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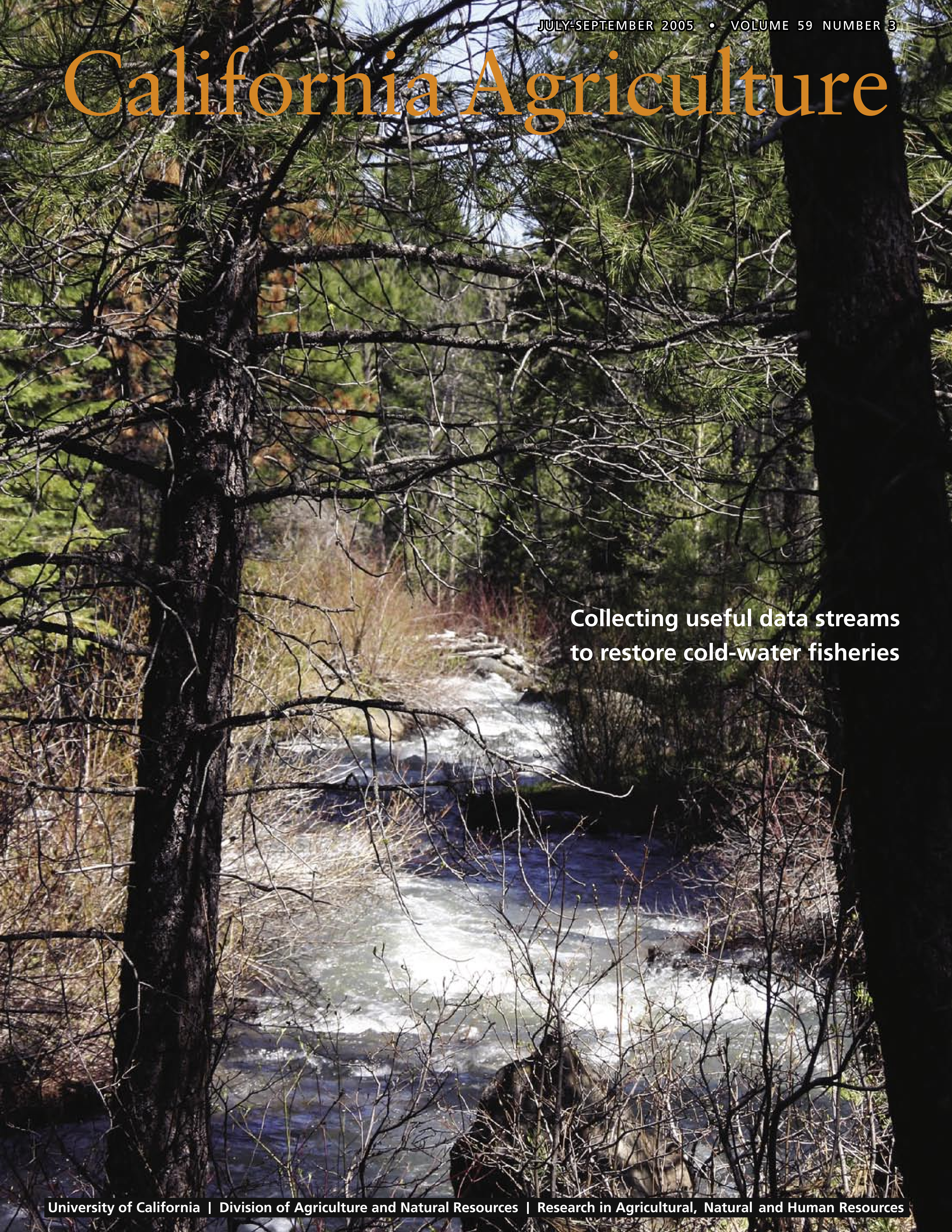
California Agriculture



Collecting useful data streams to restore cold-water fisheries

University of California | Division of Agriculture and Natural Resources | Research in Agricultural, Natural and Human Resources

ANR pursues excellence in research, development and delivery

Richard B. Standiford
Associate
Vice President,
Agriculture and
Natural Resources

Editor's note: Rick Standiford was appointed associate vice president of ANR in January 2005.

Over the past 6 months I've been traveling California to meet with UC Agriculture and Natural Resources (ANR) faculty and specialists on the campuses, advisors and staff in county offices, and scientists at research and extension centers. I've also talked with hundreds of people — growers and ranchers, regulators, nutrition professionals, land managers, elected officials, environmental advocates — who rely on the University for research findings, new technologies, and practical know-how to make decisions affecting the economy, health and nutrition, and natural resources.

These visits have been an eye-opener and an enormous source of pride and satisfaction. Even though I had worked with UC for 25 years as a Cooperative Extension forestry specialist, I hadn't fully appreciated the range of agricultural, natural and human-related challenges facing California's growing population. It gives me tremendous satisfaction to know that talented ANR professionals are making a real difference in the lives of millions of Californians.

However, I've also seen the fallout from the state funding cuts we experienced several years ago, resulting in the loss of nearly 350 positions in UC's Agricultural Experiment Station (AES) and Cooperative Extension (UCCE). Our campus- and county-based professionals are working longer hours, taking on greater responsibilities and seeking more effective ways to disseminate research findings to stakeholders.

My travels have confirmed that UC is the leading public research university in the world, with ANR being a major contributor to this success story. Even with budget cuts, we have nearly 1,000 research and extension academics at UC Riverside, UC Davis, UC Berkeley, county UCCE offices, and research and extension centers statewide. It is unprecedented to have three great campuses in the same state dedicated to the land-grant mission.

The University — through Cooperative Extension — has a world-class system for translating science-based information developed on the campuses and delivering it to end-users across the state. UCCE advisors live and work in local communities and understand the economic, environmental and community development issues facing their neighbors. This focus on local needs is critical in California where demographic diversity, rural-urban conflicts, a broad range of soils and climates, and the production of more than 250 specialty crops and other commodities, create many challenges.

ANR is distinguished by our tradition of interdisciplinary problem-solving and bringing together experts from various fields. At the core of everything we do is a commitment to practice research, development and delivery — or "R, D & D" — which means we take basic research from the lab, apply it under strict scientific conditions in the field, then deliver the results to end-users.

But we face a real challenge over the next few years in maintaining these program strengths. The state budget cuts have created gaps in campus- and county-based programs through workforce reductions and the loss of support funds. Not surprisingly, one of the major themes expressed by stakeholders at the listening sessions held across California in early 2004 was for ANR to better focus its mission, direction and resources.

Another common theme was the importance of maintaining viable, locally based UCCE programs. Our stakeholders repeatedly told us that UCCE advisors in the counties are a critical link in translating research and technology developed on our campuses into best management practices adapted for local conditions.

One outcome from the listening sessions was implementation of a broad-based planning process in ANR. A specific goal was to clearly focus our mission and resources in support of high-priority research and extension programs that maximize the public good. The planning process, which will help guide our resource allocation decisions for the next 5 to 10 years, identified 21 core issues (*California Agriculture* Oct-Dec 2004, p. 178).

As a next step, we funded 28 projects addressing many of the high- and medium-priority core issues identified last fall. The goal was to provide incentives for campus-county collaborative, multidisciplinary, systems-based research and extension efforts. More than 200 ANR academics are now involved in this core-issues grant program.

We also are in the process of rebuilding our county-based UCCE programs, which lost nearly 50 advisor positions. A major step forward was the decision in April to approve 11 new UCCE advisor positions, funded by dollars freed by recent retirements. They address many of our core issues.

For example, we are recruiting an air quality advisor to serve a four-county area in the southern San Joaquin Valley. ANR has strong air quality research programs at Davis, Berkeley and Riverside, and the new CE advisor will help bring science-based solutions and expertise to address agriculture and human health problems in an area that currently fails to meet federal ambient air-quality standards.

The other new positions are a dairy advisor in Tulare County, America's leading dairy county; three vegetable crops advisors; three nutrition, family and consumer sciences advisors; two 4-H youth development advisors; and a natural resources advisor. We are planning another round of new advisor position approvals later this year, again with funding from retirements.

We in ANR are proud of our partnership with the people of California. We look forward to our continued commitment to quality science, linked directly to solving people's real-world problems.

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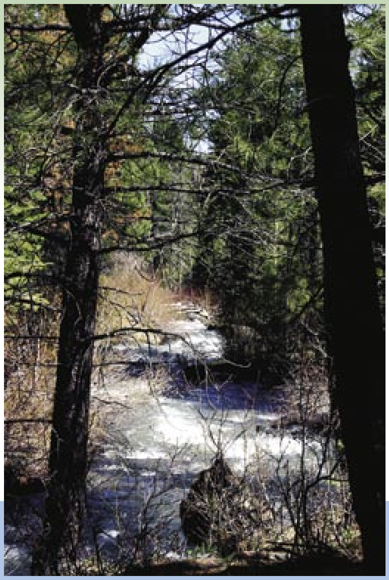
News department

Research articles

Focus: Collecting useful data streams



COVER: Monitoring of stream temperature and related factors is critical for protecting and restoring populations of salmonids and other native fish that require cold-water habitat to grow and reproduce (see pages 149, 153, 161). Likewise, the monitoring of flows into and out of irrigated pasture can help to mitigate environmental impacts (see page 168). Data collected at Lassen Creek (shown), in northeastern Modoc County, demonstrates how shade from thick vegetative cover helps to maintain cool stream temperatures. *Photo by Kenneth W. Tate.*

Letters

WHAT DO YOU THINK?

The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at calag@ucop.edu or 1111 Franklin St., 6th fl., Oakland, CA 94607. Include your full name and address. Letters may be edited for space and clarity.

Jack Kelly Clark retires

The following letter, addressed to ANR principal photographer Jack Kelly Clark, was copied to California Agriculture*:*

I really do not have the words to tell you what a great job you did with all the photos in the Kearney 40th anniversary issue of *California Agriculture* (April-June 2005). I am so thankful that you were able to make the very significant commitment to this project. Your "signature" quality flows throughout this special issue and I believe it is so fitting for you to have this Kearney issue published as a bit of a finale to your long and distinguished photography career in UC.

Fred H. Swanson
Director
Kearney Research & Extension Center

Editor's note: California Agriculture *deeply appreciates Jack Kelly Clark's nearly 4 decades of service to the magazine, which included more than 75 striking cover photos and thousands of beautiful images on the inside pages. Clark retired in June 2005, but will continue working for the University part time.*

Hail to Cal Ag!

We were in the process of packing up our offices for a move to a building three blocks away, and whilst flipping through old papers, I came across a Cal Ag–related item from the 1970s, back when it was produced by Ag Publications. The copy I found was typewritten, but today it might make an effective multimedia presentation on the Web site! So dust off your old banjo, and here we go:

CAL AG ANTHEM
(To the tune of "Sweet Betsy from Pike")

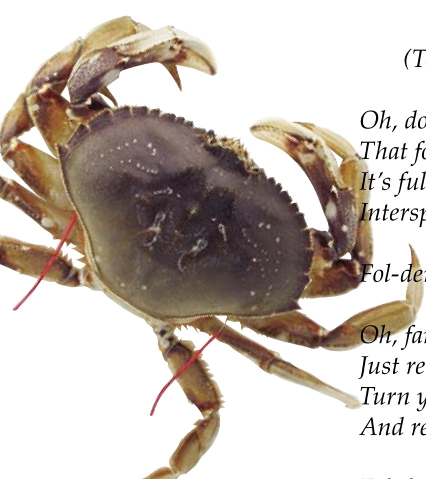
Oh, do you subscribe to our grand farming rag,
That fountain of knowledge we publish — CAL AG?
It's full of statistics on aphids and thrips,
Interspersed with genetics and wry, gnomic tips!

Fol-derol-dol fiddle-dee-dang-dang o-yodel-eeyay!

Oh, farmers, take heart — you have not far to seek —
Just read your CAL AG and grow wise in a week:
Turn your field-crops to daisies, your silage to plains,
And retire like a prince on your government claims!

Fol-derol-dol fiddle-dee-dang-dang o-yodel-eeyay!

Jim Coats
ANR Communication Services
UC Davis



Phenomenal organophosphate issue

Your January–March 2005 issue ("Beyond organophosphates") is a phenomenal resource for concise reviews of current and historical approaches to pest control. I am keeping it as a reference, and indeed, just provided the Web site to six different people this morning who had questions about the use, benefits and risks of neonicotinoids.

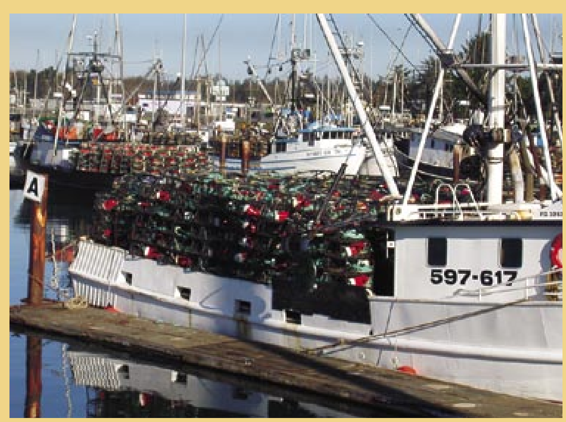
James H. Cane
USDA-ARS Bee Biology and Systematics Lab
Utah State University, Logan, Utah

Editor's note: The full text of California Agriculture*'s "Beyond organophosphates" issue can be found online at http://californiaagriculture.ucop.edu/0501JFM/toc.html. To purchase back issues, visit the* California Agriculture *home page.*

ANREP honors *California Agriculture* articles

The Association of Natural Resources Extension Professionals (ANREP) has honored the *California Agriculture* October–December 2004 issue (Vol. 58, No. 4) with its top two 2005 Educational Materials Awards in the Refereed Journal Article category: a Gold Award to "Racing for crabs: Cost and management options evaluated in Dungeness crab fishery" (page 186), and a Silver Award to "Conserving California fish: Extension approaches applied to contentious marine fisheries management issues" (page 194). Congratulations to lead author Christopher M. Dewees, Sea Grant Marine Fisheries Specialist, UC Davis, and his co-authors.

Editor's note: The full text of these award-winning articles can be found online at http://californiaagriculture.ucop.edu/0404OND/toc.html. To purchase back issues, visit the California Agriculture *home page.*



Crab boats loaded with traps in Crescent City, Calif. ***Far left*, a tagged Dungeness crab.** *Photos courtesy of Christopher Dewees.*

Don Lancaster

Regulations governing discharges of warm agricultural water into local streams are in place or in the works for many parts of California, to protect native fish species that require cold-water habitat.

Monitoring aids control of ag-related stream-temperature increases

California only has so much water to go around and using it in one place can have unintended — and undesirable — consequences in another. Take the Klamath River, where large-scale water diversions for agriculture contributed to low flows and warm waters in 2002, which in turn are blamed for this summer's dive in chinook salmon stocks. Likewise, salmon and other cold-water fish can suffer when warm irrigation water is discharged into streams. While the impacts are small individually, they can add up over an entire watershed, particularly in California where temperature-impaired streams and at-risk salmon populations overlap considerably.

In response to pressure from environmental groups over the salmon decline, agricultural discharge regulations for stream temperatures are now in the works. To help ranchers and other stakeholders comply with these upcoming temperature regulations, UC Cooperative Extension (UCCE) researchers are developing ways to monitor and mitigate stream temperatures (see pages 153, 161). "Our goal is to help ranchers and other stakeholders figure out what's going on in their creeks, and start seeing how management affects stream temperature," says UCCE rangeland watershed specialist Kenneth Tate.

California has 10 populations of chinook, coho and steelhead that are federally listed as threatened or endangered. Fish in the salmon family depend on cold water for all stages of their life cycle, from migration to spawning to rearing. While the temperature requirements vary with species and age, the preferred ranges for growth and survival are generally 45˚F to 58˚F (see figure, page 150). "Higher temperatures are usually less than optimal and those above the upper seventies are usually lethal," says UCCE anadromous and inland fisheries specialist, Lisa Thompson.

Irrigation systems can raise stream temperatures to the suboptimal or even lethal range. For example, flood-irrigation water can heat up as it crosses pastures, thus adding warm runoff to streams. Other types of land use that can increase stream temperatures include logging and grazing, which can reduce the riparian vegetation that shades and so keeps streams cool.

Until recently, such agricultural discharges were allowed under a statewide waiver granted by the State Water Resources Control Board. Now, however, the regulations for agricultural discharge are in flux. In addition, the particulars vary from region to region because they are set individually by local water-quality control boards. For example, the Central Valley region (from Modoc County to Kern County) has adopted a conditional discharge waiver tied to a compliance process. In contrast, the North Coast region (from Del Norte/Siskiyou counties to Sonoma County) does not currently grant irrigation waivers.

"We have no plans for a waiver," says Catherine Kuhlman, executive officer of the North Coast Water Quality Control Board (NCWQCB). "It is reasonable to forecast that at some point in the future, anyone in the state discharging pollutants that affect water quality will need to be covered by a waiver or permit. That said, it is going to take us awhile to get there."

TMDLs and water quality

However, the North Coast region does have total maximum daily loads (TMDLs), which under the federal Clean Water Act address temperature and other pollutants that impair water quality. TMDLs entail first accounting for the pollutant sources in impaired waters and then developing and implementing plans for meeting water-quality standards. "The conditional discharge waivers and TMDLs are pushing agriculture to start complying with water-quality regulations," says UCCE's Tate.

So far, temperature TMDLs in the North Coast region have focused primarily on streams and rivers in areas with timber. But that is about to change. Soon, streams and rivers in areas with sizeable rangelands and crop lands will also have temperature TMDLs. "The urgency is in the Scott and Shasta rivers, where TMDLs need to be adopted by December by court order," says the NCWQCB's Kuhlman. Next on the horizon is the Klamath mainstem.

As a first step in preparing for these upcoming temperature TMDLs, Kuhlman advises ranchers to develop range management plans with help from agencies such as the Natural Resources Conservation Service, and by taking the UCCE Ranch Water Quality Planning Short Course (see *California Agriculture*, July–September 2004). Developed in partnership by the UCCE Rangeland Watershed Program, ranchers and state agencies, this short course helps ranchers reduce temperature and other water pollutants on rangelands. The short course also encourages landowners to form watershed management groups, which dovetails with the next step Kuhlman recommends for North Coast ranchers: monitoring stream temperatures on a watershed basis. "Comprehensive, collaborative monitoring, rather than landowner by landowner, makes the most sense for temperature," she says.

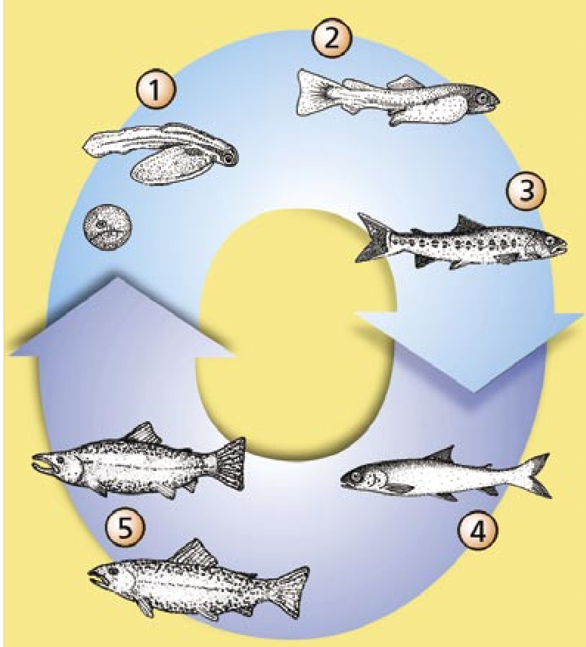
Monitoring stream temperatures

Tate and a team of UCCE researchers have developed a process for collecting, analyzing and interpreting the data. "The challenge for UC in this rapidly changing regulatory climate is to identify research that will be helpful in the long term," Tate says. "We chose monitoring because it will have value over time, no matter how the regulations change."

The process entails repeatedly monitoring streams and analyzing the data, first to see if management practices are affecting streams and then to see if management changes that are intended to lower temperatures are actually working (see pages 153, 161 and 168). If not, ranchers may need to adjust their management further. For example, if reducing pasture runoff is not enough to make streams cooler, then ranchers could also try keeping cattle away from riparian areas to increase the vegetation that shades streams. Tate also strongly recommends monitoring for several critical variables in addition to stream temperature, including canopy cover and air temperature.

Since being incorporated into the UCCE ranch water quality short course, this monitoring method has resulted in the first case studies of stream-temperature monitoring in California rangelands and irrigated pastures. "These field studies show the real-world management challenges that local ranchers face every day, and how monitoring can help them make informed decisions to overcome these challenges," Tate says. — *Robin Meadows*

Life cycle of salmonids



Drawings by Lisa Thompson (adult salmonids) and Michelle Babione (all others). Text based on ANR Pub 8112 and http://www-unix.oit.umass.edu/~dpugh/cycle.html.

The life stages of anadromous salmonids include those spent in fresh water (top), and saltwater (bottom). Steelhead species living in landlocked water bodies do not smolt, but otherwise their life cycles are similar. All salmonids depend on cool water temperatures. The length of each stage varies depending on species, stock and environment. (1) In late autumn, the female salmonid buries fertilized eggs in stream-bottom gravel nests. They develop and hatch into larval fish after 1 to 3 months, rear in stream gravel an additional 1 to 5 months, then emerge as (2) fry in spring or summer. (3) Fry and later stages of juvenile fish rear in the stream for several days to 4 years. (4) If the salmonid is going to migrate to the ocean, it will become a smolt some time between the age of a few days and 4 years. During smoltification, the fish's physiology changes to survive the transition from fresh to salt water. Smolts migrate to the ocean, usually in spring or early summer, and may spend time rearing in a river estuary. Fish live and grow in the ocean for 1 to 4 years. (5) In the spring, adult salmonids begin returning, usually to their native streams, to repeat the spawning cycle.

For more information

Central Valley Regional Water Quality Control Board/Discharges from Irrigated Lands
www.waterboards.ca.gov/centralvalley/programs/irrigated_lands/index.html

Klamath Resource Information System/North Coast Region Total Maximum Daily Loads Fact Sheet
www.krisweb.com/policy/tmdl_factsheet_northcoast.htm

UC Cooperative Extension/Nonpoint Sources of Pollution on Rangeland
http://danr.ucop.edu/uccelr/h03.htm

UC Cooperative Extension/Fishery Habitat: Temperature Requirements
http://danr.ucop.edu/uccelr/h27.htm

More than 50% of California's beef cattle are produced in small herds of 50 animals or less. UC beef quality assurance programs have improved cattle health and increased the competitiveness of California beef in national markets. Cattle graze in the Santa Ynez Valley of northern Santa Barbara County.

Beef quality program meets evolving consumer and producer concerns

California is the sixth-largest beef-producing state in the country, with more than 1 million animals sent to slaughter in 2004. Although large producers are still the backbone of the state's commercial beef industry, more than 50% of the state's beef cattle are produced in herds of less than 50 animals. Ironically, as California continues to urbanize, the number of small herd operators is predicted to increase as the number of mid-sized operations declines.

Consumer preferences and health concerns are among the key factors driving the nation's beef industry. California was one of the first states in the nation to offer a comprehensive series of educational programs for the full spectrum of beef production — from the hobby farmer with a few head to large feedlots shipping overseas.

James Oltjen, Cooperative Extension animal scientist at UC Davis, helped to develop the state's first beef quality assurance program (QAP) more than a dozen years ago. "Through this program we've made a lot of cattle healthier and shown thousands of people how to give proper injections to their livestock," Oltjen says.

Most of California's cow-calf producers have participated in at least one component of a QAP developed cooperatively by UC Cooperative Extension (UCCE) and industry trade groups. This voluntary effort continues to make a significant difference in animal husbandry practices that ultimately lead to improved beef quality, greater consumer satisfaction and more producer profitability.

QAP evolves to meet industry needs. Following a successful educational effort begun with California feedlots in 1990, a survey of producers, feeders, packers, veterinarians and others in the industry led to the formation of a cow-calf quality assurance committee by the California Cattlemen's Association in 1992. About the same time, the National Cattlemen's Association identified a number of management-related quality problems such as injection-site blemishes, hide damage, bruises and carcass condemnations that were costing the industry $700 million a year.

Formal trainings with UCCE veterinarians and animal scientists began in 1993. Improperly administered injections are one of the chief concerns because damaged tissue is tough and if noticed before sale must be disposed of during processing. Producers learn to avoid such losses by using subcutaneous injections instead of intramuscular injections; mixing an hour's worth of vaccine at a time; injecting vaccines and antibiotics in the neck, instead of the hindquarters; changing needles more frequently; and limiting the volume of animal health products injected into any one site.

QAP trainings are held on demand from county cattlemen's organizations at ranches, sale barns, fairgrounds and occasionally the UC Sierra Foothill Research and Extension Center. When the program was first initiated, trainings were held throughout the state. Now, about four of them are presented each year. The 4-hour basic course includes lectures, videos and accountability quizzes. In addition to needle and injection-site preferences, attendees learn about sanitation, how to understand drug labels, record-keeping, transportation, animal handling and facility design.

"The beef industry needs to assure the consumer that the beef he or she is buying is safe and wholesome and grown with consideration for the animal's welfare," Oltjen says. "The packers want meat that will not have injection sites or excessive bruises that have to be removed or condemned. The quality assurance program is a seal of approval that producers know how to prevent these defects."

Bill Sanguinetti, a cattle rancher in San Joaquin County, says the start of the QAP marked the beginning of an industry revolution. "That's when the beef industry became more consumer-oriented, rather than strictly production-oriented," he says. "It started at the national level with a lot of farsighted people who saw the need to educate producers to address inconsistency and other quality problems."

California beef producers are increasingly taking advantage of opportunities to provide higher-quality products for premium prices. Specialty butcher shops such as Lobel's in New York City will ship high-end beef all over the country, for a price.

Judging from the feedback he's gotten, Sanguinetti believes the program has been a success. "We've heard from the packers that there's been a marked increase in carcass quality. This is a field-to-fork system and the strong beef demand tells me it's working."

About 5,000 participants have taken the basic cow-calf program since October 17, 1993, when UCCE farm advisor Roger Ingram held the first workshop for about 100 local cow-calf producers in the once-rural Placer County community of Lincoln. Since this original program is only 4 hours long, three additional advanced programs with more in-depth information have been offered and another is in development.

Advanced programs offered. According to industry trade groups, the primary factor affecting beef's cost competitiveness with other protein sources is excess carcass fat. This concern led to the development of a program on advanced genetics and value-based marketing. Producers learn the basics of beef genetics, including bull selection, the use of ultrasound technology and carcass quality. The program also teaches producers how to match cattle types to the area in which they will be raised and how to manipulate breeding systems to their advantage. First offered in 1995, more than 380 producers had taken the advanced genetics and value-based marketing course.

The advanced residue avoidance and reproduction program, begun in 2000, has been one of the most popular with 564 attendees in 14 sessions through November 2004. This program provides in-depth information on pharmacokinetics, anatomy, estrous cycle, reproductive technology, maximizing calf production and symptoms of reproductive problems. Breakout sessions cover proper medication administration, drug-use regulations, body-condition scoring and nutrition, artificial insemination and estrous synchronization, prevention of calving problems, bull breeding soundness, and record-keeping and computer programs.

The advanced animal health program was designed in 1994 to teach producers how to focus on diseases common to a specific region. Twelve of these programs have been held so far with more than 460 attendees.

Finally, a program in development will acquaint producers with new technology designed to track individual animals to improve management and to address concerns about transmissible animal diseases such as foot and mouth and bovine spongiform encephalopathy (BSE, or "mad cow disease"). This program will show producers how to participate in a new animal identification system proposed by the U.S. Department of Agriculture.

"It's a very ambitious program that USDA is developing," says UCCE veterinarian John Maas, co-author of educational materials for the quality-assurance trainings. Through a microchip embedded in an ear tag, Maas says, animals will be traceable through the ranches, feedlots and packinghouses they pass through along the way to the consumer.

Industry trends. The beef industry is moving toward increasing accountability, and those who embrace such changes are being rewarded, Maas says. Producers who have voluntarily adopted radio frequency identification (RFID) technology to "trace back" cattle are receiving premiums from large retail end users such as McDonald's.

In addition, name-brand beef such as Harris Ranch is more evident in supermarkets throughout California. And boutique butcher shops such as Lobel's of New York can overnight vacuum-sealed, high-end beef across the country to consumers willing to pay the price.

"It's beyond safety," Maas says. "What's happening in the beef industry is similar to what happened with microbreweries. Consumers want to know where their food comes from. They want to know it's local and there's a real person standing behind it."

— John Stumbos

RESEARCH ARTICLE

Graphical analysis facilitates evaluation of stream-temperature monitoring data

Kenneth W. Tate
David F. Lile
Donald L. Lancaster
Marni L. Porath
Julie A. Morrison
Yukako Sado

Data gathered from stream monitoring can be useful for formulating workable plans to safeguard cold-water fisheries. Ken Tate, UCCE rangeland watershed specialist, uses a solar pathfinder to estimate the percentage of available sunlight reaching a stream.

John Harper

Watershed groups, individuals, and land management and regulatory agencies are collecting stream-temperature data in order to understand, protect and enhance cold-water fisheries. While great quantities of data are being generated, its analysis and interpretation are often not adequate to identify stream reaches that are gaining or losing temperature, or to correlate temperature changes with factors such as vegetative canopy cover or stream-flow levels. We use a case study from the Lassen and Willow creek watersheds in northeastern Modoc County to demonstrate graphical methods for displaying, analyzing and interpreting stream-temperature data.

Temperature is an important water-quality attribute in many of California's streams, especially those that support cold-water salmonids such as trout, steelhead and salmon. Several species of salmonids are threatened or endangered, and elevated stream temperature is often cited as a cause. In rangeland and forest watersheds, summer stream temperatures can be increased by activities such as flow diversion to irrigate pastures, return of warm irrigation runoff to streams, and reduction in riparian canopy cover due to logging and grazing. While extremely high water temperatures (generally over 77˚F) can be lethal to salmonids, of equal or greater concern is chronic exposure to sublethal temperatures (generally 67˚F to 76˚F), which can affect their growth, reproductive success and tolerance of pollutants or disease (Sullivan et al. 2000). To reduce stream temperatures and improve cold-water fisheries habitat, water-resource protection agencies have targeted numerous California river systems for the development of watershed-scale restoration plans stating total maximum daily loads (TMDLs). These include nutrients, sediments, pathogens and increases in stream temperature.

Fish responses to temperature vary by species and life stage (such as larval, fry, juvenile and adult; see page 150)(Beschta et al. 1987; Thompson and Larsen 2004). As a result, stream-temperature criteria and objectives to safeguard cold-water fisheries habitat are often dependent upon the species occupying a particular stream reach and the life stage at which the species are present. For example, Oregon's Department of Environmental Quality established

Glossary: stream-temperature metrics

Daily maximum temperature: Maximum of 48 observations collected every half hour during each 24-hour day.
Daily average temperature: Average of 48 temperature observations collected every half hour during each 24-hour day.
7-day running average of daily maximum temperature: Calculated for each day as average of daily maximum temperature observed for that day and for 6 consecutive prior days.
7-day running average of daily average temperature: Calculated for each day as average of daily average temperature observed for that day and for 6 consecutive prior days.
Maximum weekly maximum temperature: Maximum 7-day running average of daily maximum temperatures observed during a period of interest (such as a specific month or critical fish life stage).
Maximum weekly average temperature: Maximum 7-day running average of daily average temperatures observed during a period of interest.

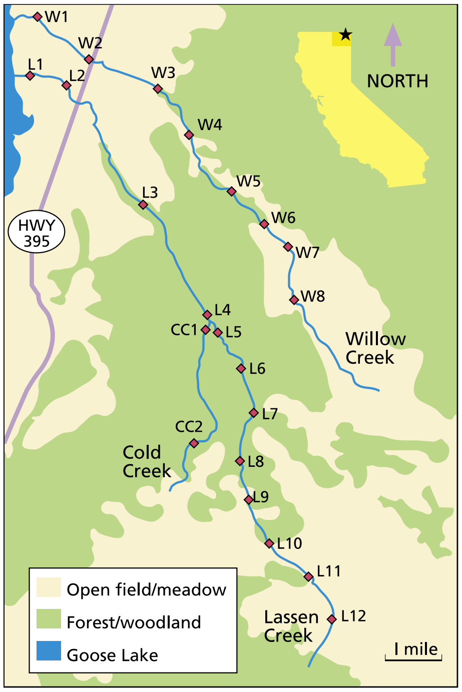
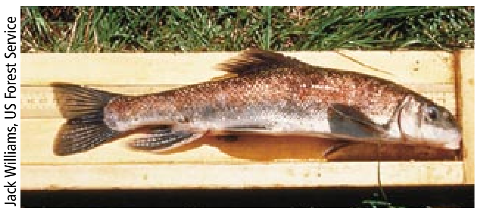
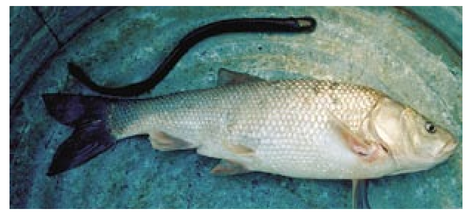


Fig. 1. Stream-temperature monitoring locations on Lassen, Willow and Cold creeks in northeastern Modoc County, Calif.

Michael Graybrook



Jack Williams, US Forest Service



Peter Moyle

Salmonids and other native fish need cold-water stream habitat to successfully grow, reproduce and tolerate pollutants and disease. In the Goose Lake Basin, native fish requiring such habitat include: *top*, Goose Lake redband trout; *bottom left*, Goose Lake sucker; and, *bottom right*, Goose Lake lamprey (top) and Goose Lake tui chub (bottom).

a standard of 66˚F as the 7-day moving average of daily maximum stream temperature for general salmonid use, but recommends 55˚F for spawning, egg incubation and fry emergence.

Monitoring and data collection are frequently undertaken in streams across California and the western United States. The objectives often include: (1) the evaluation of compliance with specific stream-temperature criteria; (2) the determination of temperature changes above and below a land-use activity, through a given property or stream reach, or along an entire stream network; and (3) the examination of watershed-specific associations between stream temperature and factors such as air temperature, stream flow and riparian canopy cover. Several publications provide guidance on how to plan and implement water-quality and stream-temperature monitoring (ODF 1994; MacDonald et al. 1991; US EPA 1997), but few provide guidance on how to analyze and interpret the resulting data.

While the availability of inexpensive, automatic temperature recorders has facilitated data collection, in our experience the sheer volume of data gathered often overwhelms individuals, watershed groups and agencies. As a result, the data is often not analyzed. We have also observed that when groups collect stream-temperature data, they often neglect to collect data on associated factors (such as air temperature, stream flow, canopy cover and reach length) that are required to fully interpret the stream-temperature data, in order to reach defensible conclusions for management, restoration and regulatory decisions.

The objective of our study was to demonstrate methods for the graphical display and analysis of the kind of stream-temperature data typically collected in monitoring efforts. We illustrate presentation formats and non-statistical approaches to facilitate the synthesis and interpretation of data for the purposes of monitoring compliance and evaluating the impacts of land-use activities. In the paper that follows (see page 161), we illustrate a statistical approach to analyzing complex sets of stream-temperature data and associated parameters. For both papers, we utilize the same data set, collected during the summers of 1999, 2000 and 2001 across the Lassen and Willow creek watersheds in northeastern Modoc County (in the northeastern-most corner of California).

Lassen and Willow creek watersheds

Located on the western slope of the Warner Mountains, the Lassen and Willow Creek watersheds lie parallel to each other, have a northwest aspect and flow directly into Goose Lake, which is at 4,700 feet (fig. 1). The upper reaches of both watersheds are in the Modoc National Forest and extend as high as 6,000 to 7,500 feet. Both streams flow out of predominantly publicly owned (U.S. Forest Service) mountains and into predominantly privately owned valleys and plains above Goose Lake. The public lands are managed for multiple uses including extensive livestock grazing and dispersed recreation. The private lands are used primarily for livestock grazing, as well as irrigated and dryland hay production. We selected these watersheds for study due to the willingness of landowners to cooperate, as well as in response to requests for stream-temperature information driven by local concerns for native fishes that use these streams for spawning and rearing habitat.

Although both streams reach peak runoff with snowmelt in the spring (May through June), they are primarily spring-fed during the summertime base flow (between rain-storm events, before and after snowmelt). Lassen Creek is about 14 miles long and Willow Creek is about 11 miles long. The streams are similar, but do have some clear differences. In Lassen Creek, perennial

The researchers collected data in watersheds feeding Goose Lake, *above*; the outlets of Lassen and Willow creeks are located on the peninsula in the center. *Right,* Shannon Cler, UC Davis postgraduate researcher, uses a velocity meter to estimate stream flow.

stream flow begins at about 6,000 feet and the stream stair-steps its way down through a series of small mountain meadows and steep canyons on its way to Goose Lake. In addition, Lassen Creek has one perennial tributary, Cold Creek (fig. 1). In Willow Creek, perennial stream flow begins at about 5,200 feet and the stream meanders through two relatively large open valleys connected by a canyon reach. As is typical of most mountain streams in Northern California, Lassen and Willow creeks provide cold-water habitat for trout, as well as other native fish and invertebrates. Four of these native fish species occur only in the Goose Lake basin: the Goose Lake redband trout *(Oncorynchus mykiss)*, Goose Lake sucker *(Catostomus occidentalis lacusauserinus)*, Goose Lake tui chub *(Gila bicolor thalassina)* and the Goose Lake lamprey *(Lampetra tridentata)*. These species spend much of their adult lives in Goose Lake, but depend on Lassen and Willow creeks for annual spawning and rearing habitat, as well as for emergency refuges during prolonged drought when Goose Lake goes dry. Our group initiated stream-temperature monitoring in conjunction with the Goose Lake Fishes Working Group (a multiagency stakeholder group) in the late 1990s, due to the proposed listing of all four species under the federal Endangered Species Act. Elevated stream temperature was proposed as one of the main factors impairing habitat in both streams.

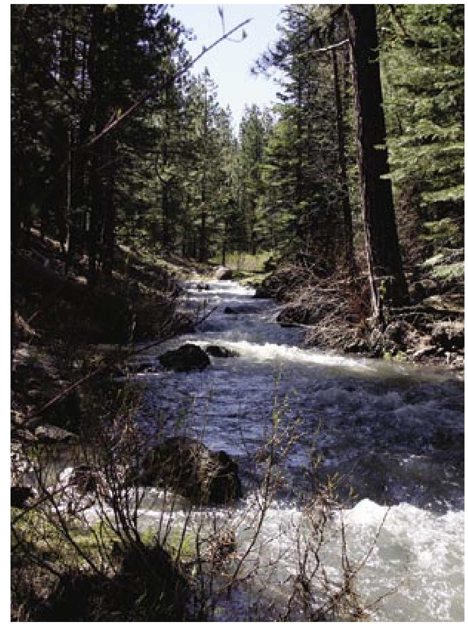
Monitoring protocols

Stream-temperature data was collected from June through September in 1999, 2000 and 2001 across Willow, Lassen and Cold creeks (fig. 1). We identified the monitoring locations in 1997 and 1998 by combining field surveys of each stream with preliminary stream-temperature data collection. Monitoring locations were selected to: (1) systematically track temperature changes from the upper to lower extent of each stream; (2) dissect each stream into discrete reaches based upon changes in stream morphology and gradient, vegetative community and canopy, aspect and land management; and (3) account for the confluence of tributaries and springs within each stream channel.

At each monitoring location, stream temperature was recorded every half hour using commercially available automatic recorders (Optic StowAway, Onset Computer Corporation). Data collection at the half-hour time-step allows for the capture of daily maximum and minimum temperatures, as well as the calculation of daily average temperature (48 readings per day), 7-day running average of daily maximum temperature, and other metrics of interest (see box, page 153). Here we only report the daily average stream temperature and the 7-day running average of daily average temperature. Recorders at all locations were set to take readings simultaneously on the hour and half hour (1:00, 1:30, 2:00, and so on). Temperature recorders were submerged at the bottom of the stream in areas of thorough mixing (riffles or runs) and held in place with a weight. Their depth ranged from 6 to 16 inches due to declining water levels as the season progressed, and variability in stream size and morphology (narrow and deep versus wide and shallow shape) among monitoring locations.

In order to interpret the stream-temperature data relative to environmental conditions and land-use management, we collected additional data on several associated factors. Air temperature was measured at both the lower and upper reaches of each stream (fig. 1; L1, L10, W1, W8) and recorded every half hour with automatic recorders (Optic StowAway, Onset Computer Corporation) suspended 6 feet above the ground surface, out of direct sunlight and in areas of adequate air mixing. Stream flow was measured in late May, late July and late September each year at every monitoring location. Instantaneous stream flow was measured by hand as cubic feet per

While the availability of inexpensive, automatic temperature recorders has facilitated data collection, in our experience the sheer volume of data gathered often overwhelms individuals, watershed groups and agencies.



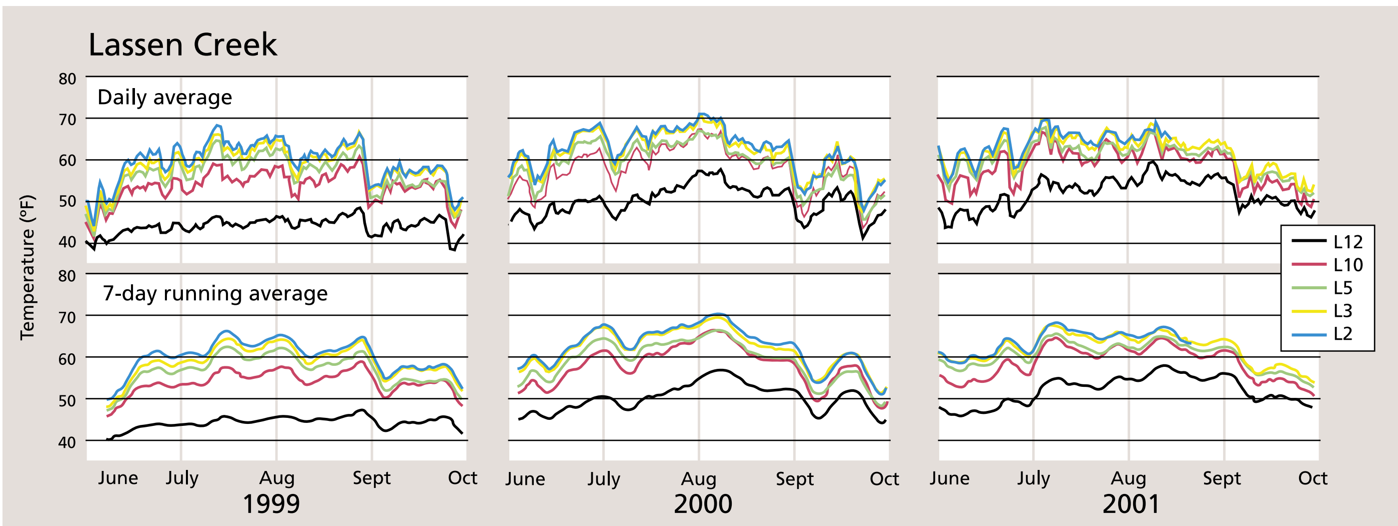


Fig. 2. Daily average and 7-day running average of daily average stream temperature observed at sampling locations, representing the longitudinal profile of Lassen Creek for 1999, 2000 and 2001.

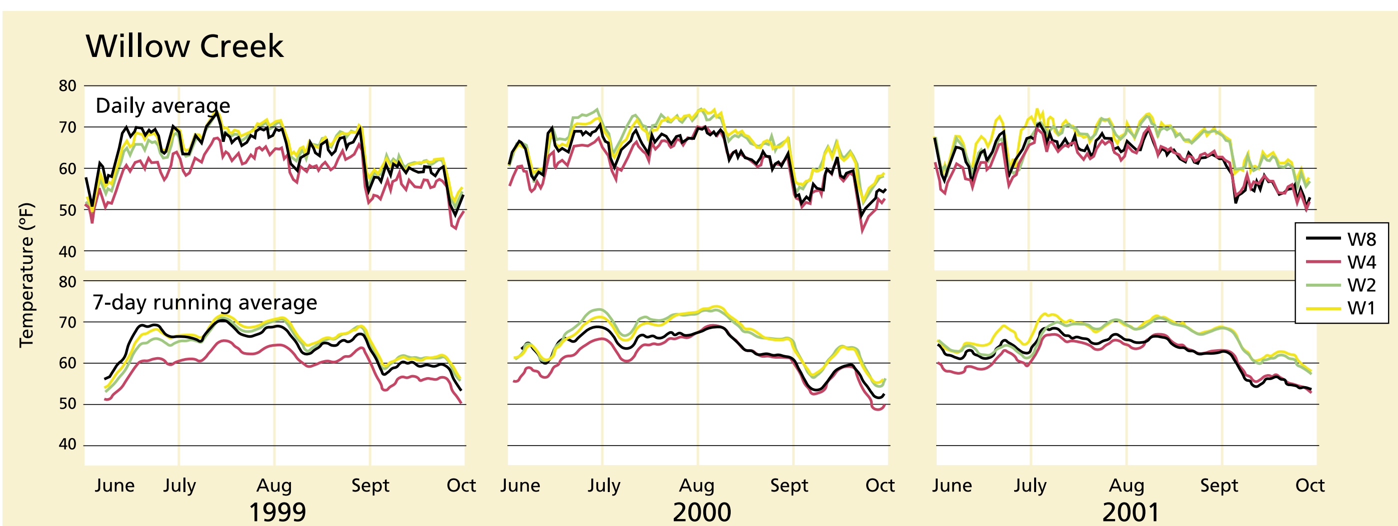


Fig. 3. Daily average and 7-day running average of daily average stream temperature observed at sampling locations, representing the longitudinal profile of Willow Creek for 1999, 2000 and 2001.

Stream flow is an important factor determining stream temperature, with daily maximum temperatures decreasing as flow increases. *Facing page, left*, flatter meadows, such as in the Lassen Creek watershed, slow down flow and allow warming; *facing page, right*, narrow canyon reaches provide natural shade and potentially force the emergence of cool subsurface stream flow. Snowpack in the Warner Mountains, *above*, feeds Lassen and Willow creeks in the northern range and the Pit River in the southern range (shown).

second (cfs) using the area velocity method (stream width in feet times average stream depth in feet times average stream velocity in feet per second). Stream velocity was measured with a hand-held velocity meter at the same times as water width and depth.

Canopy cover and solar input were measured in July 2000 at five sample locations equally spaced along the 1,000-foot stream reach immediately upstream of each monitoring location. Canopy cover — the percentage of sky blocked by vegetation — was measured with a densiometer. Solar input — the percentage of available solar input reaching the stream surface — was measured using a solar pathfinder. Canopy cover at each location was calculated from four densiometer readings taken in the middle of the stream at each location (facing upstream, left bank, downstream, right bank) following California Department of Fish and Game protocol (DFG 1998). Solar input was measured at the same locations as canopy cover with the solar pathfinder held just above the stream surface in the middle of the stream, following standard methods (Platts et al. 1987). The design of the solar pathfinder allows for calculation of monthly solar input from a single reading. Solar input readings are correlated to the vegetative canopy readings but are also affected by stream aspect and topographic features such as canyon walls or nearby mountains, which may block the sun during portions of the day or year.

Temperatures along streams

Monitoring groups are often interested in comparing stream temperature at specific locations along a stream, for example, on a specific reach (such as L12 versus L10) or along a longitudinal profile from upper to lower stream locations (such as L12 versus L11 versus L10)(fig. 1). This information can be used to identify and prioritize points of concern for fisheries (such as areas exceeding temperature standards), restoration opportunities (such as riparian planting to increase canopy cover) or land-use activities that should be mitigated (such as excessive warm irrigation-water returns).

One way to display and analyze data from monitoring locations along a stream system is to plot temperature at multiple locations over time on the same graph. Figures 2 and 3 synthesize a cumbersome raw data set of 158,112 data points (nine locations, times 3 years, times 122 days per year per location, times 48 readings per day), yet still reveal seasonal trends (such as peak temperatures in August and rapid reduction during the first week of September) that would be lost in monthly, seasonal or annual statistics (such as average and maximum). These figures provide a simple means of illustrating which stream was warmer or colder, and how stream temperature changed through the summer and across years, as well as an initial assessment of how stream temperature changed over time along a given stream reach or system.

For example, we found that Willow Creek was consistently warmer than Lassen Creek, which means that Lassen Creek provided more cold-water habitat than Willow Creek (figs. 2 and 3). Mean stream temperature from the top to bottom of Lassen Creek could increase from 10˚F to 20˚F on a given day (L12 versus L2), with the greatest increase in temperature occurring on a reach flowing through a naturally open meadow (between L12 and L10). Willow Creek, on the other hand, cooled as it flowed through a long, shaded canyon reach (between W8 and W4) and then increased in temperature as it continued downstream. The reduction in stream temperature between locations W8 and W4 on Willow Creek varied by year. Cooling through this reach was greatest in 1999, which had higher stream flows than 2000 and 2001, both years of regional drought and low flow.

For simplicity and clarity, the statistics that best reveal the area of concern should be plotted. The 7-day running average results in a smoother plot that facilitates comparisons among multiple locations. By contrast, if the concern is the acute effects of daily temperature variations, then plotting the daily average or maximum for only one or two sites is more clear and informative.

Comparisons between stream reaches

While graphics such as figures 2 and 3 allow for the efficient display and initial interpretation of the large, raw data sets typically collected by stream-temperature monitoring efforts, additional data reduction and graphical analysis are required to compare the change in stream temperature occurring between different reaches. With limited budgets for

On Cold Creek, willows budding in early spring will provide shade to reduce stream-temperature gains in the summer.

restoration efforts (such as riparian planting), reach-specific information on rates of temperature change can facilitate the optimal allocation of restoration resources to stream reaches within the watershed.

As in most monitoring efforts, the locations on Lassen and Willow creeks were selected to isolate reaches based upon changes in factors such as geomorphology, vegetation and flow, which are primary environmental variables that interact with land use to determine stream temperature. This approach is important to insure that the data collected relates spatially to important core watershed characteristics, land uses and the habitat available to resident fish. As a result, the distance between monitoring locations, and thus stream reach length, varies (fig. 1). Reach length confounds the direct interpretation of stream-temperature changes (figs. 2 and 3). One would expect greater overall change in temperature across longer reaches than across shorter ones. As such, the direct comparison of stream-temperature change through reaches of different lengths requires standardization for reach length.

An efficient and simple approach to account for reach length is to divide the change in temperature through each reach by the length. The resulting unit is "change in temperature per stream mile" (or unit length). To illustrate this approach, we examined the change in daily average stream temperature during the summer (June through September) across four reaches of Lassen and Willow creeks (figs. 4A and 4B [top]). We took the average of the differences in daily average temperature between two monitoring locations (such as L12 and L10) for the summers of 1999, 2000 and 2001, then divided this average by the distance between the two locations. Depending upon the specific interest of the monitoring group, similar calculations could be generated and graphed on a daily, weekly or monthly basis, using average, maximum or minimum temperatures.

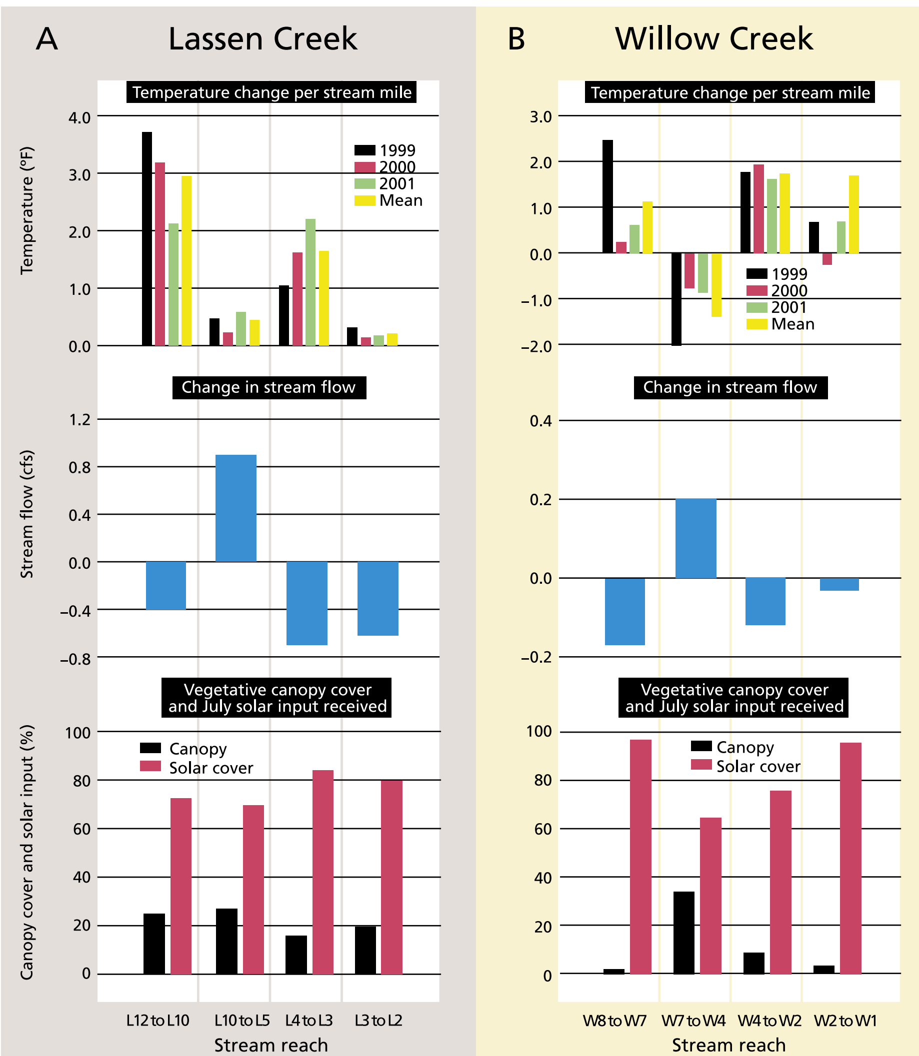


Fig. 4. For reaches of (A) Lassen Creek and (B) Willow Creek: (top) change in daily average stream temperature (˚F) from June through September per stream mile for 1999, 2000 and 2001, including the average (mean) for 1999, 2000 and 2001; (middle) average change in stream flow in cubic feet per second (cfs) measured during August 2001; and (bottom) percentage vegetative canopy cover and percentage of available solar input in July.

Figures 4A and 4B (top) provide directly interpretable information for managers, groups and other interested parties working on watersheds. For example, they clearly identify stream reaches within each watershed with the highest gains in temperature per stream mile. In Lassen Creek, the rate of warming was far greater in the reaches between L12 and L10 and between L4 to L3 than other reaches. In Willow Creek, the rate of temperature increase was consistently highest in the reach between W4 and W2. Although Willow Creek is warmer (figs. 2 and 3), the rate of heating across Lassen Creek was consistently greater. It is conceivable that the background, or natural, temperature of Willow Creek is greater than that of Lassen Creek, perhaps because perennial flow starts at a lower elevation in Willow Creek and flows through two large open meadows, while Lassen Creek flows through more-forested canyons.

Although both Lassen and Willow creeks gained heat through their lower reaches, which are associated with irrigation-water diversion and return, these lower reaches were not the sections of either creek with the highest temperature gains. This does not imply that irrigation management does not influence stream temperature, but rather that temperature gains in the middle and upper reaches must also be considered if reduced temperatures in the lower reaches are a habitat objective. These graphs do not establish cause and effect; rather, they facilitate understanding of watershed-scale temperature dynamics and serve as an effective assessment tool.

Temperature and associated factors

The collection of data on factors that may affect stream temperature is the first step in translating speculation into defensible conclusions. It is difficult to use graphical analysis for evaluating the simultaneous and interacting relationships that might exist between stream temperature and associated factors such as air temperature, stream flow and riparian canopy. However, graphical analysis can provide useful insights for improving local monitoring schemes and more thoroughly quantifying statistical relationships. To illustrate this point, we display data on the change in stream flow as well as riparian canopy and solar input (fig. 4).

Comparison of figures 4A and 4B (middle) indicates that temperatures rose in all Willow Creek reaches that lost stream flow (that is, less water emerged from the reach than entered it), while the temperature dropped in the reach that gained stream flow (W7 to W4). This reach is situated in a bedrock canyon below a meadow reach. It is likely that stream flow lost to the channel's subsurface zone (the gravels and sediments in and under the channel bed) in the reach immediately upstream (W8 to W7) was forced up by bedrock to re-emerge as surface flow in the reach from W7 to W4. In addition, this area of the watershed has multiple diffuse seeps and springs along the stream channel. Regardless of the source of the increased subsurface flow, it is likely that it would be cooler (about 50˚F to 55˚F) than surface water in the stream (Stringham et al. 1998). Similarly, on Lassen Creek the reach from L10 to L5 gained stream flow and had relatively low rates of temperature gain.

Following a graphical approach that only considers a single associated variable (univariate), one might conclude that flow is the main factor influencing the direction and rate of temperature change, because stream reaches that lost

Stream cover is provided by trees and shrubs such as, *top*, conifers and aspens, and, *above*, willows.

flow also gained temperature, and those that gained flow also lost temperature or had relatively low rates of heating. However, by the same logic, one could examine the bottom row of figures 4A and 4B relative to the top row and conclude that riparian canopy was the primary factor explaining the temperature variation. Figure 4 (bottom) illustrates that in the cooling reach of Willow Creek (W7 to W4), both stream flow and canopy cover increased. The increase in canopy cover resulted in an associated reduction in solar input to this reach relative to others on the stream, and less solar input would logically lead to lower rates of temperature increase. Although less pronounced, the situation was similar on Lassen Creek for the reach from L10 to L5.

This graphical comparison indicates that there are probably strong relationships between the factors considered. However, it is inappropriate and likely misleading to use a univariate, graphical analysis approach to (1) fully explore and quantify these relationships, (2) determine if stream flow and canopy interact to influence stream temperature, or (3) determine if the influence of canopy or stream flow is different between streams. Answering these complex monitoring questions requires a multivariate statistical analysis of a data set containing stream temperature and associated factors (see page 161). Fortunately, relatively simply collected data sets can be subjected to appropriate graphical and statistical analyses.

In order for stream-temperature data to be useful, related data such as stream canopy, air temperature and stream flow should be collected. In mid–Lassen Creek, shade is naturally low, and willows serve as the primary source of vegetative cover.

Data helps prioritize resources

We have demonstrated a graphical display and analysis approach by which data collected in typical stream-temperature monitoring projects can be interpreted by and presented to land managers, watershed groups and other interested parties. This approach is simple and nonstatistical, facilitating timely local analysis to achieve monitoring objectives such as evaluating stream temperature across a watershed for comparison to temperature criteria, and identifying watershed areas with high or low rates of stream-temperature gain. This level of analysis can translate large raw data sets into information that local managers and water-resources agencies can use to identify and prioritize the allocation of limited restoration and management resources.

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RESEARCH ARTICLE

Statistical analysis of monitoring data aids in prediction of stream temperature

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A 3-year monitoring data set was collected from watersheds in Modoc County in order to demonstrate approaches for displaying and analyzing stream-temperature and related data in meaningful ways. ***Left***, a densiometer is used to estimate the percentage of vegetative canopy cover over a stream. ***Above***, willows (foreground) and aspen (background) budding in early spring will provide shade cover to reduce temperatures during the summer.

Declines in cold-water habitat and fisheries have generated stream-temperature monitoring efforts across Northern California and the western United States. We demonstrate a statistical analysis approach to facilitate the interpretation and application of these data sets to achieve monitoring objectives. Specifically, we used data collected from the Willow and Lassen creek watersheds in Modoc County to demonstrate a method for identifying and quantifying potential relationships between stream temperature and factors such as stream flow, canopy cover and air temperature. Our monitoring data clearly indicated that a combination of management practices to increase both in-stream flow and canopy cover can be expected to reduce stream temperature on the watersheds studied.

IN our previous paper on graphical analysis (see page 153), we utilized a 3-year stream-temperature data set — collected from the Lassen and Willow creek watersheds in northeastern Modoc County (in the northeastern-most corner of California) — to demonstrate graphical analysis approaches to reduce, display and interpret a typical large, raw stream-temperature data set. In this paper, we report the results of statistical analysis conducted on this same data set, to identify and quantify relationships between stream temperature, air temperature, stream flow, stream order and riparian canopy cover.

Stream-monitoring efforts typically produce data sets composed of temperature readings (such as hourly, daily) from a set of discrete locations across a stream system. These cross-sectional, longitudinal surveys — in which a cross-section of available locations is monitored over time (longitudinal) — are common across Northern California and the West. To optimize the analysis and interpretation of such stream-temperature data sets, we believe it is critical to collect data on associated factors such as air temperature, stream flow and stream canopy for each location. To identify and quantify relationships between stream temperature (the dependent variable) and associated factors (the primary independent variables), we propose a regression-based analysis approach.

Regression analysis can be applied to data to determine, for predictive purposes, the degree of correlation of a dependent variable with one or more independent variables. The objective is to see if there is a strong or weak relationship.

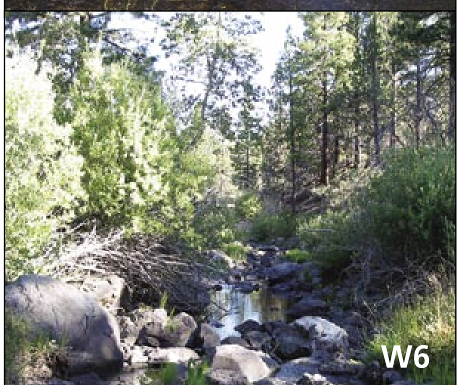
In this case, we developed a linear equation (model) that displayed the estimated effect of several independent variables on the dependent variable, stream temperature. The simple form of the equation is:

$$y = a + (b_1X_1) + (b_2X_2) + \ldots + (b_iX_i)$$

where y is the dependent variable, a is the intercept of the equation, b_1 is a coefficient that estimates the relationship between the independent variable X_1 and the dependent variable y, given that the other factors ($X_{2, 3 \ldots, i}$) are also present in the model. The model coefficients (b_i) represent the best-estimate identification and quantification of the relationships between stream temperature (y) and the factors of interest (X_i).

This approach is not a definitive test of cause and effect, as would be expected in a controlled experiment. However, experimental tests of how associated factors affect stream temperature, particularly at the watershed scale, are generally impractical due to the lack both of "replicate" streams and of experimental

It is important to examine and plan for data analysis options during the initial development of the monitoring plan, not only after the data has been collected.



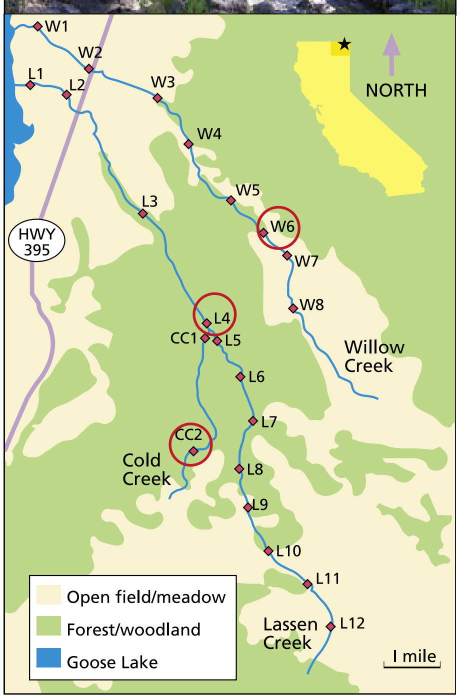


Fig. 1. Stream-temperature monitoring locations on Lassen, Willow and Cold creeks in northeastern Modoc County, Calif.

The authors calculated the significance and 95% confidence intervals of the coefficients for each independent variable associated with daily maximum stream temperature, including stream flow and canopy cover on Lassen Creek, *above*.

control over the independent variables. Caution must be taken in the development and interpretation of regression models examining relationships between stream temperature (y) and associated factors (X_i). As with any analysis, the results are only as good as the data used. The appropriateness of the monitoring locations selected (e.g., are the locations representative of the stream system, watershed or region?) and data collection methods must be considered.

It is important to confine conclusions drawn from regression analysis only to the factors that were examined for inclusion in the final model (e.g., conclusions about the importance of stream flow relative to air temperature can be drawn only if both factors were examined simultaneously). A good rule is to examine if the relationships make sense in light of existing knowledge and basic principles. If the relationship is not readily explainable, then additional research or monitoring is warranted to refute or confirm it.

Regardless of the analysis approach used, the potential effect introduced by repeatedly measuring stream temperature at each monitoring location must be considered. A basic assumption of many statistical analysis techniques is that each observation in the data set is independent of all other observations in the data set. However, it is unlikely that the daily maximum stream temperature at monitoring location W1 (fig. 1) on June 15 is independent of the daily maximum stream temperature at this location on July 1. This problem is typical of most longitudinal data sets (repeated measurement at a fixed site through time). The codependence introduced by repeated measurements of a single location through time can be addressed using a linear mixed-effects regression analysis (Pinheiro and Bates 2000), which we employ in this paper, or other approaches such as a repeated-measures analysis of variance.

Statistical analysis of data

The dependent variable that we analyzed was daily maximum stream temperature (°F) collected at numerous fixed dates across the summer, at fixed sites across the Lassen and Willow creek watersheds (fig. 1). We selected daily maximum as an example because it is a simple and biologically important measure of cold-water habitat; however, the same analysis could be conducted on other metrics of interest, such as 7-day running average of daily maximum stream temperature or change in maximum stream temperature per stream mile (see page 153). The maximum stream temperature for each 24-hour time period from June 15 through Sept. 15, in 1999, 2000 and 2001 was extracted from the half-hour time series of data at each of 22 monitoring locations (see fig. 1). To further reduce the data set, we used the daily maximum stream temperature at each site for June 15, July 1, July 15, Aug. 1, Aug. 15, Sept. 1 and Sept. 15 from each year as the dependent variable ($n = 462$ observations).

To estimate flow volume, Bobbette Jones, UC Davis graduate research assistant, measures the stream's: *left*, width; *center*, depth; and *right*, velocity. In this study, every cubic-foot-per-second increase in stream flow was associated with a 1.64˚F decrease in daily maximum stream temperature.

Graphical analysis of this data set (in our previous figs. 2 and 3, page 156) clearly illustrated that stream temperature increases to a peak in July and August and decreases in September. For this statistical analysis, we selected bimonthly data from the larger continuous daily maximum stream temperature data set in order to capture the evident seasonal pattern in temperature while limiting data redundancy. Depending upon the monitoring and analysis objectives, alternative approaches could be the use of weekly or monthly calculations (e.g., average or maximum) across the summer or the use of all daily maximum stream temperature records.

The linear mixed-effects analysis (Pinheiro and Bates 2000) conducted on bimonthly daily maximum stream temperature from locations on Lassen, Willow and Cold creeks contained the following fixed-effect independent variables: date (June 15, July 1, and so on), daily maximum air temperature (˚F), stream flow (cubic feet per second [cfs]) and stream canopy cover (percentage of sky blocked by vegetation) of the 1,000-foot reach upstream of the site (DFG 1998). Daily maximum air temperature for each date from the nearest air-temperature monitoring location was matched to each stream-temperature observation. Additional terms introduced in the initial model included all possible interactions among independent variables as well as the quadratic form of all continuous variables (air temperature, stream flow and canopy cover). An interaction occurs when the effect of one independent variable on y depends upon another independent variable. Including the quadratic form (X_i^2) of each continuous independent variable allows for the potential that the relationship between x and y is not a straight line.

To account for each location's position in the watershed, stream order for each monitoring location was introduced as an independent variable. A headwater channel is a first-order stream, the merger of two first-order channels forms a second-order stream, and the merger of two second-order channels forms a third-order stream. Monitoring location identity and year (1999, 2000 and 2001) were treated as random effects to account for repeated measures and for random variations in annual weather, respectively. A backward stepwise approach was followed until only significant ($P \leq 0.05$), factors remained in the model. Insignificant main effects were left in the model if interaction terms containing the main effect were significant. For example, if the interaction term for stream flow and air temperature was significant ($P \leq 0.05$), then both stream flow and air temperature were retained in the model regardless of their significance. The evaluation of residual error plots indicated that assumptions of normality, independence and constancy were met.

Model predicts stream temperature

The evaluation and interpretation of statistical models require the display of several important outputs, including: (1) the final statistical model with coefficients, coefficient confidence intervals and significance levels for all variables; (2) the display of the "fit" of the model, or how the model predictions compare with the observed data; and (3) the graphical display of relationships between the independent and dependent variables reported in the final statistical model. The evaluation and interpretation of the statistical model and the relationships that it implies should always be coupled with local knowledge of the system modeled and the application of basic scientific principles. Basically, do the results make sense in terms of accepted principles of hydrology, ecology, and so on? If not, is there a logical explanation that could be tested?

We calculated the significance *(P)* and 95% confidence intervals of the coefficient estimated for each independent variable associated with daily maximum stream temperature (table 1). The coefficient value indicates the estimated effect (positive or negative) and magnitude of the relationship between each variable and daily maximum stream temperature. For continuous variables (canopy cover, daily maximum air temperature and stream flow), the coefficient indicates the change in daily maximum stream temperature expected with each incremental change in the variable, given that all other factors are held constant. For example, in our case study a 1 cfs increase in stream flow was associated with 1.64˚F reduction in stream temperature.

TABLE 1. Linear mixed-effects analysis predicting daily maximum stream temperature (˚F) on Willow, Lassen and Cold creeks, June–Sept., 1999–2001*

Fixed variable	Coefficient†	*P* value‡	95% low CI§	95% up CI§
Intercept	–41.68	< 0.001	–63.79	–19.50
Creek¶				
Willow	0.00	—	—	—
Lassen	–4.43	0.003	–6.99	–1.86
Cold	–10.16	0.000	–14.46	–5.86
Date#				
June 15	0.00	—	—	—
July 1	3.17	< 0.001	2.02	4.31
July 15	3.15	< 0.001	1.99	4.29
Aug. 1	3.30	< 0.001	2.05	4.54
Aug. 15	1.55	0.014	0.31	2.77
Sept. 1	–0.92	0.179	–2.25	0.42
Sept. 15	–2.92	< 0.001	–4.07	–1.76
Stream order**				
First	0.00	—	—	—
Second	13.32	< 0.001	8.51	18.12
Third	14.05	< 0.001	9.07	19.02
Canopy cover (%)	0.19	0.100	–0.04	0.42
Daily max. air temp. (˚F)	2.29	< 0.001	1.75	2.82
Daily max. air temp. (˚F)^2	–0.012	< 0.001	–0.009	–0.016
Stream flow (cfs)	–1.64	< 0.001	–2.50	–0.78
Daily max. air temp. (˚F) × stream canopy cover (%)	–0.004	0.004	–0.006	–0.001

* Random effects in the analysis were year (1999, 2000 and 2001) to account for random annual weather patterns and monitoring location ID to account for repeated measures.

† Coefficient for each significant fixed variable in the linear model. Coefficient value indicates the effect (+ or –) and the magnitude of the relationship between each variable and daily maximum stream temperature. For continuous variables (canopy cover, max. air temp. and stream flow), the coefficient indicates the change in daily maximum stream temperature associated with each incremental change in the variable.

‡ *P* value associated with each fixed variable.

§ Upper and lower 95% confidence interval for the coefficient of each fixed variable.

¶ Referent condition for the categorical variable "stream." The coefficient for the referent condition (Willow Creek) is set to 0.0; coefficients for Lassen Creek and Cold Creek represent the estimated difference in daily maximum stream temperature between these streams and Willow Creek (e.g., Lassen Creek is estimated to be 4.43˚F colder than Willow Creek given that all other variables are held constant).

Referent condition for the categorical variable "date." The coefficient for the referent condition (June 15) is set to 0.0; coefficients for other levels (July 1, July 15, etc.) represent the estimated difference in daily maximum stream temperature between each subsequent date and June 15 (e.g., July 1 is estimated to be 3.17˚F warmer than June 15 given that all other variables are held constant).

** Referent condition for the categorical variable "stream order." The coefficient for the referent condition (first order) is set to 0.0; coefficients for other levels (first and second order) represent the estimated difference in daily maximum stream temperature between each stream order and a first-order stream (e.g., second-order stream is estimated to be 13.32˚F warmer than a first-order stream given that all other variables are held constant).

Equation 1

$$\begin{aligned}
\text{Daily maximum stream temperature (˚F)} &= -41.68 \\
&+ [0.00 \text{ if Willow Creek}, -4.43 \text{ if Lassen Creek}, -10.16 \text{ if Cold Creek}] \\
&+ [0.00 \text{ if June 15}, 3.17 \text{ if July 1}, \dots, -2.92 \text{ if Sept. 15}] \\
&+ [0.00 \text{ if first-order stream}, 13.32 \text{ if second-order stream}, 14.05 \text{ if third-order stream}] \\
&+ 0.19 \times \text{canopy cover (\%)} \\
&+ 2.29 \times \text{daily max. air temp. (˚F)} \\
&- 0.012 \times [\text{daily max. air temp. (˚F)}]^2 \\
&- 1.64 \times \text{stream flow (cfs)} \\
&- 0.004 \times \left[\begin{array}{c}\text{daily max. air temp. (˚F)} \\ \times \text{ canopy cover (\%)}\end{array}\right]
\end{aligned}$$

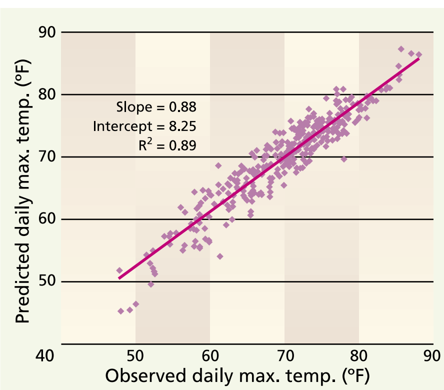


Fig. 2. Observed versus predicted daily maximum stream temperatures, as calculated by linear mixed-effects model containing independent variables of stream flow, canopy cover, daily maximum stream temperature and stream order. The model was developed with data collected in 1999, 2000 and 2001 at 22 stream locations on Lassen, Willow and Cold creeks in northeastern Modoc County.

For categorical variables (stream, date and stream order), the coefficient represents the estimated difference between the referent level and other variable levels, given that all other variables are held constant. The referent level for a categorical variable is the level to which other levels for that variable are compared. The coefficient for the referent level (stream = Willow Creek, date = June 15, stream order = first) was set to zero. The coefficients for other levels represent the estimated difference in daily maximum stream temperature between each level and the referent level. For example, the referent level for "stream" was Willow Creek, and Lassen and Cold creeks were estimated to be 4.43˚F and 10.16˚F colder than Willow Creek, respectively (table 1).

The coefficients reported in table 1 may be more easily conceptualized as equation 1 (see box). The fit of the statistical model reported in table 1 can be evaluated graphically in figure 2. We used simple linear regression of the form *"predicted* = a + b × *observed"* to evaluate the fit of the model. If the model perfectly predicted observed stream temperature, the slope (*b*) of the regression would equal 1.0 with an R^2 of 1.0. Figure 2 indicates that the model in table 1 is not perfect, but with a slope of 0.88 and an R^2 of 0.89, it certainly is a reasonable fit.

Interpreting, presenting model

A simple graphical display of this statistical model can facilitate the interpretation and presentation of the results to audiences with limited statistical backgrounds, which can in turn help to achieve monitoring or restoration objectives. Figures 3 and 4 illustrate the use of the statistical model reported in table 1 and equation 1 to "predict" or display the relationships identified between daily maximum stream temperature and significant environmental and management factors. These figures also illustrate the potential to use equation 1 to examine "what if" scenarios, such as the benefit of increasing canopy cover versus stream flow on second-order streams. Such speculation should be limited to the range of the data used to develop the model.

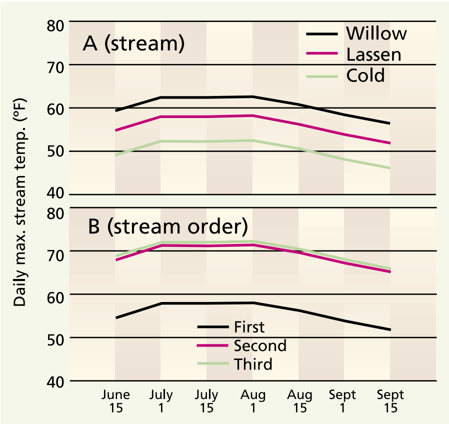


Fig. 3. Relationship of daily maximum stream temperature and (A) stream (Willow, Lassen, Cold) and (B) stream order (first, second, third) across the summer season, developed from linear mixed-effects analysis of data from 1999, 2000 and 2001. Other significant factors are set to fixed values: stream order = first (A), stream = Lassen (B); canopy cover = 25%, daily maximum air temperature = 85˚F, and stream flow = 2 cfs.

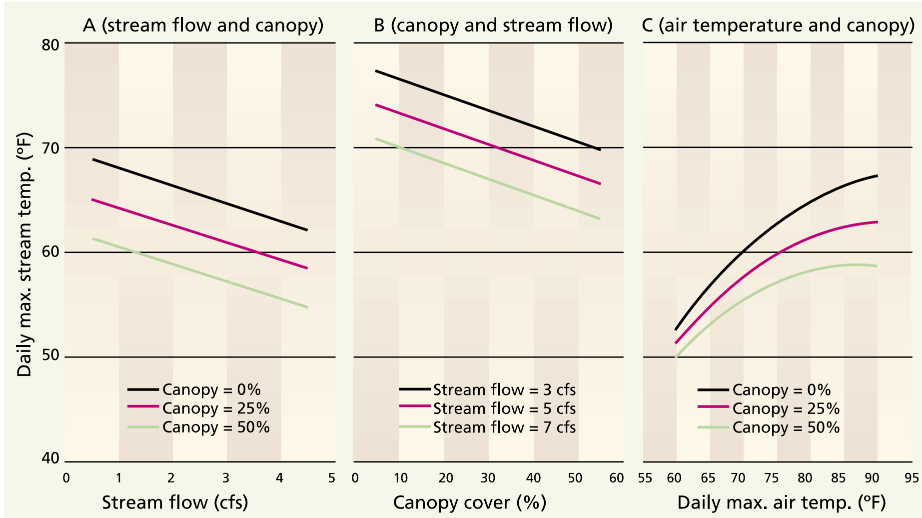


Fig. 4. Relationship of daily maximum stream temperature and (A) stream flow (cfs), (B) stream canopy cover (%) and (C) daily maximum air temperature (˚F), across the summer season, developed from mixed-effects analysis of data from 1999, 2000 and 2001. Other significant factors are set to fixed values: stream = Willow; date = Aug. 1; stream order = first (A and C) and second (B); daily maximum air temperature = 85˚F (A and B); and stream flow = 2 cfs (C).

Stream. Figure 3A displays the relationship between stream (Lassen, Willow and Cold creeks) and daily maximum stream temperature over the summer season. This relationship was identified and quantified, given that all other significant variables (table 1) were constant and accounted for. In order to generate figure 3A, we set stream order at first, canopy cover at 25%, daily maximum air temperature at 85˚F and stream flow at 1 cfs. We then used equation 1 (the statistical model) to estimate daily maximum stream temperature for each stream at each date (fig. 4). Figure 3A is in agreement with raw data presented in our previous article (see figs. 2 and 3, page 156), which illustrated that Willow Creek was on average 4.43˚F warmer than Lassen Creek for daily maximum stream temperature. It is also clear that Cold Creek is aptly named, being on average 10.16˚F cooler than Willow Creek for daily maximum stream temperature. The seasonal pattern from June through September was also captured with this statistical model.

Stream order. Figure 3B displays the relationship between stream order and daily maximum stream temperature over the course of the summer. It is no surprise that first-order (headwater) stream locations are significantly cooler than second- and third-order locations in the middle to lower reaches of these

Spring bud break and the onset of leaf set and shade are delayed in the higher elevation reaches of Lassen Creek, while the peak snow melt generates significant stream-flow volumes.

Don Lancaster, UCCE Modoc County natural resources advisor, monitors the stream temperature of lower Willow Creek in the late summer, when its flow volume is lowest.

Lassen Creek provides critical spawning habitat for several native fish species; temperatures over 77˚F can be lethal to salmonids, while sublethal temperatures (67˚F to 76˚F) can affect growth and spawning.

watersheds. In general, stream temperature will progressively increase from the upper to lower reaches of a stream system, as was the case for all but one reach of Willow Creek (see figs. 2 and 3, page 156). Daily maximum stream temperature was not different between second- and third-order stream locations, given that all other factors were equal. It is clear that the primary sources of cold-water habitat within these streams, as with most, are in headwater locations.

Stream flow. Figure 4A displays the relationship identified between stream flow (cfs) and daily maximum stream temperature for the Lassen and Willow creek watersheds, which have summer stream flows ranging from 1 to 5 cfs. For every cubic foot per second (cfs) increase in stream flow at a site, there was an estimated 1.64˚F decrease in daily maximum stream temperature (table 1). This is an important result, given that one of the suspected sources of elevated stream temperatures is the diversion of stream flow for irrigation.

This result provides local irrigation managers and water-resources professionals with tangible evidence that investments in reducing stream-flow withdrawal demands (e.g., improving the efficiency of irrigation delivery, and matching irrigation amounts and timing to plant water demand and current soil moisture status) will result in reduced daily maximum stream temperatures, as well as reasonable expectations of the likely magnitude of these reductions. The lack of significance of the interaction term for stream flow and stream order ($P > 0.05$) in this model indicates that the relationship between stream flow and daily maximum stream temperature was constant from the upper to lower reaches of these streams.

This is interesting, given that the sources of increased stream flow in the upper reaches are likely natural phenomena (e.g., the return of subsurface stream flow to the surface, or diffuse springs), while increased stream flow in the lower reaches is likely due partly to warm irrigation-water returns. One might expect increased stream flow in the lower reaches to be associated with increased stream temperatures. However, if a significant portion of irrigation return flow is reaching the stream as cool subsurface flow, then the relationship identified in this analysis is plausible (Stringham et al. 1998). These statistical results agree with our graphical analysis, reporting relatively low rates of change in stream temperature across the lower reaches of Willow and Lassen creeks (see fig. 4, page 158).

Canopy cover and air temperature. There was a significant interaction between stream canopy cover and daily maximum air temperature (table 1), which requires the relationships between stream canopy cover, air temperature and stream temperature to be discussed together for proper context. For every 1% increase in canopy cover in the 1,000-foot reach above a site, there was an estimated 0.15˚F reduction in daily maximum stream temperature at that site (fig. 4B). This relationship is logical, given that a reduction in the amount of solar energy reaching a stream's surface should result in a reduction in its temperature.

For every 1˚F increase in daily maximum air temperature, there was an expected 0.1˚F to 0.8˚F increase in daily maximum stream temperature (fig. 4C). This range exists because the relationship is not a straight line as indicated by the significance of the quadratic term ([max. air temp.]^2) in the final model (table 1). This quadratic relationship is revealed in the curve of the lines plotted in figure 4C. Basically, the rate of stream-temperature increase associated with rising air temperature is reduced as air temperature increases from 60˚F to 90˚F (fig. 4C). This is an important relationship in determining the background, or natural, temperature regime for streams in arid, hot regions of the western United States.

The significant interaction between air temperature and canopy cover illustrates the complex relationships between environmental and management variables that determine stream temperature (table 1). As daily maximum air temperature increased, the cooling effect of canopy cover increased (fig. 4C), with the implication that increased canopy cover is more effective at reducing daily maximum stream temperature as air temperature increases. This provides evidence that increasing riparian vegetation and thus stream canopy cover can be expected to reduce daily maximum stream temperature. Most importantly, these results provide local managers with information about the expected reductions that could occur by using vegetation management as a restoration tool, allowing realistic expectations regarding the potential to create cold-water habitat simply by increasing canopy cover alone. For instance, a combination of increased canopy cover and stream flow may generate greater stream-temperature reductions than either practice by itself. It is also important to realize that there are natural limits on the amount of canopy cover and stream flow that each stream reach can generate (e.g., in meadows compared to canyon reaches).

Support for local decision-making

While the relative temperatures of Willow, Lassen and Cold creeks may be of little concern outside of northeastern Modoc County, being able to clearly and defensibly identify warm or cold streams is important for determining possible regulatory actions, allocating limited restoration funds and making other controversial decisions locally across Northern California and the western United States. Stream-temperature monitoring can provide a significant amount of information for making decisions about management changes and restoration projects in order to increase or improve cold-water habitat in streams. On a watershed or regional scale, information about the relationships between stream temperature and factors such as stream canopy cover, stream flow and watershed position are important for identifying and quantifying the expected benefits of practices to reduce stream temperature. For instance, monitoring data presented in this paper clearly indicates that a combination of management practices to increase both in-stream flow and canopy cover can be expected to reduce stream temperature on the watersheds studied.

Practices such as the modification of irrigation and riparian grazing management come with real costs to managers, and decisions to implement these practices should be based on reasonable expectations of the return on that investment in terms of improving cold-water habitat. The monitoring data presented here also places constraints on the expected extent of cold-water habitat given seasonal patterns, air temperature and the position of the stream in the watershed, regardless of increases in canopy cover and stream flow. Collectively, these results provide local information required for watershed groups to reach a balance between restoration desires, management possibilities and inherent environmental constraints.

On this meadow reach of mid–Lassen Creek, shade from willows is naturally low. The data collected indicates that management practices to increase stream flow and canopy cover can bring down stream temperatures in areas where logging, stream diversions and other uses have caused them to increase.

For monitoring data to be interpreted and integrated into restoration plans, regulatory processes and land-use management decisions, data must be appropriately collected and analyzed. In our previous paper, we illustrated the value of simple graphical analysis to address certain typical stream-temperature monitoring objectives. In this paper, we illustrated the potential of using relatively simple statistical analysis to achieve additional monitoring objectives and information needs. It is important to examine and plan for data analysis options during the initial development of the monitoring plan *prior* to data collection, not only *after* the data has been collected. While most individuals and groups planning and conducting monitoring may not have the statistical expertise to conduct the analysis described here, such support is available within many state and federal agencies and organizations (both regulatory and nonregulatory) to assist with monitoring plan development, implementation and analysis. Many such agencies are active members of local and regional restoration, conservation and watershed groups, including UC Cooperative Extension, the U.S. Department of Agriculture Natural Resources Conservation Service, the California State Water Resources Control Board, the California Regional Water Quality Control Boards and the California Department of Fish and Game.

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RESEARCH ARTICLE

Monitoring helps reduce water-quality impacts in flood-irrigated pasture

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Northern California has extensive areas of irrigated pasture, which provide critical summer forage for livestock. In many of these systems, water is diverted directly from a stream into ditches or pipes and transported to individual pastures, where it is applied as flood surface irrigation. Our case study of discharges from irrigated pastures on Willow and Lassen creeks in Modoc County illustrates an assessment and monitoring approach for land managers and natural-resources professionals working to resolve water-quality impairments related to agricultural discharges from similar systems. We report correlations between four indicator variables measured in the field and the variables determined in the laboratory, to evaluate the potential for employing a strategic combination of the two.

Irrigated pasture provides critical summer forage for California livestock, but the environmental impacts on fish of diverting streams to pastures are coming under increasing regulatory scrutiny. *Above,* Shannon Cler, UC Davis postgraduate researcher, measures dissolved oxygen in a delivery ditch in lower Lassen Creek.

Northern California has extensive areas of irrigated pasture, which provide critical summer forage for livestock. The irrigation season on these pastures can last from April through September, depending upon factors such as elevation, annual precipitation and site-specific water rights. In many of these irrigated-pasture systems, water is diverted directly from a stream into ditches or pipes and transported to individual pastures, where it is applied as flood surface irrigation. Irrigation frequency varies from continuous to regularly scheduled applications.

It is common for a significant amount of runoff to be generated from pastures during flood irrigation. In previous research, 40% to 70% of irrigation water applied to pastures in the Sierra Nevada foothills became runoff (Bedard-Haughn et al. 2004; Tate et al. 2001). Irrigation runoff can transport non-point-source pollutants such as nutrients, sediment and pathogens into downstream waters as well as increase stream temperatures.

In the past, such agricultural discharges within the boundaries of the Central Valley Regional Water Quality Control Board (CVRWQCB) were allowed under a conditional waiver granted by the CVRWQCB (2005). The CVRWQCB includes the Sacramento and San Joaquin river systems and tributaries, as well as terminal basins such as the Tulare Basin in the southern Central Valley and Goose Lake in extreme northeastern California. Recent review of this waiver by CVRWQCB — following a petition by concerned stakeholder groups to rescind the waiver — has resulted in a new compliance process for coalitions of agricultural operators, as well as individual operators who discharge irrigation runoff into water bodies within the boundaries of CVRWQCB.

This compliance process has increased the need for efficient methods by which irrigators can (1) assess the quality of irrigation water discharged from their fields, (2) improve the quality of discharges that degrade downstream waters, and (3) monitor to ensure that downstream water-quality degradation is eliminated. Agricultural operators are concerned about the potential costs and management constraints associated with this compliance process. We present the results of an irrigated-pasture case study to illustrate an assessment and monitoring approach for land managers and natural-resources professionals working to resolve water-quality impairments related to agricultural discharges from similar systems.

Modoc County study site

This study was conducted on the lower reaches of Lassen and Willow creeks in northeastern Modoc County (in the northeastern-most corner of California). Stream flow in both streams is generated by snowmelt in the higher

A self-cleaning fish screen at a stream-flow diversion on lower Lassen Creek prevents fish from entering irrigation delivery ditches and becoming stranded.

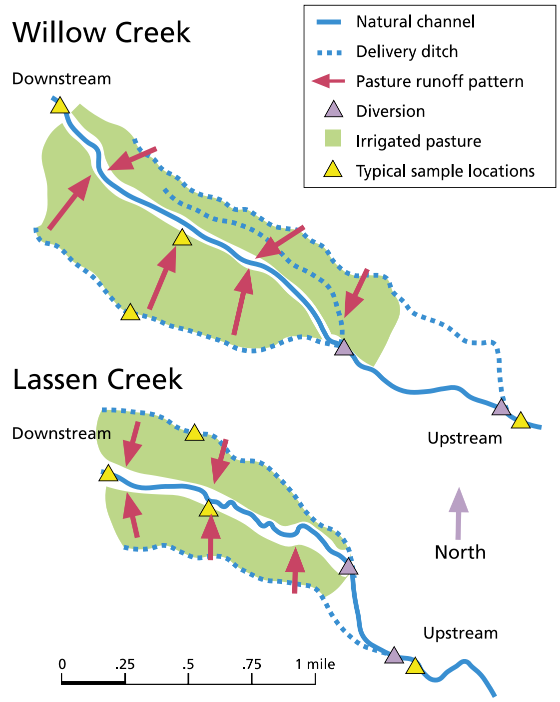

Fig. 1. Irrigated-pasture systems of Lassen and Willow creeks, Modoc County, Calif.

elevations of each watershed, with flows peaking in early spring (April until mid-May) and diminishing significantly by the end of July. Stream flow from both creeks is diverted into open irrigation delivery ditches starting in May and ending in June or July, depending upon annual snowpack and stream-flow levels.

During the 2003 irrigation season, when we conducted our study, flow was diverted through July from Lassen Creek and through June from Willow Creek. Diverted water is applied as flood irrigation continuously to pastures grazed by beef cattle, and during June and the first week of July to hay meadows. A substantial volume of this irrigation water returns to the creek it originally came from both as surface runoff in ditches and shallow swales, and as subsurface flow. There are four pastures in the Lassen and Willow creek systems ranging from 34 to 95 acres, with irrigation application rates (cubic feet per second [cfs] per acre) varying between and within pastures from 0.01 to 0.13 cfs per acre. Total applied water (acre-feet per irrigation event or season) is quite variable, with some pastures receiving 2 to 3 daylong irrigation events and others irrigated continuously.

Monitoring scheme

In late May 2003, 30 permanent sampling locations were established across the Lassen (n = 15) and Willow (n = 15) creek irrigation systems. Sample locations were selected to provide water-quality and flow-volume data from (1) each creek above the irrigation diversion, (2) along all irrigation-water delivery ditches, (3) all pasture surface-runoff ditches and swales immediately above the return of pasture runoff to the natural stream channel, and (4) each creek below all pasture runoff (fig. 1). We did not attempt to sample or measure subsurface return flow, and each site was monitored in June and July.

Flow volume (cfs), electrical conductivity (deciSiemens per meter [dS/m]), turbidity (nephelometric turbidity units [ntu]) and dissolved oxygen (milligrams per liter [mg/L]) were measured weekly at each sampling location using standard field-sampling equipment. In addition, approximately half of all the water samples were analyzed for total suspended solids (TSS), nitrate (NO_3), ammonium (NH_4), phosphate (PO_4), sulfate (SO_4), potassium (K) and dissolved organic carbon (DOC) using standard laboratory techniques. Water temperature was monitored every half hour at each sampling location in June and July using commercially available automatic recorders.

This sampling strategy allowed us to: (1) examine above and below in-stream water-quality changes due to irrigation; (2) examine changes in water quality as irrigation water passed through delivery ditches and across pastures; (3) account for differences in flow volume for each water source (in-stream/above, delivery ditch, pasture runoff and in-stream/below); and (4) account for changes in water quality and flow over the course of the 2-month irrigation season. Due to the availability of relatively inexpensive and accurate field meters, four water-quality variables (electrical conductivity, turbidity, water tempera-

Delivery ditches transport water from stream diversions and deliver it to irrigated pastures. The authors collected water-quality data from streams above and below such pastures, as well as from pasture runoff and delivery ditches.

ture and dissolved oxygen) can serve as "indicators," which can be monitored frequently in the field with appropriate training and quality-control procedures. In contrast, laboratory-based water-quality analysis (such as of nitrate and phosphate) is relatively expensive and time-sensitive, while sample analysis for other water-quality constituents (such as ammonium or bacteria) must be done within 24 hours of collection.

Irrigators need field-based, rapid, inexpensive and defensible monitoring tools to use across many acres of pasture, providing real-time data to facilitate daily operational decisions and adaptive management to minimize water-quality impairment. We report correlations between the four indicator variables measured in the field and the variables determined in the laboratory, to evaluate the potential for employing a strategic combination of the two.

Impact on in-stream flow volume

Excessive irrigation diversion can reduce in-stream flow levels, which in turn can result in the reduction of available aquatic habitat, elevated stream temperatures (see pages 153 and 161) and increased pollutant concentrations. Managers can determine the impacts that irrigation practices are having on stream flow by measuring the diversion volume and in-stream flow volumes above and below the system.

Our pasture-runoff estimates are only for surface runoff, because we had no means to estimate subsurface returns to either creek. Stream-flow volumes were lower in Willow Creek than in Lassen Creek (fig. 2). A larger percentage of Willow Creek was diverted for irrigation, with a peak of 78% on July 1, and during the next week irrigation diversion ceased due to dropping water levels. A lower percentage of Lassen Creek was diverted for irrigation, with a peak of about 68% on July 9, and after this, less water was diverted because irrigation was discontinued on about half of the adjacent pasture area due to dropping water levels.

This data reveals that the diversion of water to irrigate pastures adjacent to these streams is reducing in-stream flow by 0.5 to 6.0 cfs over the course of the summer, and that stream-flow reductions are more pronounced on Willow Creek than on Lassen Creek. This implies that water quality is more likely to be degraded in Willow Creek due to greater in-stream flow reductions and its reduced ability to buffer against contaminants in return flow.

TABLE 1. Statistics for laboratory-determined water-quality variables across Lassen and Willow creek study sites, June-July 2003 irrigation season

Water source (n)	Statistic	pH	DOC*	TSS†	NO_3	NH_4	PO_4	K	SO_4
			ppm	*mg/L*			*ppm*		
In-stream/above (12)	Mean	8.71	4.67	9.6	< 0.001	0.006	0.010	2.64	0.18
	Max.	9.61	6.36	26.9	< 0.001	0.096	0.157	4.83	0.34
Delivery ditch (20)	Mean	8.97	5.23	15.4	0.001	0.002	0.064	1.83	0.17
	Max.	9.44	10.06	45.7	0.010	0.023	0.417	3.41	0.39
Pasture runoff (16)	Mean	8.62	6.47	10.0	0.003	< 0.001	0.140	1.26	0.10
	Max.	9.57	11.08	15.4	0.037	< 0.001	0.310	3.28	0.31
In-stream/below (12)	Mean	8.65	5.34	11.0	0.001	< 0.001	0.077	3.38	1.34
	Max.	9.55	10.64	20.0	0.009	< 0.001	0.150	5.85	2.60

* Dissolved organic carbon.
† Total suspended solids.

Water-quality effects

To assess the cumulative impact of runoff and reduced stream flows on water quality, above and below in-stream monitoring is also needed. Measuring these indicator water-quality variables in the field can provide managers with real-time information on the potential impacts of their irrigation practices (fig. 3).

Electrical conductivity and dissolved nutrients. Electrical conductivity is a measure of the ability of water to conduct electricity (dS/m). It can serve as an inexpensive surrogate for laboratory-based chemical analysis. This is because the electrical conductivity of the water generally increases as the levels of dissolved pollutants (such as nitrate, ammonium, phosphate, sulfate and potassium) increases.

However, laboratory-based chemical analysis on a subset of samples is also necessary to appropriately interpret conductivity data from individual systems. Stream-flow diversions can increase conductivity by concentrating the existing dissolved pollutants within the stream and transporting new pollutants from pastures in runoff. In-stream conductivity was significantly higher ($P = 0.005$) below the irrigation systems on both Lassen and Willow creeks, indicating that at least some dissolved constituent concentrations did increase as a result of irrigation diversion and return (fig. 3).

Laboratory analysis indicated that the increase in electrical conductivity observed below the irrigation systems was at least in part due to increases in the concentrations of potassium and sulfate (tables 1 and 2). While these increases do not represent a significant water-quality problem, they indicate the loss of important plant nutrients from the pastures (table 1). In addition, mineral nitrogen levels appeared to be low in these streams and pastures, with nitrate and ammonium levels only slightly above detection limits (0.001 ppm), and well below those of water-quality concern (for example: the nitrate drinking-water standard is 10 ppm, and mineral nitrogen [nitrate plus ammonium] stream-eutrophication levels of concern are greater than 0.1 ppm)(table 1). While phosphate concentrations in pasture runoff were above levels of concern for stream eutrophication (> 0.01 ppm), they did not appear to increase below the irrigation system.

When considering water-quality parameters such as nutrients and sediments, it is important to examine both concentration and load (concentration times flow volume). For instance, given that flow volume is reduced below the irrigation system, there is no likely increase in the phosphate load due to this particular irrigation system. In addition, it is also prudent to examine total nitrogen and phosphorus levels in runoff in a complete evaluation for water-quality impacts.

Turbidity, total suspended solids and dissolved organic carbon. Turbidity is a measure of the cloudiness or opaqueness of a water sample, and it increases with the level of suspended solids (such as particulate organic matter and sediments ≥ 0.45 micrometer [μm] in size) and dissolved solids (such as dissolved organic carbon < 0.45 μm in size)(table 1). The transport of organic matter and sediment in pasture runoff can increase in-stream turbidity levels; however, well-vegetated pastures can also serve as sinks, or filters, for suspended solids. Furthermore, when stream water used for municipal drinking water has high levels of certain types

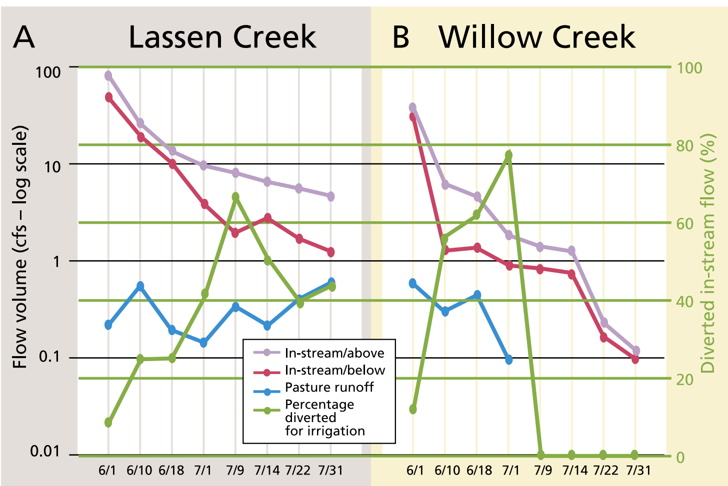

Fig. 2. In-stream flow volumes, pasture runoff volumes (cubic feet per second [cfs]) and stream-flow diversion for pasture flood irrigation from Willow and Lassen creeks, June and July 2003.

TABLE 2. Pearson's correlation coefficient* comparing indicator and laboratory-determined water-quality variables across Lassen and Willow creek study sites, June-July 2003 irrigation season

Water chemistry variable	Elec. con.	Turb.	Daily max. temp	DO†
	dS/m	*ntu*	*°F*	*mg/L*
Dissolved organic carbon	0.17	0.15	0.22	0.04
Total suspended solids	0.10	0.28	–0.10	0.07
Nitrate (NO_3)	–0.09	–0.12	0.26	–0.36
Ammonium (NH_4)	–0.15	–0.04	–0.10	0.11
Phosphate (PO_4)	–0.09	–0.07	–0.06	–0.55
Potassium (K)	0.40	–0.14	0.12	–0.60
Sulfate (SO_4)	0.67	–0.03	0.11	0.17

* Pearson's correlation coefficient measures the correlation between two variables. A perfectly positive correlation would be +1.0, a perfectly negative (inverse) correlation would be –1.0, and no correlation would be 0.0. Values greater than +/– 0.50 generally indicate correlation.

† Dissolved oxygen (DO) is a measure of the oxygen available in water for use by aquatic macroinvertebrates and fish.

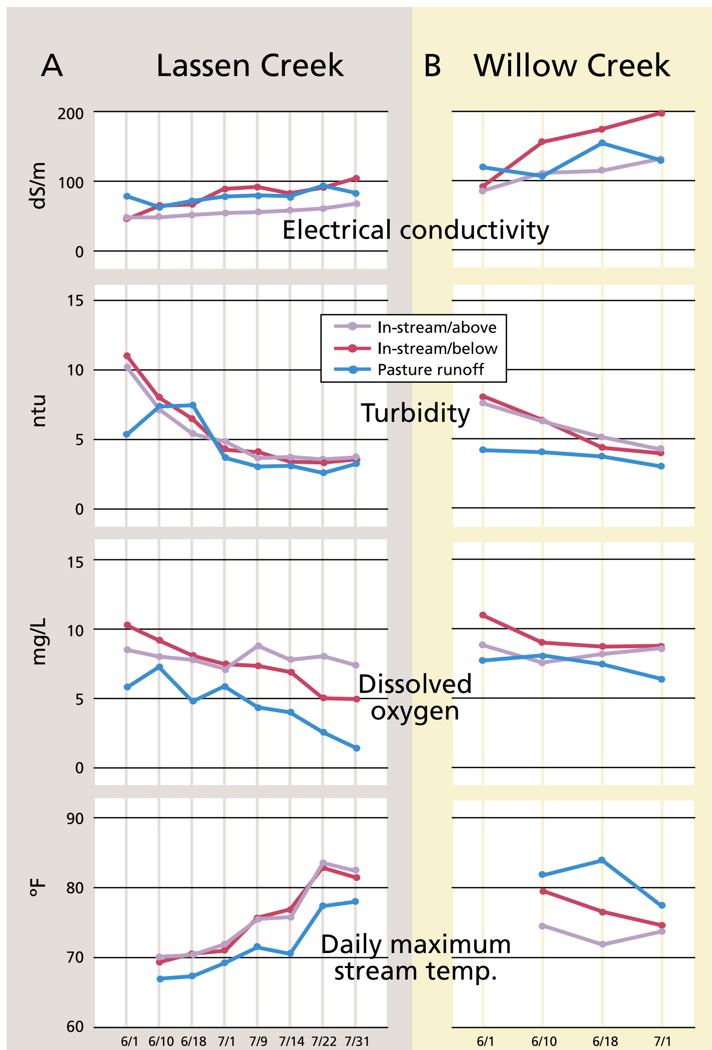

Fig. 3. Indicator water-quality levels in (A) Lassen and (B) Willow creek irrigated-pasture systems, June and July 2003.

Compliance with water-quality standards and targets will continue to be a major challenge for California agriculturalists who discharge water from irrigated fields and pastures.

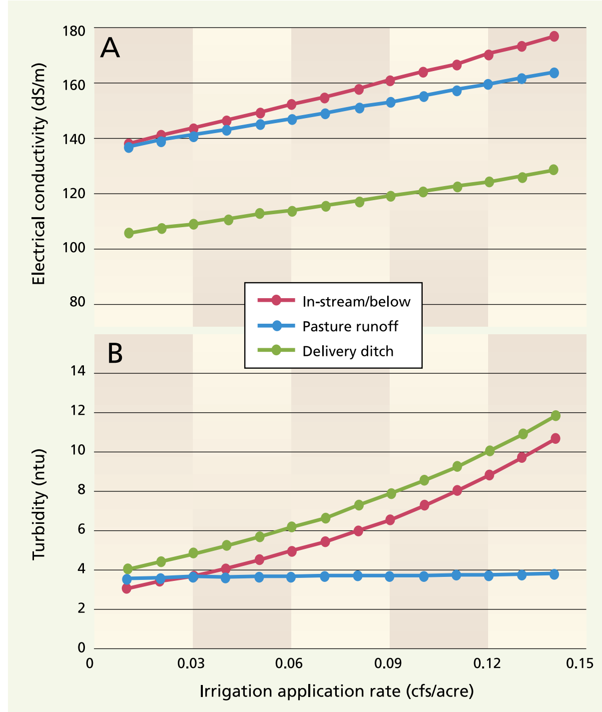

Fig. 4. Relationship between irrigation application rate and (A) electrical conductivity and (B) turbidity, developed from linear mixed-effects analysis of data collected from Willow and Lassen creeks, June and July 2003.

of dissolved organic carbon (DOC), the chlorination process can generate carcinogenic byproducts (Krasner et al. 1989).

The levels of turbidity and total suspended solids were not significantly higher below than above the irrigation systems on Lassen and Willow creeks ($P = 0.35$)(fig. 3, table 1). However, during the first 3 weeks of irrigation on Lassen Creek, the turbidity of the runoff was elevated. This is likely due to an initial flushing of suspended and dissolved solids from the pastures (Tate et al. 2001). The turbidity of irrigation water increases as it travels through delivery ditches, which are bare earth and add suspended solids via erosion (table 1). As the irrigation water travels across these well-vegetated pastures, total suspended solids and turbidity are reduced due to filtration, as demonstrated by the relatively low levels in pasture runoff. However, as water moves through the system, DOC increases slowly but steadily and is slightly higher in the creeks below the pastures.

Dissolved oxygen and temperature. Dissolved oxygen and stream temperature are critical variables in determining habitat quality for cold-water fisheries and stream macroinvertebrates. The concern is that irrigation systems can reduce dissolved oxygen below critical levels (4 to 6 mg/L) and raise stream temperatures to levels suboptimal (67˚F to 76˚F) and lethal (> 77˚F) for cold-water fisheries. Dissolved oxygen in a stream has a natural diurnal pattern: levels are highest in mid- to late afternoon due to oxygen production by photosynthesizing aquatic plants, and are lowest before dawn due to the plants' nighttime respiration (oxygen consumption). Dissolved oxygen can be decreased by adding nutrients (which can stimulate aquatic plant growth and so oxygen consumption due to respiration), by reduced stream flow (which decreases water mixing and, in turn, reoxygenation) and by increased stream temperature. Water temperature can be increased by reduced stream flow and as well as by flow in shallow sheets across pastures (see page 161). In some instances, water temperatures are lower in irrigation discharge that returns to streams beneath the soil surface (Stringham et al. 1998); however, these subsurface water returns often also have low dissolved-oxygen levels.

Minimum and mean dissolved-oxygen levels were reduced in pasture runoff from Willow and Lassen creeks, but within a significantly variable range (fig. 3). This variability was due to the amount of turbulence (mixing) in each runoff ditch and swale sampled, with turbulent pasture runoff having the highest dissolved-oxygen levels. Since dissolved oxygen is dependent upon the time of day, a direct comparison of readings from different times is difficult. All of our reported readings were made between 10 a.m. and 3 p.m. Linear regression analysis indicated that there was no significant effect of time of reading on dissolved-oxygen levels under our sample strategy ($P > 0.1$). If dissolved-oxygen levels are of significant concern, managers should take readings at predawn or dawn, when levels are at their lowest.

The effect of these irrigation systems on daily maximum stream temperature varied (fig. 3). In Willow Creek, stream temperatures were increased as much as 5˚F below the pastures. This could be due to the observed warming of pasture runoff, in-stream flow reductions, or most likely a combination of both processes. In contrast, in Lassen Creek, stream temperatures were the same above and below the pastures. Pasture runoff was actually cooler by several degrees than the original stream temperature. Additional monitoring and observation are needed to determine why return flows are cooler in Lassen Creek, but identifying the reason could lead to the development of management strategies to reduce the temperature of agricultural discharges from these systems.

It is important to note that stream temperatures in Willow Creek are inherently 5˚F to 10˚F warmer than in Lassen Creek (see page 161). In addition, the percentage of stream flow diverted from Willow Creek is much greater (30% to 40%) than from Lassen Creek (fig. 2), resulting in lower remaining in-stream flow levels, which we have shown can increase stream temperatures (see page 161). Moreover, pasture-surface runoff volumes are approximately the same in the two creek systems, but pasture runoff is a larger component of

Managers can use site-specific information to alter variables such as irrigation timing and frequency, in order to mitigate water-quality impacts. Don Lancaster, UCCE Modoc County natural resources advisor, monitors the delivery ditch in an irrigated pasture.

in-stream flow below the pastures on Willow Creek. Thus, the temperature of pasture runoff is more likely to influence in-stream temperatures on Willow Creek. It is possible that there is more subsurface return of pasture runoff on Lassen Creek, which could be cooler than surface returns (Stringham et al. 1998). Cooler surface return flows from Lassen Creek could be the result of the re-emergence of infiltrated water at the bottom of fields.

Irrigation rates and water quality

Site-specific information on how irrigation decisions affect agricultural discharge and stream water quality is of particular value to managers, who control practices such as the application rate and frequency of irrigation. If runoff water quality is a problem, opportunities to reduce those impacts via alternative irrigation practices should always be investigated. While the graphical analysis shown allows one to observe and evaluate pollutant levels in discharge above and below the management system, this approach provides limited guidance on opportunities to improve discharge quality. If variables (such as irrigation-water application rate, irrigation frequency and fertilization levels) are monitored and quantified simultaneously with the water-quality and flow data, all the data can be analyzed to identify the relationships between management decisions and resulting water quality.

To illustrate, we examined this data set for relationships between irrigation-water application rate (cfs/acre), flow volume (cfs) and water source (in-stream/above, delivery ditch, pasture runoff and in-stream/below), electrical conductivity, turbidity and dissolved oxygen. We used a linear mixed-effects analysis. The fixed effects were irrigation application rate, flow volume and water source. Day (June 1 = 1, July 31 = 61) was included as a fixed effect to account for seasonal trends in variables such as stream flow. Sample location was treated as a group effect to account for codependence due to repeated measurements (Pinheiro and Bates 2000). Electrical conductivity and turbidity data were natural log transformed to normalize residuals. This analysis provides a robust determination of differences in water quality above and below the pasture systems, with statistical control of flow-volume differences (fig. 4)(see page 161). The full results of this analysis are not shown, rather plots depicting significant ($P \leq 0.05$) relationships between irrigation management and water quality in delivery ditches, pasture runoff and in-stream/below are presented and discussed; the full analysis is available upon request from the lead author.

Electrical conductivity. Electrical conductivity for delivery ditch, pasture runoff and in-stream/below increased significantly as irrigation application rate increased, responding to the potential for increasing pollutant transport. Conductivity was also positively correlated to day, indicating that levels increased as the season progressed (fig. 3).

A significant, negative, irrigation-rate-by-day interaction indicates that the increase in electrical conductivity realized with increased irrigation application rate became less pronounced as the season progressed, due to the flushing and loss of available soluble pollutants for transport from the pasture. It is possible that this conductivity increase became less pronounced over time because the longer a pasture is irrigated, the fewer available soluble pollutants remain to be flushed out and transported from the pasture. This tapering conductivity increase may also be due to the uptake of available soluble nutrients by pasture grasses as plant growth rates increase in the summer. A significant negative relationship between flow volume and electrical conductivity accounts for the potential dilution of additional volume, given a relatively limited soluble pollutant supply. This further illustrates the importance of measuring flow simultaneously when collecting

Water-quality variables such as dissolved oxygen and stream temperature are dependent upon factors such as stream flow and shade. Lassen Creek flows through a meadow reach with a naturally low vegetative canopy.

water-quality samples. Reductions in irrigation application rates will result in lowered levels of dissolved pollutant transport from pastures and higher downstream flow volumes, which can dilute solutes returned as pasture runoff.

Turbidity. There was a positive, significant relationship between irrigation rate and turbidity, reflecting an increasing flushing and transportation potential for total suspended solids with increasing irrigation application rate. However, there was a significant irrigation-rate-by-water-source interaction, indicating that the positive relationship was only valid for in-stream/below and delivery ditches (fig. 4B). Pasture runoff turbidity was not dependent upon irrigation rate, indicating the capacity of the pasture to act as a filter and remove suspended solids contributed by source water and bare delivery ditches. As with electrical conductivity, there was a negative interaction between irrigation rate and day, indicating that the increase in turbidity realized with increased irrigation application rate becomes less pronounced as the season progresses.

These results indicate that, as with soluble nutrients, reductions in irrigation application rate will reduce turbidity levels in pasture runoff. These pastures appear to have the capacity to serve as sinks for solids (sediment and particulate organic matter) in source water and contributed by delivery ditches, but when the irrigation rate exceeds about 0.09 cfs per acre (in this instance, given these pasture sizes), this filtering capacity is exceeded and in-stream turbidity levels below the pasture become higher than above.

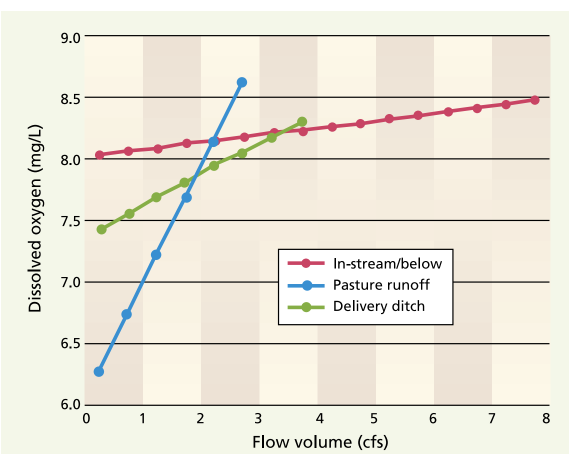

Fig. 5. Relationship between dissolved oxygen and flow volume developed from linear mixed-effects analysis of data collected from Willow and Lassen creeks, June and July 2003.

Dissolved oxygen. Dissolved-oxygen levels in delivery ditches, pasture runoff and in-stream/below were directly related to flow volume (fig. 5). In this system, flow volume in delivery ditches, pasture return and in-stream/below were determined by irrigation application rate, so that dissolved oxygen was indeed affected by irrigation management. Flow velocity and turbulence increased as flow volume increased, resulting in greater oxygenation and thus dissolved-oxygen levels at higher flow volumes. Pasture return had the greatest correlation to flow volume, indicating that low dissolved-oxygen levels in return flow were offset at high runoff volumes. In-stream/below dissolved-oxygen levels were also positively related to flow volumne.

These results indicate that maintaining in-stream flow volumes by reducing diversion volumes will reduce the impact that these irrigated-pasture systems have on in-stream dissolved-oxygen levels. In addition, increasing pasture runoff volume will increase dissolved-oxygen levels in return flow. However, this will also increase the potential for the transport of pollutants from pastures (fig. 5). Water managers should

While some water-quality variables in the studied streams were impaired by stream diversions and flood irrigation, the impacts were relatively low and measures to mitigate them are available. Irrigated pasture on Willow Creek provides forage to livestock and sometimes pronghorn antelope.

identify and implement opportunities to reduce return flow volume, but also allow for the mixing of return flow, such as weirs, plunge-pools and cobbled return ditches.

Management and monitoring

Compliance with water-quality standards and targets will continue to be a major challenge for California agriculturalists who discharge water from irrigated fields and pastures. This case study is an example of how to employ water-quality monitoring techniques and logic to address specific information needs to aid or facilitate compliance with water-quality standards. The information gathered under this approach indicates that while some water-quality impairment is associated with stream diversion and flood irrigation on these particular streams, these impacts are relatively small and there are clear measures available to mitigate them. Similar techniques and logic can be applied to other agricultural systems to address similar concerns (such as pesticides and pathogens) and to provide management solutions.

Indicator water-quality variables such as electrical conductivity, turbidity, water temperature and dissolved oxygen should be considered to supplement laboratory-based water-quality analyses. Electrical conductivity can be a valuable real-time indicator of increased dissolved pollutant concentrations in runoff or receiving bodies of water. Some conductivity and dissolved pollutant data must be collected simultaneously to establish site-specific correlations and to ensure the proper interpretation of the conductivity data.

Critical components of water-quality compliance include farm-scale assessments of agricultural discharges, potential water-resource impairments, and the implementation of management measures and effectiveness monitoring. In developing such on-farm programs, agriculturalists should establish specific monitoring objectives as well as a framework of sample-site location and collection frequency that is synchronous with agricultural discharge patterns. Farm-scale monitoring programs should target the specific pollutants of concern in receiving waters (such as a stream with high nitrogen levels) and on-site agricultural practices that could generate the pollutant (such as nitrogen fertilization of a pasture). For instance, we would have included indicator bacteria (such as fecal coliforms, *Escherichia coli*) in our monitoring if Lassen and Willow creeks were sources of municipal drinking-water supplies. Opportunities to use monitoring data to quantify relationships between specific agricultural management practices and resulting water quality should be capitalized upon to increase both site-specific knowledge and the return on financial investments in monitoring.

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Soil sterilization and organic carbon, but not microbial inoculants, change microbial communities in replanted peach orchards

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Methyl bromide is highly effective in reducing soil pathogens. Although its use was to be phased out completely in the United States by Jan. 1, 2005, due to environmental concerns, a 1-year critical-use exemption will allow tree fruit growers to use the fumigant through the end of the year. To explore possible replacements for methyl bromide, we compared the effects of pre- and postplant treatments and amendments on soil microbial communities and tree vigor in a replanted peach orchard. Both soil sterilization treatments and organic carbon amendments changed the composition of microbial communities in the soil. High microbial biomass is generally considered beneficial to agricultural soils; we found that it was usually highest in soils that received the organic carbon amendment and lowest in those with soil sterilization. However, tree vigor was highest with the sterilization treatments. The effects of a microbial inoculants/organic carbon combination on microbial communities and plant vigor were no different from simply adding organic carbon.

When old, low-yielding orchards are replaced in the San Joaquin Valley, growers must first combat nematodes and pathogens resident in the sandy soils or run the risk of reduced yields due to the replant problem or "disorder." The replant problem is caused by a complex of soil-borne nematodes and poorly characterized microbial pathogens (Radewald et al. 1987; Browne et al. 2004). Several nematodes are common in these soils, including ring *(Mesocriconema xenoplax)*, root lesion *(Pratylenchus vulnus)* and root knot (*Meloidogyne* spp.). Ring nematodes are associated with the bacterial canker complex, which can kill limbs and often entire trees in young replanted *Prunus* species orchards. Preplant soil fumigation with methyl bromide reduces the level of plant pathogens and can often increase tree vigor and yield even in areas without bacterial canker. However, while fumigated orchards grow more vigorously at first, they still may eventually succumb to bacterial canker. In addition, fumigation with methyl bromide reduces nonpathogenic taxa of the native soil microbial community, which can result in a reduced competitive environment for pathogens (Shiomi et al. 1999; van Elsas et al. 2002).

Furthermore, methyl bromide fumigation may contribute to the depletion of the Earth's ozone layer, and it was scheduled to be phased out completely in all "developed" nations by Jan. 1, 2005, forcing growers to find alternative soil treatments. Although alternative fumigants have been studied in the greenhouse or on a small scale in the field, there have been few large-scale, commercial, field trials comparing these strategies until recently. At the same time, interest in organic and microbial amendments as possible pest-management strategies is increasing among Central Valley growers. Organic amendments — such as composted green waste and manures — provide nitrogen and other nutrients, and supply organic carbon necessary for native microbial community growth, which may improve soil quality. Microbial soil amendments are commercial preparations that include various microbial taxa, often in conjunction with fertilizer or an organic carbon–based microbial "food source." Marketers claim that their products will provide "beneficial" microorganisms and improve the health and vigor of the soil microbial community and, consequently, improve the performance of cultivated crops. However, the efficacy of these alternative products compared to, or in addition to, methyl bromide and other fumigants has not been rigorously assessed.

With methyl bromide in the midst of being phased out, the authors compared replacement treatments for replanted peach orchards, including: *facing page*, tarped methyl bromide fumigation; *above*, compost spread down the row prior to planting; *right*, tree roots dipped in microbial inoculant; and, *far right*, the nematicide sodium tetrathiocarbonate (Enzone) injected through the drip-irrigation system after planting.

We conducted a trial in a replanted peach orchard, which compared the effects of a suite of pre- and postplant treatments on tree growth and yield as well as on soil microbial community composition. Microbial community composition was measured using phospholipid fatty acid (PLFA) analysis. Phospholipids are integral cell-membrane components, which rapidly degrade following cell death, and different types of microorganisms have different phospolipids. Since phospholipids turn over rapidly in soil, PLFA composition offers a snapshot of the living microbial community at the time of sampling. PLFA analysis also provides a quantitative biomass measurement and, since specific lipids are considered biomarkers for different groups of microorganisms (such as fungi versus bacteria, and gram-positive versus gram-negative bacteria), results can indicate the relative abundance of different microbial groups. PLFA analysis is also very sensitive to environmental perturbations and can detect shifts in microbial community composition following treatments. This method has been used in other agricultural systems to compare management practices and crop and soil types (Bossio and Scow 1997; Calderon et al. 2001; Steenwerth et al. 2002; Yao et al. 2000).

A field study of the effects of pre- and postplant treatments on plant vigor and microbial community composition was initiated in fall 2000 at a former peach orchard site north of Modesto, Calif. The peach orchard suffered from bacterial canker and had been removed 2 years prior. The soil at this site is classified as a Delhi sand. Each treatment replication was 36 feet by 65 feet and consisted of two adjacent rows of 10 trees each. In total, a factorial combination of 30 pre- and postplant treatments was applied in a randomized complete block design in an area covering 6.6 acres. For this study, nine of these treatments were analyzed (table 1).

The preplant soil fumigants methyl bromide (98% methyl bromide, 2% chloropicrin), metam sodium (Vapam) and 1,3-dichloropropene (Telone II) were applied in October 2000 with commercial application equipment. Composted green waste and steer manure were banded on the soil surface down some of the tree rows in fumigated and unfumigated areas before the planting of peach trees in February 2001. Compost and native soil were backfilled into the planting holes. Kelp extract, humic acid and microbial inoculants were applied at planting and periodically through the growing season in 2001 and 2002 in two of the three compost-amended treatments. Composted green waste and manure were applied again under the trees in January 2002. As a nonchemical alternative to preplant fumigants, one of the treatments included black polyethylene film mulch applied to the soil surface in April 2001, 2 months after the trees were planted. Black polyethylene mulch heats the soil to temperatures lethal to nematodes and soil-borne pathogens but sublethal to newly planted trees (Duncan et al. 1992). A nematicide, sodium tetrathiocarbonate (Enzone), was applied through the drip-irrigation system in October 2001 as a postplant treatment (table 1).

Measuring microbial communities

One year after soil fumigation (October 2001), the top 18 inches of soil were sampled using an Oakfield soil tube. One soil sample was collected underneath each of 10 to 12 trees in each plot. Samples were collected 2 to 3 inches from the drip emitters and then mixed together before analysis. Soil was frozen immediately after sampling and maintained at –4°F until phospholipid extraction. Each sample was analyzed for microbial community size and composition using PLFA analysis. Phospholipids were extracted from 8 grams of soil dry weight (DW), fractionated, methylated and analyzed as fatty-acid methyl esters by gas chromatography (see Bossio and Scow [1998] for complete description of methods).

Correspondence analysis. The data were analyzed using correspondence analysis to determine relationships between samples and to identify which fatty acids were similar or unique among the soil samples (Steenwerth et al. 2002; CANOCO for Windows version 4.5, Ithaca, N.Y.). Correspondence analysis transforms a data set containing many variables (in this case, amounts

The use of polyethylene mulch should be investigated further as an alternative to chemical soil fumigation.

TABLE 1. Pre- and postplant treatments, including application date and rate

Treatment	Pre- or postplant	Application date	Application rate	Comments
Methyl bromide	Preplant	October 2000	400 lb/acre	General soil fumigant; soil tarped at application.
1,3-dichloropropene (Telone II)	Preplant	October 2000	35 gal/acre	General soil fumigant; shank-applied.
Metam sodium (Vapam)	Preplant	October 2000	75 gal/acre	General soil fumigant; soil drenched at application.
Sodium tetrathiocarbonate (Enzone)	Postplant	October 2001	12.2 gal/acre	Nematicide injected through drip-irrigation system (concentration at application 750 parts per million).
Black polyethylene film mulch	Postplant	April 2001		Soil covering, which increases soil temperatures in the upper soil profile to levels lethal to nematodes and many soil pathogens.
Compost	Preplant	January 2002	4.7 ton/acre	Composted green waste and steer manure.
+ microbial inoculant	Postplant	Five applications through season	2 qt/acre (Tilth) 8 oz/acre (Iota)	Tilth & Iota; Fusion 360, Turlock, CA; injected through drip-irrigation system.
+ calcium	Pre- and postplant	Five applications through season	10 lb/tree 4 qt/acre (12% $CaCl_2$)	Oyster-shell-flour soil amendment preplant plus postplant calcium chloride ($CaCl_2$) injected through drip-irrigation system.
+ kelp extract + humic acid	Postplant	Five applications through season	2 gal/acre	Tree roots dipped in kelp extract (Shurcrop supra) and humic acid at planting; also applied through drip-irrigation system throughout growing season.
Untreated				No pre- or postplant treatments applied.

and types of fatty acids) into a smaller set of new variables, or dimensions. Each dimension is a unique combination of all the fatty acids, which explains a percentage of the total variation in the original data set. A multidimensional plot can show relationships in microbial community composition among soil samples; samples with similar microbial communities plot closer together than those with less-similar community composition.

Correspondence analysis also can identify which particular fatty acids are most important in determining the relationships among soil samples. While some of these fatty acids are biomarkers for specific groups of organisms, many fatty acids contributing to the fingerprints are common to large groups and cannot provide diagnostic information about which organisms increase or decrease with different soil treatments (Bossio and Scow 1998). A total of 34 lipids were included in our correspondence analysis. After statistical analysis, ellipsoids were drawn on the plots to indicate treatment groupings. ANOVA followed by a post-hoc Tukey's test was used to compare these ellipsoids, based on their first-axis correspondence analysis scores (SAS version 8.1, Cary, N.C.).

Cluster analysis. In addition to correspondence analysis, treatments were compared using hierarchical cluster analysis (SPSS version 11, Chicago, Ill.). To reduce sample-to-sample variability due to soil heterogeneity and to ease visual interpretation of the results, replicates were averaged before analysis. In cluster analysis, treatments (or samples) are compared based on how dissimilar they are in community composition (that is, lipid composition). In our analysis, we used a measure of dissimilarity that is more strongly influenced by dominant lipids (those found in many samples) rather than rare lipids (those found in few samples). Following analysis, a dendrogram (tree) was created to visualize the results. Treatments that are less similar to one another are visualized by longer branches on the tree, whereas more-similar treatments are connected by shorter branches. As with the correspondence analysis, a total of 34 lipids were used to create the dendrogram.

Evaluating tree vigor. At the end of the first growing season (November 2001), trunk circumference was measured as an indicator of plant vigor. Trunk circumference was measured approximately 12 inches from the ground. The mass of the first dormant pruning (April 2002) was also measured. For both variables, each replicate measurement is the average of 12 trees (that is, subsamples) per block for a total of four replicates per treatment. ANOVA was used to determine if treatment significantly affected tree vigor. Post-hoc Tukey's tests were used to compare means between treatments ($\alpha = 0.05$).

Effects on soil microbiology

The total amount of PLFA is an indicator of total microbial biomass present in the samples, plus a minor amount of plant biomass. The average total PLFA varied by treatment, ranging from 17 to 35 nanomoles per gram of soil dry weight (nmol g^{-1} DW)(table 2). Although not significant ($P = 0.06$), there was a trend toward higher total PLFA in soils amended with organic carbon (such as compost plus microbial inoculant, compost plus calcium, and compost plus kelp extract plus humic acid) than in nonamended soils (such as fumigated soils and untreated soils), as determined by linear contrasts following univariate ANOVA. Most soil

TABLE 2. Total nanomoles PLFA* in each treatment (n = 4 to 7)

Treatment	Mean total PLFA†
	nmol/g $^{-1}$ *± SE*
Untreated	26.4 ± 2.1
Methyl bromide	19.6 ± 2.7
1,3-dichloropropene (Telone II)	25.3 ± 2.5
Metam sodium (Vapam)	21.4 ± 1.3
Sodium tetrathiocarbonate (Enzone)	26.6 ± 2.1
Polyethylene film mulch	17.7 ± 0.9
Compost + microbial inoculant	31.7 ± 2.9
Compost + calcium	35.4 ± 3.1
Compost + kelp extract + humic acid	32.6 ± 4.0

* Phospholipid fatty acids (nmol/g dry weight soil).
† Although not significant, there was a trend toward higher total PLFA in those treatments including an organic carbon amendment, as determined by linear contrast following ANOVA ($P = 0.06$).

microbial communities are carbon-limited (Alden et al. 2001). Providing labile (available) organic carbon in the form of compost, extracts, organic acids and microbial biomass (from the inoculant) likely selected for those members of the microbial community that could rapidly use the carbon as an energy source and produce new biomass.

Organic carbon inputs and soil sterilization treatments also influenced microbial community composition, as detected by correspondence analysis (figs. 1A and 1B). Polyethylene film-mulched and fumigated (metam sodium, 1,3-dichloropropene and methyl bromide) soils grouped separately from the organic carbon–amended soils along the first axis, which explained 34.2% of the data variation. The untreated and sodium tetrathiocarbonate samples were grouped toward the center of the plot, between the sterilized soils and the organic carbon–amended soils.

When the first-axis correspondence analysis scores were compared using ANOVA followed by a post-hoc Tukey's test, the samples grouped into three classes (table 3). The soil sterilization samples had scores that were significantly different from all other samples ($P < 0.003$). Although the organic carbon–amended samples had significantly different scores ($P < 0.01$) from the untreated and soil sterilization samples, they were not significantly different from the sodium tetrathiocarbonate samples. Lastly, the sodium tetrathiocarbonate and untreated sample scores were not significantly different from one another ($P < 0.05$). It is less clear which environmental factors influenced the separation of the samples along axis 2 (figs. 1A and 1B) — which explains 21.8% of the variation in the data — because the samples did not group by any of the treatments. Likely, this axis is influenced by factors that were not measured in this study.

In general, the soil sterilization samples were more enriched in: the straight-chain saturated fatty acids (which are common in many organisms); 10 methylated fatty acids (often considered indicative of actinomycetes, filamentous bacteria often involved in decomposing complex organic matter); and the longer-chain fatty acids (containing greater than 20 carbons, which may be indicative of protozoa or other eukaryotic organisms).

Similar enrichment in actinomycete biomarker PLFAs was observed in a microcosm study that focused on the effects of the fumigant metam sodium on microbial community composition using total soil fatty acid methyl esters (Macalady et al. 1998). In contrast, organic carbon–amended treatments were more enriched in monounsaturated fatty acids, which are thought to be indicative of the presence of available carbon. The enrichment of monounsaturated fatty acids has been observed in other agricultural systems following the addition of organic carbon. For example, monounsaturated fatty acids were also enriched in rice straw incorporation in a periodically flooded California rice soil (Bossio and Scow 1998) and manure additions in a Tennessee no-till soil (Peacock et al. 2001). One of the most striking characteristics of these results is the lack of a unique fingerprint in those soils treated with microbial inoculants. Despite marketing claims suggesting that microbial inoculants enrich soil microbial communities, we did not observe this effect in our samples. Instead, inoculated soils had microbial communities very similar to uninoculated soils amended with organic carbon.

Various hypotheses can be offered as to why inoculated soils did not have unique microbial communities. First, all of the organic carbon–amended soils included compost and thus labile carbon, which may have swamped out any other treatment effects. Second, soil is a harsh environment and the microorganisms in the inoculant may not have been sufficiently competitive with the native microbial communities to significantly

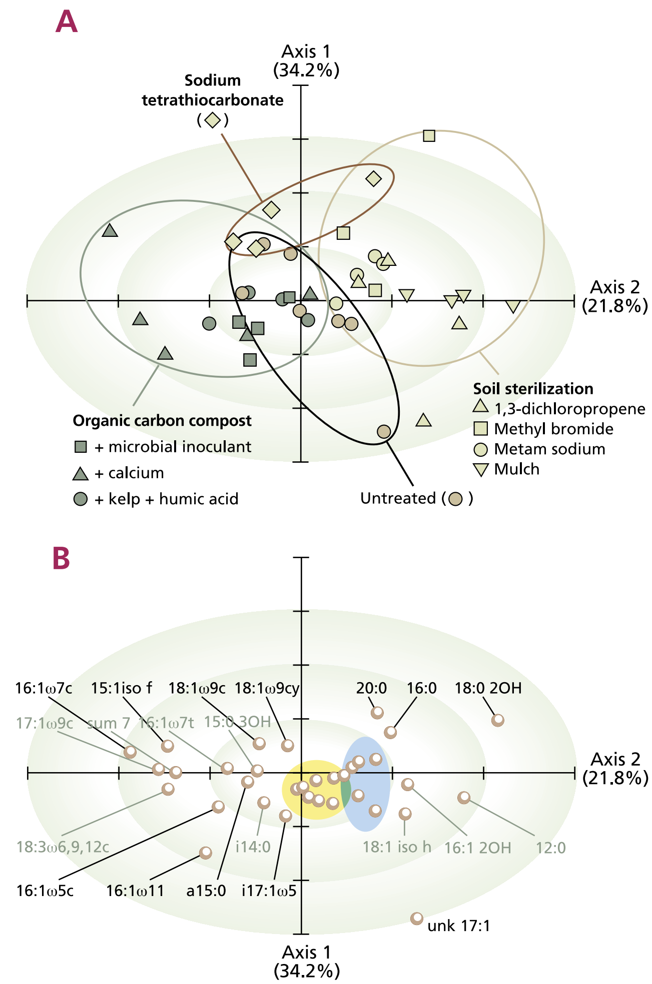


Fig. 1. Results from correspondence analysis of phospholipid fatty acid (PLFA) data. (A) In an ordination plot of the sample scores, treatments with similar microbial communities plotted closer together than treatments with less-similar microbial communities. (B) In an ordination plot of the fatty acid scores, comparison with sample plot location in fig. 1A indicates which fatty acids are enriched in specific samples. The yellow ellipsoid includes the fatty acids 15:0, i15:0, i16:0, 10Me 16:0, a17:0, i17:0, and sum 9 (a composite of the lipids); the blue ellipsoid includes the fatty acids 14:0, 17:0, 10Me 17:0, 18:0, 19:0cy, and sum 3 (a composite of four lipids).

TABLE 3. Tukey groupings based on least-squared means comparison following univariate ANOVA

Ellipsoid (fig.1, above)*	Tukey grouping
Organic carbon	a
Sodium tetrathiocarbonate (Enzone)	ab
Untreated	b
Soil sterilization	c

* The main effect, ellipsoid, was significant ($F = 26.38$, $P < 0.0001$; dfn, dfd were 3, 36, respectively). Letters indicate significant differences between treatments ($P < 0.01$).

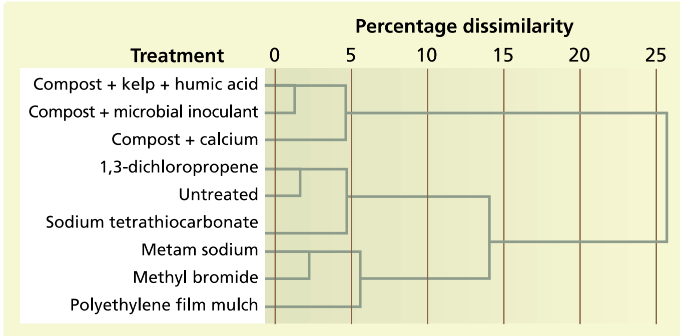


Fig. 2. Dendrogram of all treatments based on cluster analysis. Treatments are separated based on their dissimilarity, which is indicated by the top axis.

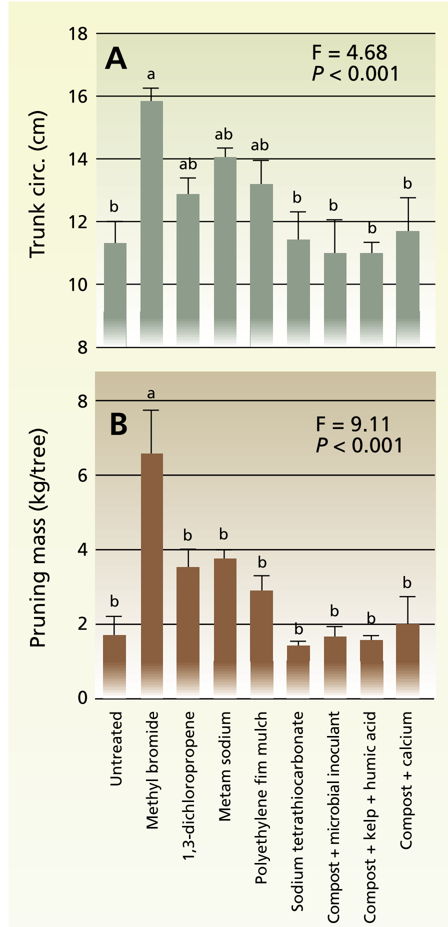


Fig. 3. (A) Average trunk circumference (centimeters) and (B) first year's pruning mass in each treatment (n = 4, bars are means ± SE). Letters indicate a significant difference between treatments following post-ANOVA Tukey's test (α = 0.05; for ANOVA model dfn = 3, dfd = 35).

alter the microbial fingerprint. As the organisms from the inoculant died, they entered the labile carbon pool and so served as an additional organic carbon resource for the native microbial community. Finally, the diversity of the inoculant community may have been too low to have an effect on overall diversity of the soil microbial community. Commercial microbial inoculants typically include fewer than 40 taxa, or even as few as 10 taxa. In contrast, the native microbial community can include as many as 1,000 microbial taxa within a gram of soil (Torsvik et al. 1990).

However, we also found that microbial inoculants had no overall effect on microbial community composition in two other California vineyard trials (R.E. Drenovsky and K.M. Scow, unpublished data). Our current data suggests that the inoculants employed here had little effect on the soil microbial community. Rather, the presence of labile organic carbon apparently had a greater influence on the composition of the orchard soil microbial communities. With organic carbon inputs, there was a trend toward higher microbial biomass, and the microbial community composition was altered.

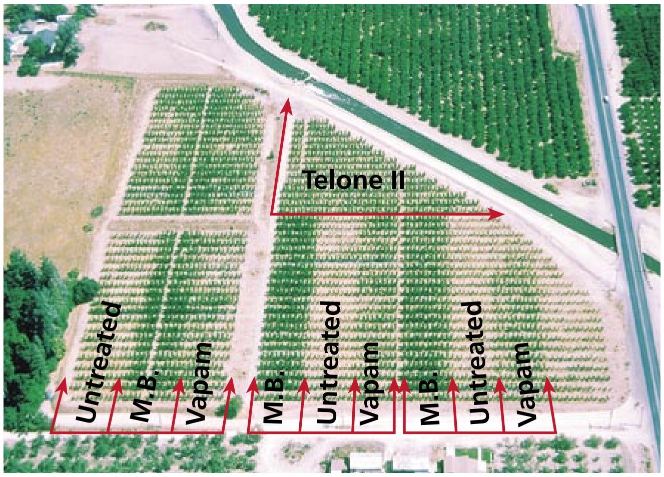
Similar to the results from the correspondence analysis, the primary factor separating treatments in the cluster analysis was the addition of organic carbon (fig. 2). The three organic carbon treatments were more than 95% similar in lipid composition to one another, and they grouped separately from all other treatments, from which they were approximately 25% dissimilar in lipid composition. The second branch of the tree was then split into two further clusters, one including sodium tetrathiocarbonate, 1,3-dichloropropene and untreated samples, and the other including methyl bromide, metam sodium and film-mulched samples. These results provide further support for our supposition that microbial inoculants had little effect on microbial community composition. Likewise, it suggests that polyethylene mulch produces a similar effect on microbial communities as chemical fumigants. From a microbial perspective, the use of polyethylene mulch should be investigated further as an alternative to chemical soil fumigation.

Tree vigor and soil nutrients

It is important to consider the soil microbial community data within the context of the entire soil food web. Although organic carbon amendments increased microbial biomass and influenced microbial community composition, they had no effect on first-year tree growth and vigor, as assessed by trunk circumference and first-year pruning masses. In contrast, trees growing in areas fumigated with methyl bromide had greater trunk diameters than trees growing in areas treated with the organic carbon amendments (compost plus kelp extract plus humic acid, compost plus microbial inoculants, and compost plus foliar and drip-applied calcium) or sodium tetrathiocarbonate, and had trunk diameters 1.4-fold greater than the control trees (fig. 3A).

However, trees growing in areas fumigated with metam sodium or 1,3-dichloropropene, or treated with the black polyethylene film mulch, had tree diameters that were not significantly different from either group after 1 year of growth. In addition, trees growing in areas fumigated with methyl bromide had the highest pruning masses (3.9-fold greater than controls), with all other treatments having significantly lower pruning masses (fig. 3B). Tree vigor may have been related, in part, to differences in soil nutrient availability due to indirect treatment effects. For example, soil sterilization treatments may have contributed to soil nutrient pools by killing soil microorganisms.

In contrast, higher microbial biomass in the organic carbon treatments may have led to greater immobilization of soil nutrients. Additionally, at our site, soil sterilization significantly lowered nematode numbers (R.A. Duncan, unpublished data), possibly promoting greater tree growth and vigor in these treat-



Peach trees in the methyl bromide (M.B.), 1,3-dichloropropene (Telone II) and metam sodium (Vapam) plots grew more vigorously (shown, darker rows), as opposed to less-leafy untreated control plots.

In general, the fumigation and polyethylene film mulch treatments tended to suppress microbial biomass in the soil but improve tree vigor. *Above,* methyl bromide–fumigated trees are in the foreground, with unfumigated trees behind.

ments. Finally, reduced numbers of other soil-borne pathogens in the soil sterilization treatments may have increased tree growth and vigor. Research in apple orchards (Mazzola 1998) and vineyards (Westphal et al. 2002) suggests that specific fungal species, such as *Pythium* spp., may play a role in replant disease.

Microbial community composition

Overall, pre- and postplant treatments had opposing effects on microbial communities and peach tree vigor. Although treatments including compost tended to increase microbial biomass and influence microbial community composition, they had no measurable effect on plant vigor. In contrast, fumigants and the black polyethylene film mulch tended to suppress microbial biomass but increase tree vigor. It is possible that there could be continued reductions in microbial biomass in future growing seasons, which could have negative impacts on the orchard such as lower nutrient pools, but this hypothesis requires further research. Lastly, microbial-based amendments (that is, inoculants) in conjunction with organic carbon amendment had the same effect on microbial biomass, community composition and plant vigor as did adding organic carbon amendments alone. This study also suggests that commercial soil inoculants should not be substituted for preplant fumigation, and may have limited value in a commercial orchard setting.

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Site-specific herbicide applications based on weed maps provide effective control

Martina Koller
W. Thomas Lanini

More-effective weed control in agricultural fields can be achieved by utilizing information about the spatial distribution of the previous year's mature weeds. In our study, variable-rate herbicide applications based on weed infestation maps developed just before the previous year's harvest provided effective weed control. The results showed that when information about the spatial distribution of the previous year's weed seedlings or mature weeds was used, weed control was comparable to uniform, one-rate, herbicide applications, while the total amount of herbicide applied decreased. Herbicide use was reduced an estimated 39% for the seedling map and 24% for the mature map approach. However, incorporating the weed-seed redistribution from harvest to application time into the treatment maps could further improve weed control.

Weed maps were developed to guide variable-rate herbicide treatments in sunflower. When herbicides were applied based on the weed-seedling and mature-weed maps, 15% and 19% of the respective plots did not receive any treatment. *Above*, the nightshade density was low in parts of the sunflower field where no herbicide was used, indicating a good relationship with the previous year's weed population.

Site-specific weed control matches site-specific conditions (such as soil properties and weed infestation densities) with the proper herbicide and application rate. Spatially variable herbicide-rate applications can achieve the most effective application, because each part of the field receives a precise amount of herbicide based on its need. The benefits of this technology include a reduction in spray volume and consequently lower herbicide costs, time savings because of fewer stops to refill, and less nontarget spraying, which reduces potential environmental risks (Felton 1995).

Reductions in herbicide use achieved with site-specific applications depend on the level of weeds in the field, but can be as high as 40% to 50% (Gerhards et al. 1997). In an evaluation of site-specific, postemergence weed control of broadleaf and grass weeds in corn, Williams et al. (2000) showed a 51% reduction in rimsulfuron and an 11.5% reduction in bromoxynil plus terbuthylazine use, compared with conventional herbicide spraying. In a preliminary trial of postemergence weed-patch spraying in spring barley, a nonsignificant yield increase was observed when weeds were controlled in patches, but 41% less herbicide was used compared with whole-field spraying (Heisel et al. 1997).

We tested the hypothesis that weed patches present in specific locations of a field before the previous year's harvest indicate where weeds will be present during the following growing season. Mapping these weed patches indicates where herbicides should be applied, and conversely, the absence of weeds indicates where little or no herbicide is required. Although sampling is often performed on a larger grid than the grid used for pesticide application, geostatistics allows the estimation of weed populations between sample points, and thus the application map can be made to correspond with the width of the sprayer. Our objective was to evaluate site-specific herbicide applications of a pre-emergent herbicide using two types of weed maps developed from weed counts made the previous year, and to calculate the herbicide savings.

Field test on sunflower

We conducted a variable-rate experiment on an 11-acre portion of a 79-acre field located in Yolo County. The crops were processing tomato in 1999 and sunflower in 2000. We developed weed maps from the tomato crop and used them to develop variable-rate applications the following year to sunflower. In sunflower, a pre-emergent herbicide is applied either before planting and mechanically incorporated, or after planting but before crop or weed emergence and incorporated mechanically or by irrigation. We studied the effectiveness of variable-rate application of a pre-emergent herbicide, although this technology can be used for postemergent herbicides as well.

Processing-tomato seeds were planted from May 4 to 8, 1999. A pre-emergent herbicide, napropaminde (Devrinol), was applied in an 8-inch band, centered on the crop row before tomato planting. The field was hand-weeded on May 26 and cultivated on June 3. A layby postemergent herbicide,

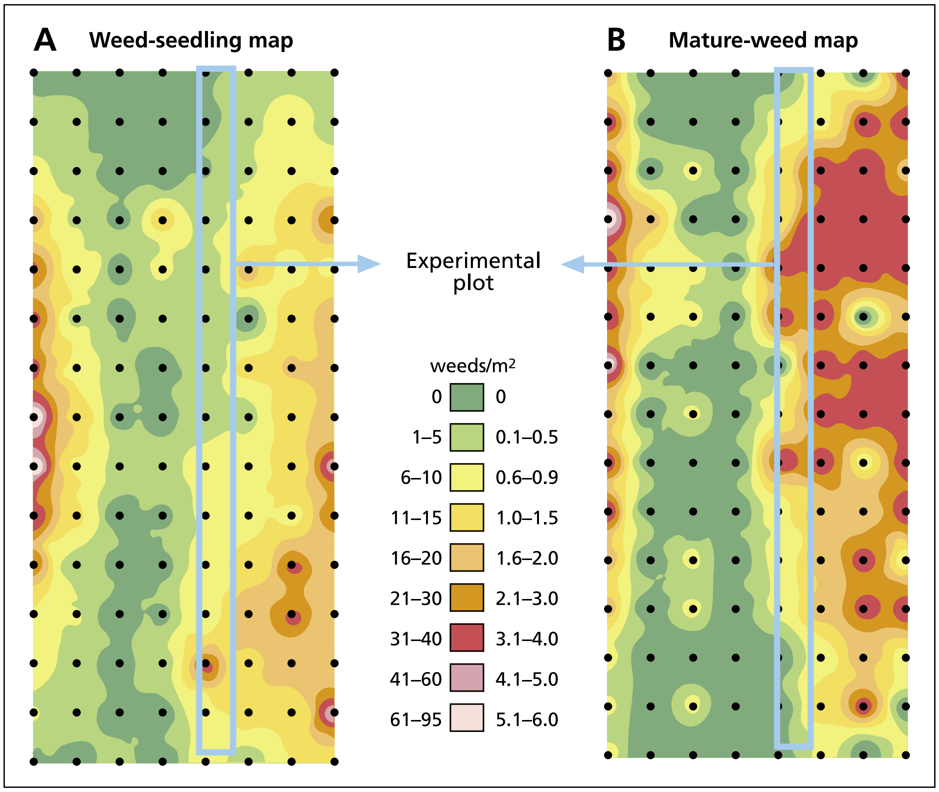


Fig. 1. Interpolated weed maps developed in 1999, based on (A) cumulative weed-seedling counts and (B) mature-weed counts.

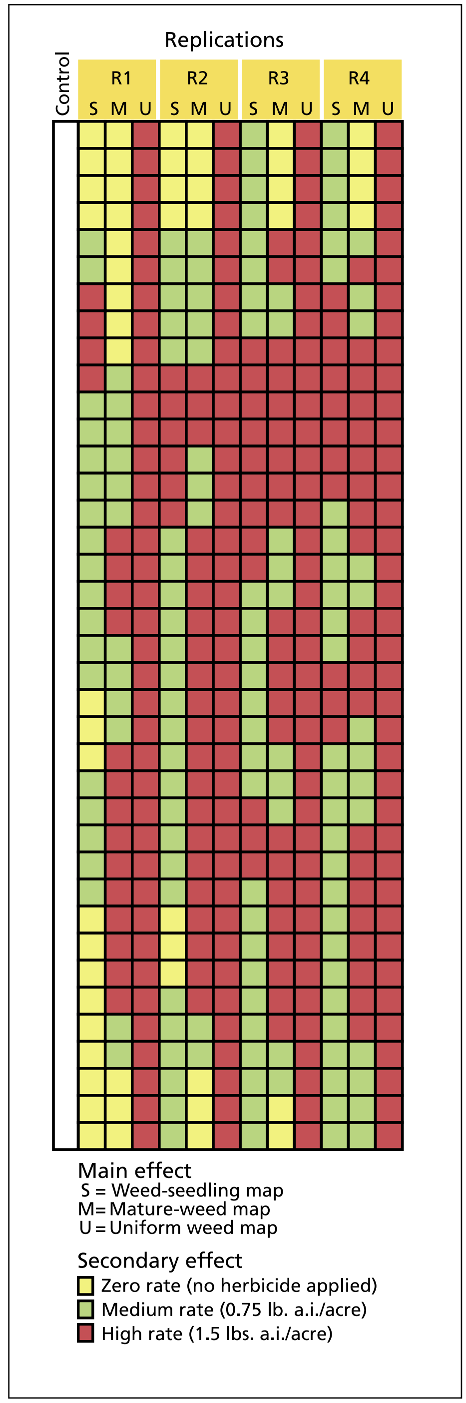


Fig. 2. Treatment map and layout of the experimental plot (split-plot design). Replications were 135 feet by 2,508 feet each; the untreated control plot was 5 feet by 2,508 feet.

trifluralin (Treflan), was applied on the sides of the bed and in furrows on June 20. Another hand-weeding followed on June 27. Furrows and sides of beds were again cultivated on July 26. The crop was harvested from Sept. 10 to 14, 1999.

Using weed maps developed from the 1999 tomato crop, we developed variable-rate application maps for the following year. In 2000, sunflower was planted on March 4 (male plants) and March 23 to 25 (female plants). Ethalfluralin (Sonalan) was applied postplant, pre-emergent on March 28, followed by two cultivations (May 2 and June 6). Sunflower male plants were destroyed on July 15, and female plants were harvested on July 21 to 22. Both crops were furrow-irrigated.

Weed distribution maps developed

Weed distribution was mapped in the tomato crop in 1999. The density of the weed population was assessed in two ways: (1) by cumulative weed-seedling counts throughout the crop season (May 25, June 19 and July 20, 1999)(fig. 1A) or (2) by mature-weed counts at the time of crop harvest (Sept. 9, 1999)(fig. 1B). Weed densities were estimated using a grid 165 feet wide (across beds) and 185 feet long (along the direction of beds). The measurement unit was a 20-inch-by-20-inch quadrat for seedling counts, and a 15-feet-by-17-feet grid cell for mature-plant counts. All data points were assigned north and east coordinates (georeferencing) to allow the weed maps to be spatially analyzed in a geographic information system (GIS)(ESRI, ArcView 3.1, 1996).

Weed population densities estimated by the different methods were used to create continuous weed-density maps, utilizing an interpolation method (ordinary kriging) to estimate weed densities between the sampled locations. The interpolated weed-density maps were used to create treatment maps based on weed infestation levels. The field map was divided into a matrix of cells, and the average weed infestation level was estimated for each cell.

Infestation levels were defined as weed-free (less than 10 seedlings per square yard or less than one mature plant per square yard), medium (11 to 30 seedlings per square yard or one to three mature plants per square yard) or high (more than 30 seedlings per square yard or more than three mature plants per square yard). Levels were arbitrarily set to cover the range of observed densities. Herbicide treatment maps were created by assigning varying herbicide rates to each location according to infestation levels, and dividing the field into zones receiving the same herbicide rate. Zones were marked with colored flags. (Typically, colored flags would not be needed because the GIS map information is downloaded directly into the sprayer controller; however, the sprayer we used did not have a spray controller and we used colored flags.) The three herbicide rates were 0, 0.75 and 1.50 pounds active ingredient per acre (lb. a.i./acre) of ethalfluralin (Sonalan, 3 lb. a.i./gallon).

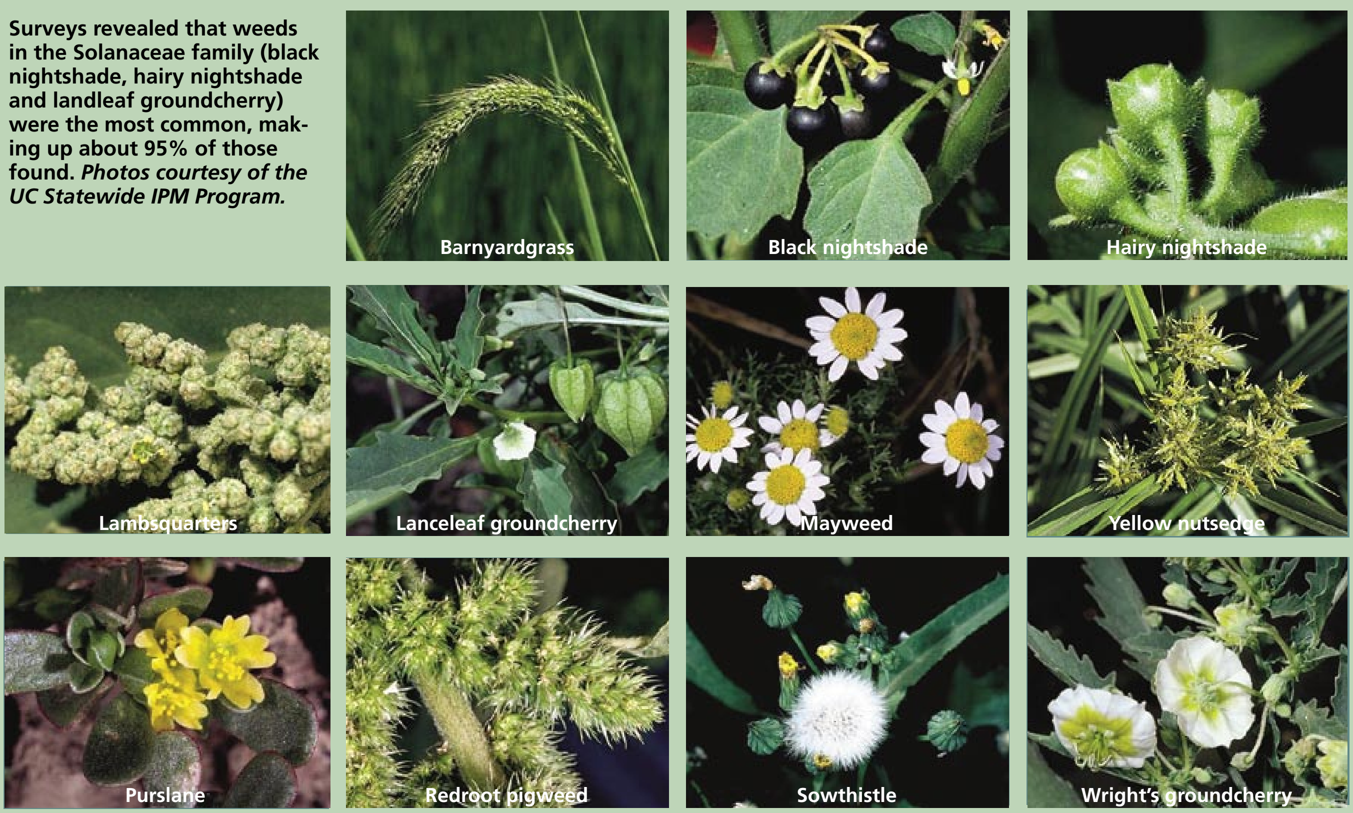
A portion of the field with the steepest gradient in weed infestation was selected for a split-plot experiment. The main effect was the treatment map source (seedling counts or mature weeds), and the secondary effect was ethalfluralin rate at three levels (0.00, 0.75 and 1.50 lb. a.i./acre)(fig. 2). The main plots were 15 feet (three beds) wide and 2,508 feet long, and replicated four times. Each plot was split into 38 subplots of 15 feet wide and 66 feet long. One of the three herbicide rates was applied to each subplot based on the weed map. Each replication included a three-bed strip, which received a constant, full herbicide rate (1.50 lb. a.i./acre). One bed strip (5 feet by 2,508 feet) did not receive any herbicide application and served as an untreated control.

All plots except the control were treated on March 28, 2000. Ethalfluralin was applied to the soil surface and cultivated immediately after application to incorporate the herbicide and remove any emerged weeds. The entire study area was cultivated at that time, including plots where no herbicides were applied. The variable-rate herbicide application was evaluated by density measurements of weeds that survived the treatment. Weed density measurements were made 2, 4 and 6 weeks after the herbicide application or cultivation. Measurements consisted of visual estimates of total weed cover for each subplot and counts of weed seedlings in 100-square-inch quadrats placed randomly 10 times per herbicide level in each replication.

A prototype variable-rate applicator (VRA) developed by the UC Davis Department of Biological and Agricultural Engineering was used in the experiment (Giles and Slaughter 1997). Zones corresponding to the same treatment were marked with colored flags and rate changes were done manually. The VRA changes the application rate in about 0.1 second. The VRA traveled at a speed of 5 miles per hour (mph), resulting in 1 to 2 feet of travel before the desired application rate was reached. A 3-foot buffer area around each change in herbicide rate was delineated and excluded from measurement after the variable-rate herbicide application.

Weed surveys

The 1999 weed surveys revealed that weeds from the Solanaceae family — black nightshade (*Solanum nigrum* L.), hairy nightshade (*Solanum sarrachoides* Sendt.) and lanceleaf groundcherry (*Physalis lancifolia* Nees) — were the dominant weeds in this field, making up about 95% of the total weed counts. The most common grass weed was barnyardgrass (*Echinochloa crus-galli* [L] P. Beauv.), and yellow nutsedge (*Cyperus esculentus* L.) was also present, although together they covered less than 5% of the field. The other weed species present, which together covered less than 1% of the field, were: redroot pigweed (*Amaranthus retroflexus* L.), tumble pigweed (*Amaranthus albus* L.), lambsquarters (*Chenopodium album* L.), nettleleaf goose-



Surveys revealed that weeds in the Solanaceae family (black nightshade, hairy nightshade and landleaf groundcherry) were the most common, making up about 95% of those found. *Photos courtesy of the UC Statewide IPM Program.*

***Left*, former UC Davis graduate student Martina Koller uses a portable digital global positioning system (DGPS) and data logger to georeference samples and map weed population densities. *Right*, in the foreground, weed seedlings are light-green on the soil; in the background, the half-rate herbicide plots appear to be weed-free.**

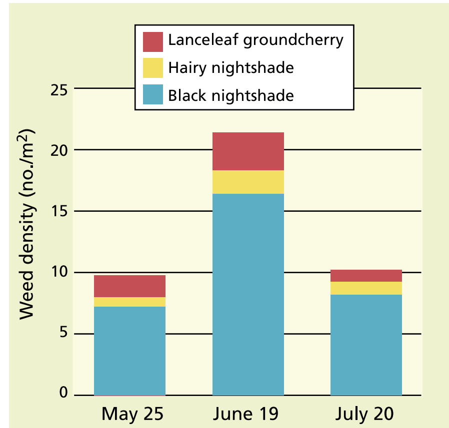


Fig. 3. Seedling counts from 1999 weed surveys. The total sampled area was 110 square yards.

foot (*Chenopodium murale* L.), purslane (*Portulaca oleracea* L.), annual sowthistle (*Sonchus oleraceus* L.) and prostrate knotweed (*Polygonum aviculare* L.).

The cumulative weed-seedling density throughout the growing season was 35.6 plants per square yard, and average mature-plant density was 1.2 plants per square yard. Eighty-five percent of all weeds were from the Solanaceae family (seedlings averaged 28.8 plants per square yard; mature plants, 0.8 plants per square yard) and therefore, these were used for the subsequent development of weed density maps. The dominance of a few weed species in arable fields is characteristic of different cropping systems (Forcella et al. 1992). Since tomato was the crop in 1999, it was reasonable to expect that weeds escaping control would be from the same family (Solanaceae). Members of the same family of plants have similar physiology, which would make them less susceptible to herbicides used in that crop. The combination of hand-weeding, cultivation and herbicide treatment reduced the number of weeds reaching maturity. As a result, mature-weed density in the 1999 tomato field was much less than the seedling density.

Two weed-density maps were used for the variable-rate herbicide experiment: one created from seedling counts and another based on mature-weed counts. The weed-seedling map was based on cumulative counts of the seedlings. For example, three field surveys were conducted during the 1999 season. Weed densities and distribution measured from the three surveys had a high degree of spatial correlation, indicating that highly infested areas of the field had high densities of nightshade weeds throughout the season. For the tomato crop, it was observed that the weed-seedling density was highest in June, 1.5 to 2 months after planting (fig. 3). Conditions were ideal for nightshade emergence in June given the warm temperatures and a tomato canopy that was still open enough for light to reach the soil surface. Cultivation occurred after the May seedling counts and may have moved seed into the ideal position for germination and subsequent irrigation.

Impact of map source

Where no herbicides were applied, weed cover was significantly less when using the mature-weed map, because it better-estimated weed cover the following year (fig. 4). There was no significant difference between map source for the 0.75 and 1.5 lb. a.i./acre herbicide rates. Based on seedling emergence 2 weeks after application, overall weed control was significantly better when the treatment maps were based on mature weeds with 58 weeds per square yard than on seedlings, which had 142 weeds per square yard. Weed cover was significantly less at 2 and 4 weeks after herbicide application when treatments were based on mature-weed maps compared

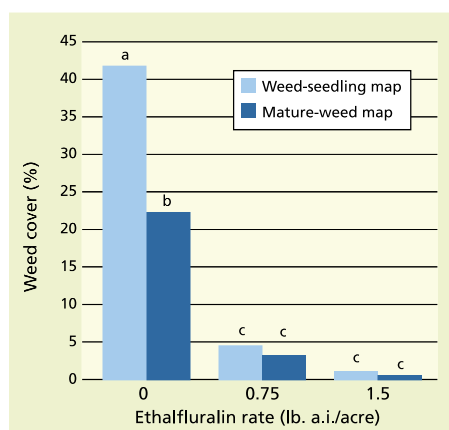


Fig. 4. Weed cover 2 weeks after experiment was initiated, as visually assessed in each subplot. Same letters indicate no significance; different letters indicate significant difference between treatments at the 0.05 significance level based on LSD multiple pairwise comparison test.

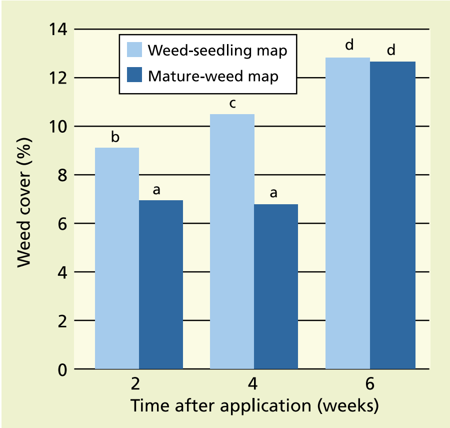


Fig. 5. Weed cover at 2, 4 and 6 weeks after variable-rate application, averaged over the three herbicide rates. Weed cover was visually estimated in each subplot. 0 = no weeds present. Different letters indicate significant difference between treatments at the 0.05 significance level based on LSD multiple pairwise comparison test.

In some parts of the field where no herbicide was used, nightshade density was high, probably due to the redistribution of seeds during harvest.

with seedling maps, but did not differ at 6 weeks after treatment (fig. 5).

Weed cover when no herbicide was applied ranged from 15% to 55%, 2 weeks after the experiment was initiated. High weed cover on some no-herbicide plots points to a major pitfall of map-based, variable-rate applications of pre-emergent herbicides: Locations where no weeds were predicted to grow received no herbicide. This prediction was based on the presence or absence of weeds the previous year. The treatment map shows the no-herbicide plots in the middle of the field surrounded by plots receiving medium and high rates. Although this location was predicted to have weeds below the treatment threshold, weed seedlings emerged here the following year. Redistribution of seeds during harvest is probably the main reason for poor estimates in the no-herbicide areas, although other factors, such as seed dormancy and movement of seed by water or animals may also be a factor.

Reduced rates of herbicide

There was a significant difference in weed control among herbicide rates. The no-herbicide plots had the highest number of seedlings, averaging 86 plants per square yard, 2 weeks after the experiment was initiated. The average number of surviving seedlings in the medium-rate plots was significantly lower, nine plants per square yard. The plot with ethalfluralin at the full rate had the least number of weeds (four plants per square yard), but there was no statistically significant difference between the half rate and full rate. All plots receiving the medium or full herbicide rate had weed cover below 10%, 2 and 4 weeks after application.

Black nightshade and hairy nightshade were the only weed species surviving the high-rate treatment in relatively higher numbers. Occasionally, mayweed (*Anthemis cotula* L.), Wright's groundcherry (*Physalis wrightii* Gray) and volunteer tomato (*Lycopersicon esculentum* L.) survived the 1.5 lb. a.i./acre rate of ethalfluralin. Weed species composition after the 0.75 lb. a.i./acre treatment of ethalfluralin was similar, but also included a few surviving seedlings of lambsquarters. Weed composition on plots that received no herbicide resembled the 1999 weed survey and included barnyardgrass, black nightshade, hairy nightshade, redroot pigweed, annual sowthistle, Wright's groundcherry, cheeseweed (*Malva neglecta* Wallr.), purslane and lambsquarters.

Generally, higher weed-seedling survival after reduced herbicide-application rates is typical. Griffin et al. (1992) reported lower weed control with reduced rates of soil herbicides in soybean fields. Preplant incorporated application of imazaquin at the full rate (0.125 lb. a.i./acre) gave 95% control, whereas the half rate (0.062 lb. a.i./acre) gave 88% control. Greater seedling survival after reduced herbicide rates may be due to the density thresholds used in this study.

For example, Williams et al. (2000) used a reduced rate at or below one seedling per square yard of *Polygonum aviculare* in corn. Norris et al. (2001) recommended economic thresholds of one barnyardgrass plant per 50 feet of tomato crop row. A relatively high weed-density threshold used for the no-herbicide plots was probably responsible for the low success of the no-herbicide approach in this experiment. The threshold for the zero rate was defined as a seedling density below 10 plants per square yard and for mature plants, as less than one weed plant per square yard. Since treatment maps were based on counts of emerged plants, the threshold for the no-herbicide rate should be set to zero weed plants per square yard.

In this experiment, areas treated with the medium rate had about 5% weed cover at 2 and 4 weeks after application and about 12% at 6 weeks; whereas, the high-rate plots had about 2% weed cover at 2 weeks, 5% at 4 weeks and 8% at 6 weeks. Increases in weed cover over time are due to herbicide decomposition in the soil, although ethalfluralin persists for a long time, with an average field half-life of 60 days (WSSA 2002).

High or full herbicide rates should only be applied to high-density weed patches. However, even the full herbicide rate was not able to control weeds in highly infested areas. Other researchers have also observed that weed clumps persist despite uniform full-rate treatment (Dieleman and Mortensen 1999). High weed-density areas may require a slightly higher rate than what is currently considered full rate, assuming crop tolerance is sufficient. Variable-rate herbicide applications could allow higher rates to be applied in high weed-density areas, while still applying less herbicide to the field as a whole.

Since weed distribution within a field is slow to change, maps created in one year may be useful for several years.

Herbicide savings

When the herbicide application was based on the seedling map, 15% of the experimental area did not receive any herbicide and 63% received a medium rate. The treatment map indicated that 2.18 acres of the site were treated with 0.75 lb. a.i./acre, 0.75 acre with 1.5 lb. a.i./acre, and 0.52 acre with no herbicide. A 47% reduction in herbicide use was achieved with the seedling-map approach when compared with a uniform full-rate application. Reduced rates were applied to 78% of the experimental area.

The treatment map that we developed based on mature plants recommended that 1.02 acres of the site be treated with 0.75 lb. a.i./acre, 1.77 acres with 1.5 lb. a.i./acre, and 0.66 acre with no herbicide. Nineteen percent of the experimental area did not receive any herbicide and 30% received the 0.75 lb. a.i./acre rate. A 34% reduction in herbicide use was achieved with the variable-rate application based on a mature-plant weed map when compared with a uniform full-rate application, and 49% of the experimental site received a reduced herbicide treatment.

Since using no herbicide may present too much risk for many growers — particularly in the early stages of adoption for precision weed management — rates may be limited to medium and high applications, in which case the herbicide reduction would have been 39% for the seedling-map and 24% for the mature-map approach.

Time-cost analysis

It took approximately 20 seconds to count mature weeds in each 32-square-yard measurement area. Depending on the level of experience, it would take 2.2 to 6.6 hours to count the weeds in 100 acres (approximately 400 cells). In the variable-rate experiment, a 34% herbicide reduction was achieved with the mature-weed map approach. At a commercial price of $50 per gallon for the herbicide Sonalan, savings were $17. It would take $22 to produce a detailed weed map (at a cost of $10 per hour of labor skilled in weed surveying). In this scenario — based on a mature-weed map — no financial benefits would be achieved. In the case of the weed-seedling map approach, where a 49% herbicide reduction and $24 herbicide cost savings was achieved, plus the approximate $22 cost of a weed map, variable-rate application brings some modest financial benefits of about $2 per acre.

However, we did not account for the conversion of a weed map into an herbicide treatment map in this estimation of economic returns. Our economic analysis should be verified in another study before a firm decision is formed about the economic value of variable-rate technology. The economic efficiency of site-specific herbicide application depends on the cost of herbicide, cost of producing the weed map and treatment map, and the spatial characteristics of the weed population. Since weed distribution within a field is slow to change, maps created in one year may be useful for several years. Additionally, there are research efforts currently examining the use of camera systems to mechanically map weeds, which will likely decrease the cost of weed mapping and improve its accuracy, since a greater portion of the field will be sampled.

Maps reduce application rates

The results from this experiment show that when information about the spatial distribution of the previous year's mature weeds is used, weed control in terms of subsequent weed cover is comparable to uniform one-rate herbicide application, while simultaneously the total amount of herbicide applied decreases.

We conclude that variable-rate spraying based on maps created from estimating weed population density and levels of infestation just before harvest gave the best weed control. However, further improvement is likely when the prediction and modeling of weed-seed redistribution from harvest to application time is incorporated into treatment maps. The simulation of seed movement from the measurement event to herbicide application should be incorporated in any pre-emergent treatment map.

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RESEARCH ARTICLE

Drip irrigation can effectively apply boron to San Joaquin Valley vineyards

William L. Peacock
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Boron deficiency of grapevines occurs occasionally on the east side of the San Joaquin Valley. Its symptoms include shot berries, shoot-tip dieback and leaves with yellowish mottling between veins. Boron must be applied carefully because the range between deficiency and toxicity is narrow. Our research evaluated the safety and efficacy of boron fertigation of grapevines using drip irrigation. Applying boron annually at 1/3 pound per acre to a moderately deficient vineyard elevated tissue levels into the adequate range within 2 years. However, the amount of boron used in a fertigation maintenance program will vary with leaching potential. Blade samples should be routinely monitored following fertigation and fertilizer amounts adjusted accordingly to avoid boron toxicity or deficiency.

While San Joaquin Valley vineyards are currently fertilized with boron through the soil and foliage (Christensen 1986), some growers have expressed interest in applying boron via drip irrigation or "fertigation." Fertigation is a relatively simple, cost-effective and efficient way to apply nutrients. However, irrigation water with more than 1 part per million (ppm) boron can lead to vine toxicity, so the safety of boron fertigation is also a concern. Our research evaluates the safety and efficacy of boron fertigation in grapevines using drip irrigation.

Boron is unique among the micronutrients due to the narrow range between deficiency and toxicity in soil and plant tissues. For grapevines, this range is 0.15 ppm to 1 ppm in saturated soil extracts, and 30 ppm to 80 ppm in leaf tissue. The goal of boron fertilization of grapevines is to keep tissue levels within this narrow range, since both deficiency and toxicity can have serious negative effects on vine growth and production. Fertilization amounts must be precise to avoid toxicity while providing adequate boron to satisfy grapevine requirements (Christensen et al. 1978; Christensen and Peacock 1998).

On the east side of the San Joaquin Valley, boron deficiency of grapevines occurs on soils formed from igneous rocks of the Sierra Nevada. This parent material is low in total boron, which is crystallized in borosilicate minerals that are highly resistant to weathering. Boron deficiency is often associated with sandy soils and vineyard areas with excessive leaching, such as in low spots or near leaky irrigation valves. Vine symptoms of boron deficiency are more widespread and pronounced following high rainfall years, when greater amounts of soluble boron are leached from the root zone. In addition, snowmelt water has very low levels of boron, and vineyards irrigated primarily with this water have a greater risk of deficiency.

Boron is required for the germination and growth of pollen during flowering, and vines that are deficient in this micronutrient will have clusters that set numerous shot berries, small berries with a distinctive pumpkin shape. When boron deficiency is severe, vines produce almost no crop. Foliar symptoms appear in the spring: shoots have shortened, swollen internodes and their tips sometimes die, and leaves have irregular, yellowish mottling between the veins.

Grapevines are also sensitive to too much boron. Toxicity is common on the west side of the San Joaquin Valley, where most soils are derived from marine sedimentary and metasedimentary parent material that is rich in easily

The goal of boron fertilization of grapevines is to keep tissue levels within a narrow range, since both deficiency and toxicity can have serious negative effects on vine growth and production.

Boron-deficient vines have, *facing page, bottom*, clusters that set numerous shot berries, small berries with a distinctive pumpkin shape; or, *facing page, top*, calyptras that stick on young, developing berries. *Above*, shoots have shortened and swollen internodes, and shoot tips sometimes die.

weathered boron minerals. Symptoms of boron toxicity include leaves that are cupped downward in the spring and that develop brown spots adjacent to the leaf margin in middle or late summer, intensifying and leading to necrosis as boron accumulates. Yields are reduced, the result of diminished vine vigor and canopy development. When foliar boron sprays are applied in excess in the spring, juvenile leaves become cupped within 2 weeks; however, vines quickly recover and yields are usually unaffected.

Toxicity also occurs when boron fertilizer is applied in excess, regardless of the soil type, and this can lead to yield loss. Over-fertilization is the sole reason for boron toxicity on the east side of the San Joaquin Valley, so it is critical to establish how much boron fertilizer can be applied safely and effectively. Our research investigated the uptake of boron by grapevines when fertilizer was applied with a drip-irrigation system.

Measuring boron in grapevines

Research was conducted from 1998 to 2001 in a mature 'Thompson Seedless' raisin vineyard near Woodlake in Tulare County. The vineyard was planted in Cajon sandy loam on a recent alluvial fan associated with the Kaweah River. This soil is derived from granitic parent materials, and the surface soil is highly micaceous with a slight to moderate amount of lime. The underlying soil (2 to 3 feet deep) has a coarse, sandy texture.

At the onset of this study, the vineyard's boron status was in the questionable range for deficiency. The vine's leaf petioles and blades contained about 30 ppm boron. While the foliage had no symptoms of boron deficiency, in the past the grower had observed sticking caps and pumpkin-shaped shot berries, which are indicative of boron deficiency. During the course of the research, the vineyard was drip-irrigated from April through October. The vineyard canopy covered 60% of the land surface during summer months and about 20 inches of water was applied during the season.

Boron treatments consisted of applying fertilizer in varying amounts 3 weeks prior to bloom on May 18, 1998, and then again 3 weeks prior to bloom the following year, on May 3, 1999. Growers who fertigate grapevines with a drip system generally inject material into the irrigation water over a 45-to-60-minute period at the beginning of an irrigation set. We simulated fertigation by applying Solubor, a soluble boron product (20.5% boron), to a shovel-sized hole beneath drippers during the first hour of the irrigation set. By doing this, precise amounts of boron could be applied to each plot (the issue of dripper emission uniformity was eliminated) and plot size could be reduced. This technique has been used successfully in previous research with other nutrients (Christensen et al. 1991; Peacock et al. 1991). The experiment was designed as a randomized complete block with five treatments, five blocks and five vine plots (table 1).

TABLE 1. Actual pounds of boron applied* per acre over 2-year treatment period, 1998 and 1999

Treatment	1998	1999	Total
		lb.	
1	0	0	0
2	1/3	1/3	2/3
3	2/3	2/3	1 1/3
4	1	1	2
5	1/6	2†	2 1/6

* To determine the pounds of Solubor applied, multiply the actual boron rate by 4.9.

† The 2-pound rate was applied to evaluate potential toxicity.

To evaluate the rate of boron uptake and accumulation in tissue with consecutive years of fertilization, grape tissue samples were collected in 1998 and 1999 at bloom and then again about 6 weeks later during veraison. Veraison is the stage of development where berries begin to soften and/or color. To evaluate carryover, leaf tissue samples were also collected at this Tulare County site at both bloom and veraison in 2001, 2 years after the fertilization was discontinued. In each case, 100 petioles and 50 blades were sampled per plot from the center three vines. Petioles and blades were taken opposite inflorescences during bloom, and recently matured leaves were sampled at veraison. Samples were oven-dried, ground in a Wiley mill and sent to the UC Davis DANR Analytical Laboratory for analysis of total boron. Statistical analysis was by ANOVA using least

TABLE 2. Blade levels at bloom and veraison, following boron fertigation applied 3 weeks prior to bloom in 1998

Treatment	Cajon sandy loam (Tulare Co.)		Pollaski sandy loam (Fresno Co.)	
	Bloom	Veraison	Bloom	Veraison
actual boron, lb/acre		*ppm*		
Unfertilized control	31a*	32a	40a	48a
1/3	33ab	40ab	48ab	53a
2/3	38b	43bc	54b	60ab
1	39b	49c	58b	70b
1/6	31a	38ab	——	

* LSD$_{.05}$: means with common letters not significantly different.

TABLE 3. Boron in leaf tissue after 2 consecutive years of fertigation, Tulare County vineyard

Treatment	Bloom		Veraison	
	Petiole	Blade	Petiole	Blade
actual boron, lb/acre		*ppm*		
Unfertilized control	29a*	36a	31a	35a
2/3 lb. (1/3 lb. each year)	32b	46ab	36b	45b
1 1/3 lb. (2/3 lb. each year)	34b	53bc	38b	54c
2 lb. (1 lb. each year)	37c	62c	41c	61cd
2 1/6 lb. (1/6 lb. then 2 lb.)	39c	59c	41c	68d

* LSD$_{.05}$: means with common letters not significantly different.

significance difference to separate treatment means.

A second experiment was conducted in 1998 in Fresno County near Selma, in a mature Thompson Seedless raisin vineyard planted on Pollaski sandy loam and drip-irrigated. The soil was formed in place from the weathering of softly to moderately consolidated granitic sediments. The particle size distribution of the surface soil is 63% sand, 25% silt and 12% clay. At the onset of the experiment, boron tissue levels were in the adequate range, 40 ppm.

In both experiments, drip irrigations during the season were based on a schedule using historical evapotranspiration and developed for raisin vineyards in the San Joaquin Valley (Peacock et al. 1987; Peacock et al. 1998). The irrigation source was high-quality pump water with a boron concentration less than 0.1 ppm. The experimental design and methods were identical in both vineyards, except that the 1/16-pound-per-acre boron treatment was omitted in the second (Fresno County) vineyard. The Fresno County trial was discontinued after tissue samples were taken at bloom and veraison in 1998.

Boron uptake

At both the Tulare and Fresno county sites, boron uptake was rapid when fertilizer was applied in the spring. In both vineyards, applying boron at 2/3 or 1 pound per acre increased the boron concentration in blades by bloom, 3 weeks after application. Boron increased further in blades by veraison (table 2). In the Tulare County vineyard, boron in bloom tissue increased from a questionable deficiency range to adequate; at the Fresno location, boron in bloom tissue increased from 40 ppm to 54 ppm, a dramatic increase considering boron fertilizer was applied just 3 weeks prior. This indicates that boron uptake is rapid. None of the fertigation treatments resulted in either symptoms of boron toxicity or deficiency. Applying boron at 1/3 pound per acre or less did not significantly increase boron tissue levels by bloom or veraison at either site the first year.

Fertigation over consecutive years was evaluated at the Tulare County location. Boron in grapevine tissue continued to increase with consecutive years of application. At the higher fertilizer rate (1 pound boron per acre), boron levels in blades increased from 35 ppm in control vines to about 60 ppm. We speculate that continuing with annual applications of 1 pound boron per acre would result in toxicity within 4 to 5 years. The 1/3-pound-per-acre rate significantly elevated boron in blades by veraison of the second year to adequate levels (table 3). There were no visual signs of toxicity in any of the fertilizer treatments, even when boron was applied at 2 pounds (9.8 pounds Solubor) per acre in a single application.

Boron levels in tissue remained unchanged 2 years after fertilization was discontinued at the Tulare County location (fig. 1). This indicates substantial treatment longevity with fertigation of a drip-irrigated vineyard. Rainfall during this experiment was below normal, which helped minimize leaching. Also, well-managed drip irrigation minimizes leaching. Under drip irrigation, salts tend to accumulate near the soil surface and 2 to 3 feet away from the drip line, with minimal water and salt movement below the root zone when irrigations are accurately scheduled (Peacock 2004).

Boron concentrated more in the blades than in the petioles in response to fertilization. At the onset of the Tulare County experiment, boron concentrations in petioles and blades were similar at 31 ppm and 34 ppm, respectively. Fertilizing with 1 pound boron per acre for 2 consecutive years resulted in a 25% increase of boron in petioles but a 76% increase in blades (fig. 2). All

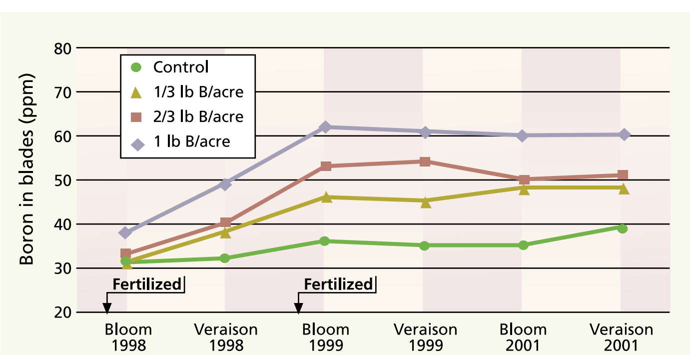

Fig. 1. Boron in blades is sustained 2 years after fertigation, indicating excellent carryover with drip irrigation.

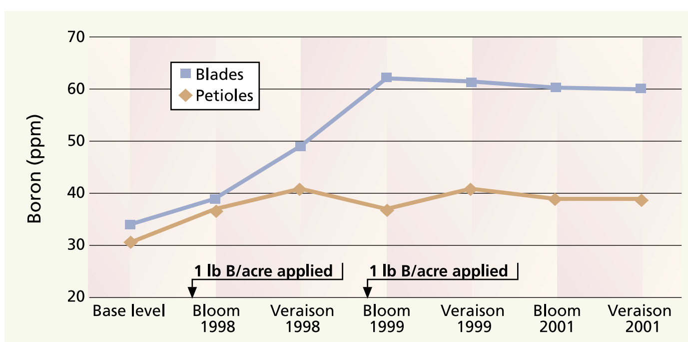

Fig. 2. Boron accumulated more in blades than in petioles following fertigation.

fertilizer treatments increased boron in blades more than in petioles, indicating that blades should be sampled when monitoring the vines' boron status following fertilization. Potential boron toxicity values at the time of sampling during the bloom period are 80 ppm for petioles and 120 ppm for blades, and in mid- to late summer are 100 ppm for petioles and 300 ppm for blades.

Leaching and treatment longevity

Annual boron fertigation at 1/3 pound per acre elevated grapevine tissue levels from questionable to the adequate range within 2 years (Tulare County location). In addition, tissue boron levels remained unchanged 2 years after fertilization was discontinued. This is probably because leaching was reduced by two factors: below-normal rainfall and accurately scheduled drip irrigations. After fertilization, boron was concentrated more in blades than in petioles, indicating that blades are the best choice for monitoring toxicity. Blade samples should be monitored on a routine basis and fertilizer amounts should be adjusted accordingly to avoid boron toxicity or deficiency.

The results of this research can be applied to other drip-irrigated vineyards in the San Joaquin Valley under similar conditions: rapidly drained soils, high-quality irrigation water, and low boron content in soil, water and vine tissue. In other regions of the state where winter rainfall is much higher, there would presumably be more leaching of boron fertilizer during winter months and less carryover time after fertilization is discontinued. In contrast, less leaching and greater carryover of boron would be expected in areas of less rainfall or on soils with finer texture and higher water-holding capacity. The amount of boron fertigation used in a maintenance program will vary with leaching potential. These variables underscore the importance of monitoring boron in tissue when developing a long-term fertilization program.

Symptoms of boron toxicity include leaves that are cupped downward with necrotic margins on mature leaves.

Solubor, a soluble boron product (20.5% boron), was applied to an excavation beneath drippers to simulate fertigation at varying amounts and timing.

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COMINGUP

On Dec. 23, 2003, the first U.S. case of bovine spongiform encephalopathy (BSE, or "mad cow disease") was confirmed in a Holstein cow from Mabton, Washington state. The farm, *above*, was quarantined by state officials.

Testing for mad cow disease

On June 24, 2005, the U.S. Department of Agriculture confirmed a second case of bovine spongiform encephalopathy (BSE), also known as "mad cow disease," in the United States. After the first case was confirmed on Dec. 23, 2003, more than 30 countries quickly closed their borders to U.S. beef, directly affecting 10% of U.S. production. To protect the U.S. meat supply and reassure trade partners, USDA moved to significantly tighten existing rules and restrictions regarding BSE, and to introduce new policies and practices. With the second case, attention is now being refocused on the critical, and controversial, question of how to test cattle for BSE. In the next issue of *California Agriculture*, UC scientists explore the ongoing policy debate over testing U.S. cattle for BSE. In addition, a laboratory study compares two technologies for detecting bovine byproduct contamination of cattle feeds, believed to be the main avenue for BSE transmission.

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