a.m. to 12:30 p.m.
Location: C.P.D.E.S Hall, 172 W. Jefferson Ave., Easton, CA
Sponsor: UC ANR Cooperative Extension Fresno County
Contact: Farm Advisor George Zhuang gzhuang@ucanr.edu or 559-241-7506

Eléna Zhukova

San Joaquin County and Delta Field Crops Meeting

http://ucanr.edu/?calitem=300166

Date: January 8, 2016
Time: 8:00 a.m. to 12:00 p.m.
Location: Robert J. Cabral Agricultural Center, 2101 E. Earhart Ave., Stockton, CA
Sponsor: UC ANR Cooperative Extension San Joaquin County
Contact: Farm Advisor Michelle Leinfelder-Miles mmleinfeldermiles@ucanr.edu or 209-953-6100

Diane Nelson

Pistachio Day

http://ucanr.edu/?calitem=292533

Date: January 20, 2016
Time: 8:00 a.m. to 4:30 p.m.
Location: Visalia Convention Center, Visalia, CA
Sponsor: ANR Program Support Unit
Contact: anrprogramsupport@ucanr.edu for logistics and registration; lferguson@ucdavis.edu for course content