OCTOBER–DECEMBER 2008 • VOLUME 62 NUMBER 4

California Agriculture

Wine grapes go green

The Sustainable Viticulture Issue

University of California | Peer-reviewed Research and News in Agricultural, Natural and Human Resources

SUSTAINABLE VITICULTURE

Wine grapes go green


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The Sustainable Viticulture Issue

Cover: The grape-growing industry, in partnership with UC scientists, has aggressively promoted sustainable viticulture practices that are environmentally friendly, economically viable and socially responsible. In the Carmel Valley, a wine-grape vineyard shows its fall colors. *Photo: David Gubernick/ AGStockUSA*

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Editor's note

California Agriculture gratefully acknowledges the faculty co-chairs for this special issue: Deborah Golino, director of Foundation Plant Services (FPS), and James Wolpert, viticulture specialist, both at UC Davis. We also thank FPS and Viticulture Consortium West for providing funds to defray the costs of its expanded length.

About California Agriculture

California Agriculture is a quarterly, peer-reviewed journal reporting research, reviews and news. It is published by the Division of Agriculture and Natural Resources (ANR) of the University of California. The first issue appeared in December 1946, making it one of the oldest, continuously published, land-grant university research journals in the country. The circulation is currently about 15,000 domestic and 1,800 international.

Mission and audience. *California Agriculture*'s mission is to publish scientifically sound research in a form that is accessible to a well-educated audience. In the last readership survey, 33% worked in agriculture, 31% were faculty members at universities or research scientists, and 19% worked in government agencies or were elected office holders.

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California Agriculture

Peer-reviewed research and news published by the Division of Agriculture and Natural Resources, University of California

VOLUME 62, NUMBER 4

6701 San Pablo Ave., 2nd floor, Oakland, CA 94608
Phone: (510) 642-2431; Fax: (510) 643-5470; calag@ucop.edu
http://CaliforniaAgriculture.ucop.edu

California Agriculture (ISSN 0008-0845) is published quarterly and mailed at periodicals postage rates at Oakland, CA, and additional mailing offices. Postmaster: Send change of address "Form 3579" to *California Agriculture* at the address above.

Editorial overview

Karen Ross
President
California Association
of Winegrape Growers

Deborah Golino
Director
Foundation Plant Services,
UC Davis

Wine grapes go green: THE SUSTAINABLE VITICULTURE STORY

Wine grapes and wine are among California's signature products, and they fuel a powerful economic engine in the state. Each year, 20 million tourists roam the state's wine regions, tasting, purchasing and taking in the beauty of the landscape. California, which produces 90% of the nation's wine supply, generates revenues of $19 billion a year for wine and wine grapes alone. The full economic impact of California wine is $51.8 billion a year.

However, the story of California viticulture — and particularly the story of sustainable wine-grape growing — is about more than productivity, wine country tours, or dollars and cents.

Beginning in the early 1990s, winegrowers worked together to make groundbreaking commitments to agricultural-environmental partnerships. They invested time, money and energy in adopting sustainable practices — sustainable not only in terms of the bottom line, but in terms of California water, soil, wildlife, conditions for workers and community-farmer relationships.

Wine grapes are cultivated on some of the most sensitive acres in the state, in areas of high population growth, high land values and environmental activism. Vineyards are part of scenic landscapes prized by Californians; they border urban and suburban development, and they are adjacent to abundant and diverse wildlife.

Growers and winemakers realized early that they could have a positive impact on this environment and their employees, and that their credibility in the wider community, outreach to neighbors, and market reputation would be strengthened through efforts to establish sustainable practices. Through early adoption by groups such as the Lodi Winegrape Commission (page 142), the Central Coast Vineyard Team, the Napa Sustainable Winegrowing Group, Fish Friendly Farming, and later through the statewide Sustainable Winegrowing Program created by the California Association of Winegrape Growers and the Wine Institute, they have promoted sustainability both in the vineyard and the winery. Their innovative efforts are now prototypes for other commodities.

Research promotes sustainable practices. Decades of UC research and extension have helped to facilitate sustainable viticulture. Growers applied years of research results to the specifics of their local production regions (see page 127). They implemented leaf removal and canopy management to control several key pests such as *Botrytis* bunch rot, sour rot complex, powdery mildew and leafhoppers; they used cover crops to improve year-round vineyard access, reduce soil erosion and encourage populations of natural enemies of pests. They adopted integrated pest management methods, using economic injury thresholds and weather data, as well as models of disease risk forecasting, to reduce pesticide use. For instance, growers were able to sharply cut their use of sulfur and other pesticides to control powdery mildew, the disease that spurs the bulk of pesticide use on grapes.

By 2006, statewide reports showed that total pesticides applied to wine grapes had declined 50% per acre planted since 1994 (see page 133). Also, according to their self-assessments, growers reduced sedimentation and pesticide pollution of water, managed dust and improved air quality, and reduced herbicide and fungicide use.

But the drive for sustainability is not over. The competitive global marketplace, continued population growth, global climate change, scarce natural resources, the need for new technology and human resource skills — all make UC research, from basic to applied, even more important if industry is to continue innovating and adopting best practices. Evidence of this ongoing work fills this special collection: work on stream-flow models to ease irrigation impacts (page 148), biological and chemical control of mealybugs and ants (pages 167, 177), improved techniques for the detection and elimination of grapevine viruses (pages 156, 161), vineyard floor management and use of cover crops (page 184, 191), and tailoring fertilization to cut costs and reduce nutrient pollution in runoff (pages 195, 202).

These examples — all involving long-term funding, commitments by distinguished scientists, collaboration across disciplines, use of UC facilities and infrastructure, and partnerships with industry — are at the heart of winegrape sustainability. This work has taken place at a time when public funding for agricultural research has been steadily declining for years. In most cases, it was made possible by a combination of public and private funds.

Public-private partnerships. Other recent milestones in public-private partnerships include the UC Davis Robert Mondavi Institute for Wine and Food Science, first established in 2001 with a $25 million gift from winemaker Robert Mondavi. In 2004, California voters funded $33.6 million for construction of the institute's academic building, and more private gifts followed. In summer 2008, the departments of Viticulture and Enology, and Food Science and Technology moved in. In June 2009, construction will begin on a teaching and research winery and the August A. Busch III Brewing and Food Science Laboratory, entirely funded with private donations.

Another $12.5 million donated to UC Davis by the Rossi family will endow faculty positions focused on grape-growing and winemaking, and will fund work on sustainable viticulture and enhancing the flavor of grapes and wine.

The Pierce's Disease/Glassy-Winged Sharpshooter Program, funded by industry, federal and state dollars, has fostered dramatic findings that could someday lead to prevention of this fatal bacterial illness of grapevines (page 127). In the last 10 years, about $36 million has been awarded in competitive grants reaching across the UC system, the United States and the world. Resulting UC research has made strong advances toward disease-resistant vines, and in another case has elucidated a signal molecule that could be used to suppress the virulence of the pathogen and offer substantial disease control.

A broad public-private coalition brought about success of another kind in the 2008 Farm Bill. Thanks to a unified effort across commodity groups and the research community, millions of dollars are now being invested in specialty crop initiatives at USDA and through state-run block grant programs.

The Farm Bill contains other big wins that directly benefit the grape industry and move it closer to sustainability, including the National Clean Plant Network (the grape portion of which will be headquartered at UC Davis) and pest and disease programs to step up detection and surveillance activities, and identify and mitigate new threats from invasive species. Without a united message from industry and the land-grant universities, none of this would have been possible.

Funding needs. Despite these successes, the funding currently available for grape and wine research is no longer sufficient to support needed projects in an increasingly expensive research environment, or to meet matching-fund requirements for new Farm Bill research programs. Many key types of research cannot be accomplished without large, multidisciplinary research teams, advanced instrumentation and updated laboratories, in addition to technicians and field trials. All require long-term funding commitments. Furthermore, competition for researchers has also become global; the United States is losing valuable individuals in the wine research community to positions in institutions around the world where their research will be better supported (often with government investment). Real and substantial increases in funding are needed to improve our position in California. That research must involve collaboration between disciplines and integrated investigations from the basic to the applied.

Sustainability is about meeting the needs of the present without compromising the livelihood and needs of future generations. Today's robust viticulture industry is the result of visionary leaders willing to make investments for the future and create partnerships between UC research and extension, and growers and vintners. Building on this past success, diverse stakeholders are exploring ways to ensure a vital research infrastructure is adequately funded to meet our current challenges and the needs of upcoming generations. The future depends on it!

Research fuels sustainable viticulture revolution

Beverly Ferguson

Foundation Plant Services staff members Sue Sim (sitting, left) and Waclawa Pudo shared information with grape nurseryman Craig Stoller and his wife Nancy about technology used to create collections of disease-screened strawberries, grapes, fruit and nut trees and other plants, during the FPS 50th anniversary celebration on July 1, 2008.

Spurred by decades of University of California research, sustainable viticulture has become increasingly mainstream in California. Sustainability helps both the environment and wine-grape growers, with benefits that range from reducing agrichemicals that pollute water and harm wildlife to cutting costs, enhancing wines and boosting public perception of the industry.

"Sustainability is a big tent," says Deborah Golino, director of the UC Davis-based Foundation Plant Services, which certifies disease-free grape stock and which celebrated its 50th anniversary in July 2008. "Some sustainable practices are driven by environmental regulations, and more are driven by green marketing and stakeholders wanting to be good stewards of the land."

For the wine industry, economic benefits are key. "The bottom line is that sustainability has to work in a business model," says Karen Ross, president of the California Association of Winegrape Growers. "The fundamental reasons to change practices are increasing quality and marketability, and decreasing costs." This industry group represents more than half of the state's grape crush and actively promotes sustainability, defining it as economically viable, environmentally sound and socially responsible.

What's good for the wine industry is also good for California, Ross says. About 4,600 wine-grape growers farm more than 520,000 acres in 46 counties statewide, and about 2,000 wineries produce more than 90% of wine nationwide. Altogether the wine industry pumps close to $52 billion yearly into the California economy.

To help keep wine-grape growers in the sustainability loop, Golino maintains several comprehensive viticulture Web sites. "People in industry don't always know where to look," she says. "We want to let everybody know how much UC is doing" (see box).

The implementation of sustainable viticulture has been spurred by important research-based advances that have been extended to grape growers.

Leaf removal for bunch rot

One of the most widely adopted sustainable practices, leaf removal to control bunch rot and improve grape quality, was developed in the 1980s by Douglas Gubler, UC Cooperative Extension (UCCE)

Subject Millardet et de Grasset 101-14
Description
Common synonyms: 101-14 Mgt
Species: Interspecific Cross
Country of origin: France
Breeder: Millardet
Year released: 1882
Pedigree: V. riparia x V. rupestris

About UC Integrated Viticulture Online

This website is designed and maintained by the University of California (UC) Division of Agricultural and Natural Resources (ANR) Integrated Grape Production Workgroup to increase accessibility to the work of UC researchers, including faculty, Cooperative Extension (CE) specialists, CE advisors, and staff.

10/25/08 ESTABLISHING THE SMALL VINEYARD
11/10/08 FPS ANNUAL MEETING
11/13/08 CURRENT ISSUES IN VINEYARD HEALTH
11/13/08 SUSTAINABLE AG EXPO
01/27/09 UNIFIED WINE AND GRAPE SYMPOSIUM
06/22/09 ASEV 60th ANNUAL MEETING

Web sites organize sustainable grape-growing info, research grants

Deborah Golino, director of Foundation Plant Services at UC Davis, has set up and runs several comprehensive, Web sites to organize critical information for wine-grape growers and viticulture researchers. "Wine-grape growing is complicated by the sheer number of clones and varieties available and the fact that each variety can have multiple names, plus the abundance of information on pest, weed and disease management," Golino says. "These sites can help."

The National Grape Registry (http://ngr.ucdavis.edu) enables growers to access information for all grape varieties available in the United States. Growers can find out which nurseries carry a particular variety or clone — the first time there has been a central site to answer this question. There is also a special search feature that allows users to sort through multiple names (or synonyms) for grape varieties.

UC Integrated Viticulture Online (http://iv.ucdavis.edu) makes UC research more accessible, listing grape researchers, a calendar of upcoming events and information about grape-growing topics in 30 categories, including diseases, rootstock and vineyard economics.

Viticulture Consortium West (http://vcw.ucdavis.edu) and **Unified Grant Management for Viticulture and Enology (http://uvegrants.ucanr.org)** coordinate grape-growing research programs and grant-making for experiment stations and universities in the Western states, as well as in Oklahoma and Texas.

Also of interest: **California Association of Winegrape Growers (www.cawg.org)** and **California Sustainable Winegrowing Alliance (www.sustainablewinegrowing.org).**

plant pathologist at UC Davis; Larry Bettiga, UCCE viticulture advisor in Monterey County; and Jim Marois, UC Davis plant pathologist. “We stumbled onto it — we were originally looking at how canopy management affected spray coverage,” Gubler says. “We found that leaf removal controlled bunch rot better than three fungicide applications.”

Caused by the fungus *Botrytis cinerea*, bunch rot infects grape berries through wounds or even directly though the skin. Once a grape is infected, if conditions are favorable the fungus spreads rapidly to infect the rest of the cluster. This type of bunch rot afflicts vineyards in cool moist areas, notably those along the coast, in the marine-influenced northern San Joaquin Valley and in the southern San Joaquin Valley (table grapes).

The technique entails removing leaves around grape clusters when the berries are just formed or the blossoms have just dried. This allows increased light penetration, decreased relative humidity and increased wind speed through the canopy. Berries dry more rapidly after rainfall, warding off or stopping infection. In addition, this technique can decrease leafhoppers and mites, because these pests are concentrated on the basal leaves that are removed. Leaf removal also exposes clusters to sunlight, which further increases bunch rot resistance by thickening the berry’s epicuticular wax layer. Another benefit of sun exposure is that it increases berry quality and therefore wine quality.

(*Eutypa* and bunch rot) William J. Moller; (Bot canker) iv.ucdavis.edu; (mildew) Jack Kelly Clark

UC researchers have developed environmentally friendly treatments for several important grape diseases. *Top left*, basic research has shown that many wood infections diagnosed as *Eutypa* dieback were actually *Botryosphaeria* canker disease; *bottom left*, the spread of Bot canker can be slowed down by double-pruning in winter and early spring; *top right*, to ward off bunch rot, leaves around clusters can be removed as berries form; *bottom right*, the Powdery Mildew Index uses weather data to help growers spray fungicide only when necessary.

In the late 1980s, Gubler and colleagues showed that machine leaf removal could control bunch rot as effectively as hand-removal, making the technique feasible for large acreages of wine grapes. By 1990, leaf removal was practiced on about one-fifth of the state’s bunch rot–susceptible wine grapes, decreasing fungicide use by at least half. Today leaf removal is widespread in most of California’s production regions and also around the world. “It’s working really well in disease control and increases quality,” Gubler says.

Powdery mildew control without sprays

Another successful tool for controlling grapevine diseases sustainably is the UC Davis Powdery Mildew Index. Also called the Gubler-Thomas Index, this approach was developed in the 1990s by Gubler and then–lab member Carla Thomas. Caused by the fungus *Erysiphe necator*, powdery mildew is among the worst grapevine diseases in California. The fungus occurs in all grape-growing regions of the state and accounts for most vineyard pesticide use. Infected leaves are covered by a web of white strands that bear dustlike spores, giving the disease its name. Powdery mildew can also cause grape berries to crack, allowing *Botrytis cinerea* to infect through the injured tissue. In addition, as little as 3% infection of berries can produce off-flavors in wine.

Powdery mildew is a fact of life for grape growers. “We can’t eradicate the pathogen,” Gubler says. “They just have to expect it.” While the infection varies over the course of a growing season and from year to year, its inevitability and huge potential for crop destruction led many growers to spray fungicides on a fixed schedule, whether they needed to or not. This was because they could not tell when powdery mildew would strike initially and when it would spike over the course of the growing season.

“The disease is driven by moderate temperatures and rainfall,” Gubler says. The team developed a model to predict the onset and severity of powdery mildew in vineyards. The onset of infection is predicted based on temperature and leaf wetness, and its subsequent severity is predicted based solely on temperature. In 1995 the researchers validated their model in Kern, Napa and Sonoma county vineyards, using networks of weather stations that were established with a grant from the UC Statewide Integrated Pest Management (IPM) Program as well as grower contributions.

Today the UC Statewide IPM Program offers an online Powdery Mildew Index (PMI) for Fresno, Madera and San Joaquin counties. In other parts of the state, grape growers can either subscribe to private online PMI services or buy their own weather stations. Following the PMI lets growers spray only when necessary, which can add up to substantial cost savings. “At $40 per acre, eliminating three sprays a year on 5,000 acres is a big savings,” Gubler says. “Spraying less also reduces environmental concerns about pesticide use.”

To assess implementation of the PMI, Gubler and Travis Lybbert, an agricultural economist at UC Davis, surveyed growers in early 2008. For the first few years after the PMI was introduced, less than one-third of growers used it. Today more than half do. Participating growers generally are more experienced, manage larger vineyards they are less likely to own, and produce higher-value grapes. Reasons for not using the PMI included not trusting it. “It’s hard to change,” Gubler says. “They’re nervous about stretching the interval between sprays.” To build trust, he encourages growers to start small, setting aside 5 acres for following the PMI while spraying the rest as usual. “Once they start, they really get hooked,” he says. “People who use it love it.”

Grape growers will soon have more reason to use the PMI than ever. “We’re refining it,” Gubler says. “Right now it errs on the side of caution and we’re making it less conservative, which means growers will be able to reduce spraying quite a bit more.”

Double-pruning for canker disease

Gubler and his colleagues also recently developed yet another widely adopted sustainable practice: double-pruning to control canker diseases. These fungi infect pruning wounds, and ultimately so much wood that grape production declines, necessitating early vineyard reworking or replacement. The infection is insidious, often escaping detection for 8 to 10 years until wedge-shaped cankers are evident in the trunk or arms. The most common canker diseases in California vineyards are Bot canker (see page 161), and Eutypa dieback. A decade ago losses to the latter were estimated to exceed $260 million statewide.

To clarify the causes of canker diseases in California, Gubler’s team identified the fungi in infected wood samples from 180 vineyards around the state between 2004 and 2007. They found that contrary to the conventional wisdom, Bot canker is more common than *Eutypa* dieback, which afflicted 90% and 55% of the study vineyards, respectively. They also identified nine species of *Botryosphaeria* causing Bot canker and found that four of these grow much faster than the others. “They grow up to 10 or 12 inches a year compared to about an inch with *Eutypa*,” Gubler says. “They can kill wood fast.”

The best way to limit canker diseases is pruning in early spring, when the wounds heal faster and also “bleed” and wash away the fungal spores. But this is not feasible in large vineyards because pruning is so labor-intensive. Gubler’s team got around this by doing the bulk of the pruning in winter and then snipping off a bit more in early spring. The second cut doesn’t take much time and removes any wood that may have gotten infected after the first cut. Gubler estimates that a high percentage of vineyards in the Napa Valley are now double-pruned. “It’s gaining every year,” he says.

Double-pruning on its own is not enough to prevent canker diseases, however, because wounds from spring pruning can still be susceptible to infection. Gubler found that painting these wounds with a boron paste could keep them virtually infection-free for up to 6 weeks. “It’s a great treatment,” he says, noting that boron is a natural, nontoxic compound. This work has resulted in a commercially available wound treatment called B-LOCK. Another promising treatment is painting vines with latex paint (see page 161).


Miguel Altieri

In Napa Valley, researchers are studying the use of summer cover crops such as alyssum planted under the vines with a buckwheat-phacelia seed mix in the middles. Early monitoring has shown that beneficial insects are attracted to the vineyard.

Following the Powdery Mildew Index lets growers spray only when necessary.

Biocontrol for vineyard pests

Other sustainable practices target the weak points of pest insects. A likely approach to controlling vineyard pests is planting summer cover crops, according to a UC study currently under way in Napa and Sonoma counties. Cover crops provide food and shelter for beneficial insects such as minute pirate bugs, which eat thrips, and Anagrus wasps, which are tiny parasites that lay their eggs inside leafhopper eggs. However, most wine-grape growers plant cover crops during the winter (see pages


Jack Kelly Clark

Cultural practices such as strategic pruning to prevent grapevine diseases are increasingly being adopted by grape growers throughout California.

184 and 190), which means that insect pests have fewer natural enemies during the summer. “Some growers are spraying insecticides several times a season,” says study leader Miguel Altieri, an agroecologist at UC Berkeley. “This increases the expense and the environmental impact.”

Altieri is testing two summer cover crops on 1- to 2-acre test plots in seven vineyards. The first summer cover crop is sweet alyssum, which is planted along drip-irrigated rows. Sweet alyssum is small with shallow roots and so does not compete with grapevines for water, nutrients and sunlight. The second is a seed mix planted between the rows, where there is no irrigation. The seed mix ensures continual blooming with no extra water: buckwheat and phacelia bloom from late March to June, and wild carrot (or Queen Anne’s lace) blooms for the rest of the season due to its taproots.

To see how well summer cover-cropping works, the researchers monitor both the pest and beneficial insects. The study began last year and so far is promising. “The results are pretty dramatic,” Altieri says. For example, last summer the plots with the buckwheat seed mix exhibited substantially fewer leafhopper nymphs than plots under organic insecticide sprays.

Altieri works closely with growers, sharing the data with them monthly. Pest control has been so effective that a participating grower plans to expand the cover-cropped area to 10 acres next year. Ultimately, Altieri envisions scaling up the study to include 10- to 20-acre test plots in 50 vineyards by the end of 2010.

Altieri also involves the participating vineyards by training farmworkers in Spanish to identify the various insects. This lets the farmworkers help monitor the insects, which benefits both the researchers and the workers themselves. “They’re very excited,” Altieri says. “They enjoy doing something more intellectual plus they know this could reduce their pesticide exposure.”

Pest-resistant rootstocks

Another way of decreasing pesticide use in vineyards is to breed pest-resistant rootstocks. Many of the currently available rootstocks are susceptible to nematodes, tiny soil worms that eat plant roots. Nematodes plague grapevines in the Central Coast and San Joaquin Valley, where vineyards were often planted following vegetable crops that had high levels of these pests. State regulations limit chemical treatments, and UC has provided growers with the environmentally friendly option of planting five new nematode-resistant rootstocks.

“Resistant rootstocks are the best solution now that fumigants are almost gone and nematicides are on their way out, as they should be,” says

Sustainable Ag Expo to feature research, best practices

The Fourth Annual Sustainable Ag Expo will feature trade exhibits and programs to help growers and ranchers maintain economic viability while also protecting the environment and promoting healthy communities. “Farmers of all crops and commodities can learn about sustainable farming methods,” says Kris O’Connor, executive director of the Central Coast Vineyard Team, sponsor of the Expo.*

Expo seminars will focus on best management practices to protect water quality, alternative energy sources, erosion control and integrated farm management practices, including reduced-risk pest control and whole-farm practices. Among speakers from government, agriculture and academia, featured UC researchers include:

- Michael Cahn, UC Cooperative Extension farm advisor.
- Trevor Suslow, UC Davis extension research specialist.
- Jay Gan, UC Riverside professor.
- Gail Feenstra, UC Sustainable Agriculture Research and Extension Program.
- Andy Walker, UC Davis professor.
- Jean-Jacques Lambert, UC Davis soil science scientist.

What: Sustainable Ag Expo
When: Nov. 13 and 14, 2008
Where: Monterey County Fairgrounds
More info: www.sustainableagexpo.org

**California Agriculture* journal is a media partner with the Sustainable Ag Expo.

Andrew Walker, UC Davis geneticist who developed these rootstocks over 15 years. “It’s either use these or other resistant rootstocks or don’t grow grapes in areas with nematode buildup.”

Released in April 2008, these rootstocks were derived from multiple parents that each resist different kinds of nematodes, including dagger, lesion and root-knot. “We bred them to be as resistant as possible,” Walker says. Even so, he expects that these pests may eventually adapt. By rotating among the five types, however, growers should be guaranteed a long period free of nematode problems.

Walker is also developing wine grapes that resist powdery mildew and Pierce’s disease, a fatal bacterial illness spread by sharpshooters. These projects entail breeding commercially grown wine grapes (*Vitis vinifera*), which are native to the Mediterranean, with disease-resistant wild North American grapes. To get as close to wine grapes as possible, disease-resistant hybrids are selected and then repeatedly crossed back to pure wine grapes. This backcrossing increases the ratio of wine grape-to-wild grape in the successive hybrids while retaining their disease resistance. The powdery mildew project is still in early stages, while the Pierce’s disease project has made strong advances. “We have good fruit quality and Pierce’s disease resistance,” Walker says. “After one more backcross, we’ll be at 96% *Vitis vinifera* and we’ll test those by evaluating for wine quality.”

In other research, UC Berkeley plant pathologist Steven Lindow has discovered a signaling system involving the secretion of a small molecule produced by *Xylella fastidiosa*, the cause of Pierce’s disease. This molecule is involved in the suppression of *Xylella* virulence when cells become abundant in the plant. Artificially increasing the abundance of this signal molecule in various ways, including the use of plants that have been genetically engineered to produce it, has led to the suppression of virulence of the pathogen and Pierce’s disease control. Extensive greenhouse tests are under way, but field studies will not commence before next year at the earliest.

As scientific advances occur and are made available, even more growers will be encouraged to adopt sustainable practices. “The work by UC has been critical to our success,” Ross says.

— Robin Meadows

Cover crops provide food and shelter for beneficial insects such as ladybugs, which eat aphids, and pyrethroid wasps, which are tiny parasites that lay their eggs inside leafhopper eggs.

Nest boxes can attract wildlife to vineyards

Placing nest boxes for songbirds, owls and bats in and around vineyards can contribute to the sustainable management of pests and help mitigate oak-woodland habitat losses, according to a new booklet published by the UC Division of Agriculture and Natural Resources, “Songbird, Bat and Owl Boxes: Vineyard Management with an Eye toward Wildlife.”

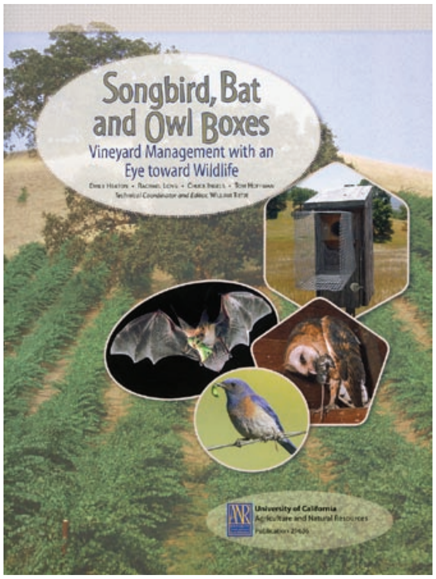
“Nest boxes are readily accepted by a number of bird and bat species and provide places for these animals to roost and nest. Used properly, they can help maintain biodiversity in vineyard landscapes,” says Emily Heaton, co-author of the 51-page booklet with Rachael Long, Chuck Ingels and Tom Hoffman.

The booklet is illustrated with color images and provides information on the rationale for placing nest boxes and bat houses in vineyards; which species may be attracted to them, as well as feeding and nesting behavior; detailed plans for building, placing and monitoring bird boxes and bat houses; and references and resources.

“The growers that I worked with really enjoyed seeing birds in the vineyards,” says Heaton, a UC Berkeley doctoral student who has conducted research on songbird boxes in vineyards. “Plus the birds are in there eating insects, and that may have some beneficial effect in terms of pest control.”

Many species native to woodlands — such as some songbirds, owls and bats — use cavities in oak trees for roosting or nesting, and they lose habitat when trees are cleared for new agricultural plantings. Vineyard development expanded rapidly during the 1990s, especially on the Central Coast and North Coast, says Bill Tietje, technical editor of the booklet. “Unlike most row crops, soil characteristics and topography did not completely restrict some new vineyard development from areas formerly classified as oak woodland.”

“There was a lot of public concern about impacts on views and biodiversity,” Tietje continues, “and growers would like to demonstrate that they are



ANR Pub 21636 can be ordered at anrcatalog.ucdavis.edu.


Laura Barrow

At Dooley Creek in Hopland, UC Santa Cruz Ph.D. candidate Julie Jedlicka (right) and field assistant Matthew Poonamallee monitor nest boxes placed in a vineyard.

practicing good conservation." For example, growers who participate in sustainability assessments such as the *Lodi Winegrower's Workbook* receive credit for placing nest boxes for birds of prey (see pages 133 and 142).

Pros and cons

Heaton monitored 288 songbird boxes placed in and around Napa and Sonoma county vineyards over 2 years. At least 85% of these boxes were used for nesting during the study. Western bluebirds and tree swallows were the most common occupants, plus five other native species. Overall, 54% of nests fledged one or more young (Heaton, unpublished data). However, nest success rates were highly variable between sites, ranging from 17% to 89%. "Predation was the main cause of nest failure," Heaton says. "Raccoons or domestic cats wiped out a significant number of nests at some sites."

Heaton strongly recommends that boxes be outfitted with predator guards and that growers monitor their boxes to make sure they are not doing more harm than good to songbirds.

Tietje and other scientists point out that studies have not been conducted to confirm whether the widespread placement of nest boxes can boost or stabilize local populations of native species; nor does existing research support the idea that wildlife can effectively reduce pest insects and rodents in vineyards.

"These practices can play an important role in an integrated pest management program, but it would be wrong, for example, to say that owl nest boxes can control rodent populations," Tietje says. "Rather, barn owls can help by extending naturally low cycles in rodent populations and thereby reduce the need for chemical pest control."

Many unanswered questions remain that, if answered, would assist both growers and biodiversity conservation. "Although some cavity-nesting birds, especially western bluebirds, readily use and fledge young from nest boxes in vineyards, what happens to the fledged young?" Tietje says. "Are the vineyards functioning as an 'ecological trap,' and is the trap sprung after young fledge from the boxes, perhaps due to increased predation or altered food resources in the vineyard?" A few studies are under way in California that will help to develop management guidelines for nest and bat boxes.

Research on vineyard wildlife

Julie Jedlicka, a Ph.D. candidate in environmental studies at UC Santa Cruz, is studying the use of nest boxes as a biocontrol agent and conservation tool. She points out that this type of research is not new: Between 1885 and 1940, the U.S. Department of Agriculture's "Department of Economic Ornithology" extensively studied the use of insect-eating birds to control pests in agriculture. But when chemical pest-control methods began to take precedence, Jedlicka says, the department was disbanded.

Jedlicka's research in Sonoma and Mendocino counties is examining the breeding success and diets of songbirds that use vineyard and riparian nest boxes. In addition, Jedlicka has placed large mesh exclosures in vineyards to monitor insect levels when birds and bats don't have access to grapevines; and to mimic an outbreak of Lepidoptera, she is pinning pupa to the undersides of grape leaves to determine the extent of consumption by birds. Finally, she is mist-netting in the vineyards to monitor and band insectivorous birds and collect fecal samples, which are being tested for the exoskeletons of vineyard pest insects.

"I am looking at whether nest boxes are boosting bird populations, and whether the birds are eating common vineyard pests such as grape leafhoppers and blue-green sharpshooters," Jedlicka says.

Long, a UC Cooperative Extension farm advisor in Yolo, Solano and Sacramento counties, is in the midst of a study on whether bats are feeding on orchard pests. The bats are being captured at night in orchards and held for a short time until they defecate. The guano samples are then analyzed for DNA evidence of codling moth, an important pest of orchard crops.

So far, the results show that nocturnal bats do eat codling moths, which fly at night. "Bats alone are not going to control these pest insects," says Long, who wrote the booklet's chapter on bat houses. "But they are one of our many beneficial natural enemies that contribute to biological control."

— Janet Byron

REVIEW ARTICLE

Agro-environmental partnerships facilitate sustainable wine-grape production and assessment

by Janet C. Broome *and* Keith Douglass Warner

The California wine-grape sector has invested considerable time, money and effort in collective enterprises to reach fellow growers and assess the industry as a whole on sustainability. At the same time, California wine-grape production has become increasingly branded by particular geographic regions. Premium wine grapes are grown in regions with high population growth, high land values and often, charged environmental politics. Growers and their institutions have developed several agro-environmental partnerships to assess, improve and publicly represent their environmental stewardship and farming practices. We review trends in several regional and statewide indicators of sustainability, including crush prices, grape acreage, population growth and pesticide use. This review is based on 2 years of field research with participants in wine-grape partnerships, a review of documentary evidence, technical advisory work with the programs and summary assessment of case-study data, as well as an analysis of 10 years of Pesticide Use Report data for California wine-grape growers.

The California wine industry has been a leader in proactively promoting sustainable practices. *Above*, IPM consultant Laura Breyer identifies natural enemies controlling a Sonoma County grower's vineyard pests.

California leads the nation in wine-grape and wine production, valued at $2.2 billion and $16.5 billion, respectively. The wine sector is estimated to collectively contribute more than $51.8 billion to the state's economy (MKF Research 2006). More than any other commodity, the California wine-grape community over the past 15 years has embraced the concept of "sustainability" (Warner 2007a, 2007b). The United Nations' Brundtland Report (WCED 1987), which popularized this term, raised concerns that agricultural production had led to resource degradation and economic and social inequality.

Sustainable agriculture has been defined as a goal, a scientific research endeavor (NRC 1989) and a social movement (Allen 1993) that prioritizes equally environmental protection, economic viability and social equity. Agro-environmental partnerships are the leading strategy for extending sustainable agriculture in California (Swezey and Broome 2000; Warner 2007a). These partnerships consist of an agreement over more than one season among growers, growers' organizations and agricultural scientists to apply agro-ecological principles to farm-scale practices and improve the stewardship of environmental resources.

These partnerships are a California version of "Third Way" agriculture (El Titi 1992), signifying a blend of organic and conventional pest-management and production practices. They draw from organic and other alternative techniques but are oriented toward a broader set of environmental goals than complying with a restricted list of inputs, as prescribed by the U.S. Department of Agriculture's National Organic Program. Particularly in the wine-grape industry, these partnerships have also involved regulators, and environmental and community leaders and their organizations.

Between 1993 and 2003, 32 partnerships were created in 16 California commodities. The biological and social systems of production in perennial crops are more suitable for these partnerships, and 24 of them were in tree and vine crops. Wine-grape growers created six partnerships, more than any other crop (Warner 2007b). We present a summary of 2 years of field research with participants in three of these wine-grape partnerships, including interviews and focus sessions, and review of documentary evidence. We supplement that work with additional and updated state and federal data, as well as examples and summary assessment data obtained from the case studies.

The future is bright for collaborative sustainability initiatives in California agriculture.

Sustainable grape innovation

Over the past decade, environmental concerns that have arisen around California vineyards and wineries include (Conaway 2002; Friedland 2002; Poirier-Locke 2002; Warner 2006):

- Oak woodland losses, and forest and wildland conversions on the North Coast and Central Coast.
- Water usage and water-quality standard violations, principally from sediment.
- Farm labor, pay and environmental health concerns.
- Introduced invasive species and new pest-disease vectors.
- Regional pesticide-use controversies, such as spray drift.
- Hillside development and erosion problems in Napa and Sonoma counties.
- Congested roads and noise around wineries.
- Community conflicts.
- The loss of endangered species and their habitat.

To address these public concerns, wine-grape growers launched coordinated efforts to enhance environmental stewardship in their region's vineyards, but also to reach out to neighbors with credible information about their progress.

Dating back to the 1970s, organic viticulturalists, including biodynamic ones, were the first sustainable viticulture innovators in California, and they have greatly contributed to later, broader attempts at designing and defining sustainable viticulture (Daane et al. 2005). Organic wine-grape growers must develop an organic systems plan, refrain from using most synthetic pesticides and fertilizers, undergo a 3-year transitional period, and obtain third-party certification for their production and processing systems based on federal regulations (see sidebar, page 138).

California wine-grape growers have created more partnerships than any other commodity because they have: (1) created strong local organizations; (2) differentiated their product quality by varieties that depend on regional environmental conditions; (3) added significant economic value to wines by geographic branding; and (4) recognized the importance of providing educational outreach to their environmentally conscious neighbors (Warner 2007b). These factors have prompted the industry to develop what may be the most comprehensive sustainability initiative of any U.S. commodity. California's more than 40 regional winegrower and vintner associations provide a preexisting set of economic and social relationships upon which these partnerships have been built (CSWA 2004).

California sustainable wine-grape production systems comprise a suite of farming practices and include self-assessment systems that allow growers to score their practices and document progress toward sustainability along a continuum. Growers, consultants, researchers, winery personnel and environmental advocates debated particular practices and their social and environmental impacts, and designated rankings or points for specific practices. These assessment systems integrate a range of practices into a whole farming system.

Many of the practices effectively implement the results of years of University of California research, such as leaf removal and canopy management, use of cover crops, integrated pest management (IPM), economic injury thresholds, use of weather data and models for disease-risk forecasting, and genetic resource improvements. Wine-grape growers and their organizations created these partnerships to apply basic research to the specifics of their local production regions. They are semiprivatized extension efforts, drawing from and partnering with UC scientists and advisors to specify and make progress toward sustainability goals. All programs described were created with extensive UC Cooperative Extension input and review.

Central Coast Vineyard Team

The Central Coast Vineyard Team (CCVT) grew out of the Central Coast Natural Vineyard Team, initiated by the Robert Mondavi Winery in 1994 to enhance wine quality in the rapidly expanding Central Coast and promote sustainability. Mondavi staff facilitated


Robert Mondavi Winery

The Robert Mondavi Winery (Mondavi, center), initiated one of the earliest sustainable viticulture initiatives, which evolved into the Central Coast Vineyard Team.

Winery operations — not just grape-growing — are included in "ground to bottle" partnerships such as the California Sustainable Winegrowing Program.

this process with vineyard management companies that had wine-grape contracts with them, but the initiative was soon opened up to include other wine-grape producers. Even though this growing region is geographically large, most vineyard management decisions were made by a small number of people who had worked together over the years. The CCVT was the first in California to develop a self-assessment system for vineyards, called the Positive Points System (PPS) (CCVT 2007). It obtained grants that enabled it to expand on-farm demonstrations and provide pest, crop and soil monitoring, and a collaborative outreach program.

Positive Points System (PPS). A first draft of the PPS was circulated on paper in 1995. Now it can be completed online or by filling in a 21-page printed version. The assessment has 152 questions, with points assigned based on the issue's importance to regional sustainability. For example, questions include: "Is sanitation regularly practiced for those diseases that are spread by infected tissue left in the vineyard (i.e., bunch rot, phomopsis, crown gall)? (4 points)" and "Are cultural practices that deter the spread of disease regularly used (i.e., late pruning for *Eutypa*; avoidance of trunk injury for crown gall; leaf removal for *Botrytis cinerea*)? (4 points)." Six sections cover pests, soils, water, viticulture management, wine quality and continuing education, with a total possible score of 1,000. Practices related to habitat protection and ecosystem management are integrated throughout the six sections.

As of 2007, the CCVT had 300 members who farmed 60,000 acres on the Central Coast, and the team had conducted 750 assessments (some of the same vineyard blocks were addressed over multiple years). Overall, PPS self-assessment scores have steadily increased and were on average about 50 points higher in 2006 than 10 years earlier, indicating that participants are farming more sustainably than in the past. Growers evaluating a single block have also improved their scores; over a 10-year period (1996–2006) there were 166 repeat assessments where 153 scores increased and 13 decreased. More than one-half of the repeat evaluations improved their scores from 1 to 100 points, indicating the adoption of as many as 10 new practices (fig. 1). Almost 10% of the repeat growers increased their scores by 300 points or more, indicating major changes.

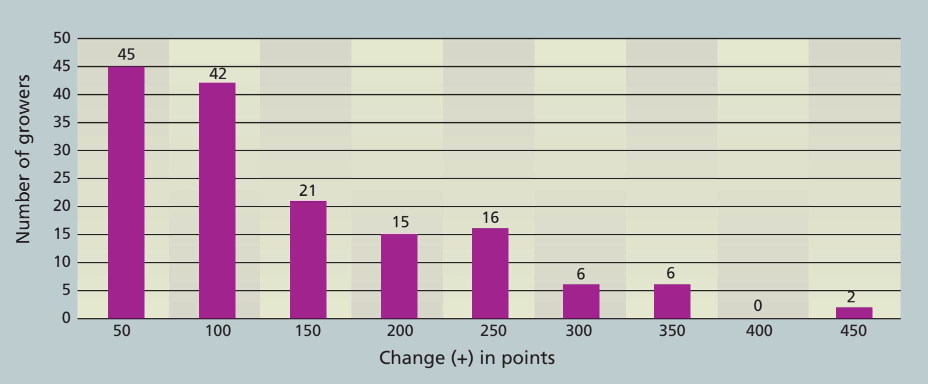


Fig. 1. Central Coast grape growers' vineyard blocks (n = 153) self-assessed using the Positive Points System (1996–2006) and total point increases in use of sustainable practices. Point scores for only 13 blocks decreased over time (data not shown). Source: Self-assessment database maintained by the CCVT through Kris O'Connor.

Water quality. The CCVT also obtained funds to assess the potential to protect water quality by relating practices in the PPS to their erosion potential, based on a nonpoint-source erosion model. Starting in 2005, the Central Coast Regional Water Quality Control Board (CCRWQCB) allowed growers to complete the PPS and its Future Plans Form to qualify as a farm plan under the conditional agricultural waiver. The CCRWQCB requires farm plans that outline best management practices to be employed on-farm so that irrigation water discharges do not cause or contribute to water-quality impairments (by releasing sediments, pesticides or fertilizers), instead of requiring waste discharge permits from irrigated lands.

Certification. In 2007, the CCVT received funding to develop a pilot sustainable viticulture third-party certification program, which they launched in early 2008 with a revised certification-oriented PPS. Wine bottles from the 2008 harvest will display this label.

Lodi Winegrape Commission

The Lodi Winegrape Commission (LWC) was established by grower vote in 1991 under a state marketing order. Membership is mandatory for any producer of more than 25 tons of wine grapes per year in this region. LWC's roughly $1 million budget is funded by a districtwide tax of 0.45% of grape value, 70% of which supports promotion and 30% research and grower outreach. There are currently about 750 LWC member growers farming nearly 100,000 acres of wine grapes, about 13% of the acreage in California, and they produce about 18% of the state's total crush tonnage (Goodhue et al. 2008).

Sustainable farming program and workbook. In 1995, LWC received a grant from the UC Sustainable Agriculture Research and Education Program's (UC SAREP) Biologically Integrated Farming Systems (BIFS) program to develop on-farm demonstrations, a monitoring program, and a grower-driven outreach effort to increase the adoption of environmentally protective and economical practices (see page 142). In 1998, they developed *Lodi Winegrowers Workbook: A Self Assessment of Integrated Farming Practices* (Ohmart and Matthiasson 2000; and revised in 2008). The workbook includes a form for growers to develop an action plan, along with detailed educational materials.

Lodi Rules. After the workbook was developed, a subset of growers, along with consultants and others, initiated the first third-party certification system for California wine grapes, called the Lodi Rules for Sustainable Winegrowing (LWC 2007). The rules are based on a set of farming standards or ranked practices, and unique to this program, a Pesticide Environmental Assessment System (PEAS) that provides a risk index for pesticides used in a vineyard. The rules outline 75 farming practices in six chapters, many of which require growers to have management plans with specific components.

Grape growers who participate in partnerships assess their own practices and develop action plans to reduce vineyard impacts on the environment, wildlife and people. Field days, such as this one hosted by the Sonoma County Winegrape Commission, provide hands-on exposure to best practices.

The PEAS score is calculated by multiplying the pounds of a pesticide applied by a toxicity factor, and it includes use patterns to further extrapolate the relative risk of exposure based on use method. Risks are assumed to potentially arise from multiple routes of exposure (for people, via food, water, dermal or inhalation exposure). Some exposures are short-term (acute risks) and others occur steadily over a long period of time (chronic risks). The PEAS model currently includes (1) worker acute risks, (2) dietary risks to people from acute and chronic exposure, (3) acute risks to small aquatic invertebrates, (4) acute risks to birds and (5) acute risks to bees and natural enemies of pest insects.

Certification. Individual vineyards that subscribe to the Lodi Rules are certified by a third-party, Protected Harvest. A vineyard qualifies for certification if it meets two criteria. First, the farming practices must achieve a score of 50% or better for each chapter; scoring below 50% on any chapter disqualifies the vineyard from certification. Moreover, a vineyard cannot score "fail chapter" on any of 11 particular standards, such as keeping written records of pest monitoring results for vineyard arthropod pests, having a comprehensive nutrient-management plan or testing soil before preplant fumigation.

Second, the "environmental impact units" for pesticides used in a vineyard for the year, calculated by the PEAS model, cannot exceed 50. In 2005, six vineyards were certified under the Lodi Rules label. In 2006, 12 growers participated, certifying 43 vineyards totaling 5,457 acres. In 2007, 18 growers certified 96 vineyards totaling 7,600 acres. In early 2008, five different wineries bottled and labeled a total of 14 different wines displaying the Lodi Rules logo on their labels. These wines are from the 2005 and 2006 vintages (personal communication, C. Ohmart, 2008).

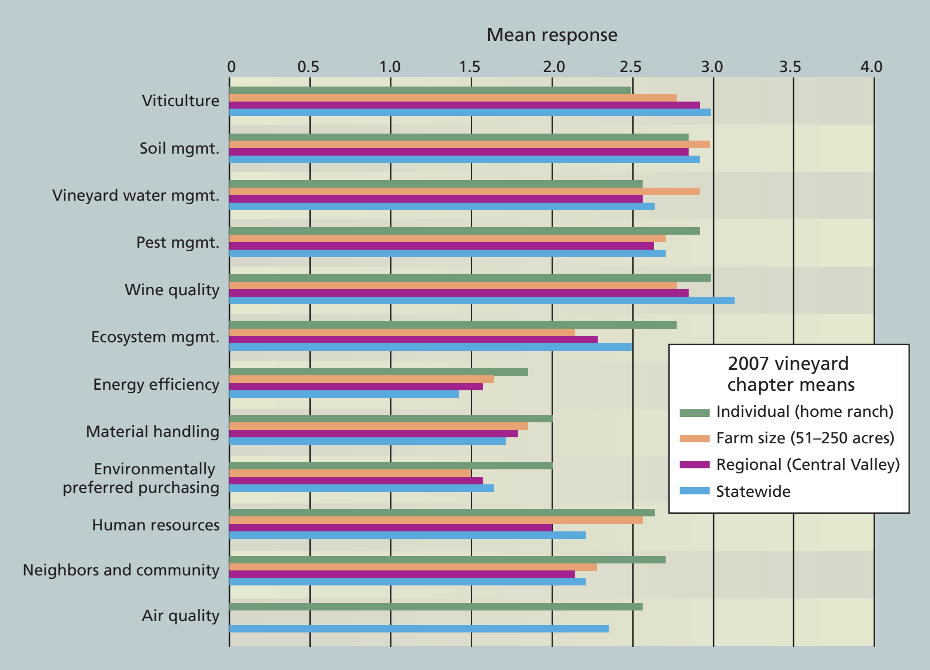


Fig. 2. California Sustainable Winegrowing Alliance's Code of Sustainable Winegrowing 2007 mean chapter responses by statewide level, regional level, farm size range and individual vineyard operation (home ranch). Average responses (1–4) are across all criteria for each of the 12 chapters (chapters 10 and 12 are for winery operations only and are not included). Source: CSWA self-assessment database.

Sustainable Winegrowing Program

The California Sustainable Winegrowing Program (SWP) began in 2001 as a statewide initiative to promote and adopt "ground to bottle" practices for producing grapes and wine. The program is led by the California Sustainable Winegrowing Alliance (CSWA), a nonprofit organization formed in 2003 of leaders from the two major statewide associations affiliated with California wine grapes and wine — the Wine Institute and the California Association of Winegrape Growers. The SWP uses the *Code of Sustainable Winegrowing Practices: Self-assessment Workbook (2nd ed.)* to outline and rank ecological, economic and social-equity practices through an integrated set of 16 chapters covering 12 areas and 227 criteria. It was first published in 2002, was revised in 2006 and is now available online (Dlott et al. 2006). Chapters cover soil, water and pest management, wine quality, energy efficiency, material handling, solid-waste reduction, purchasing, human resources, neighbors and community, and air quality. The viticulture chapters are modified from the *Lodi Winegrower's Workbook* (see page 145, table 2). The Code is, however, even more far-reaching than either regional initiative in that it includes an assessment of winery operations such as water quality and conservation.

The SWP collaborates with local grower and vintner organizations to create participatory educational programs that help growers progress toward sustainability. Winegrowers who participate in workshops submit self-assessments, which the program uses to develop confidential benchmark reports on how individual operations are performing relative to statewide and regional scores, or scores based on vineyard operation size (fig. 2). One hundred self-assessment workshops have been held since the program started.

The 2006 report indicated that 1,165 enterprises had evaluated their sustainable practices, covering 33% of California's 522,000 total wine-grape acres and 53% of the state's total annual wine production of 273 million cases (CSWA 2006). The statewide mean values for the chapters (possible range of 1 to 4, with 4 being the highest) show higher scores, closer to 3, for vineyard management practices involving soils, water, pests and wine quality (fig. 2). These rankings are similar to earlier regional programs such as Lodi's, and it appears that more of the industry that has assessed itself is at this level. The statewide mean scores for vineyard energy efficiency and environmentally preferred purchasing are lower than for vineyard production practices, closer to 2, with further room for improvement.

The mean scores can also be used to assess progress over time (CSWA 2006). Winegrowers assessed between 2002 and early in 2004 as compared to those assessed late in 2004 through 2006 increased their performance in 31 of 38 pest management criteria, by nearly 8%. Pest management along with energy efficiency, air and water quality, and ecosystem management were the focus of more than 100 targeted education events hosted by SWP during this time.

The SWP is remarkable in several respects. It involves the most sophisticated analytical tool yet developed for evaluating the production of an agricultural product, and it is the first partnership to evaluate operations based on personnel practices and community outreach.

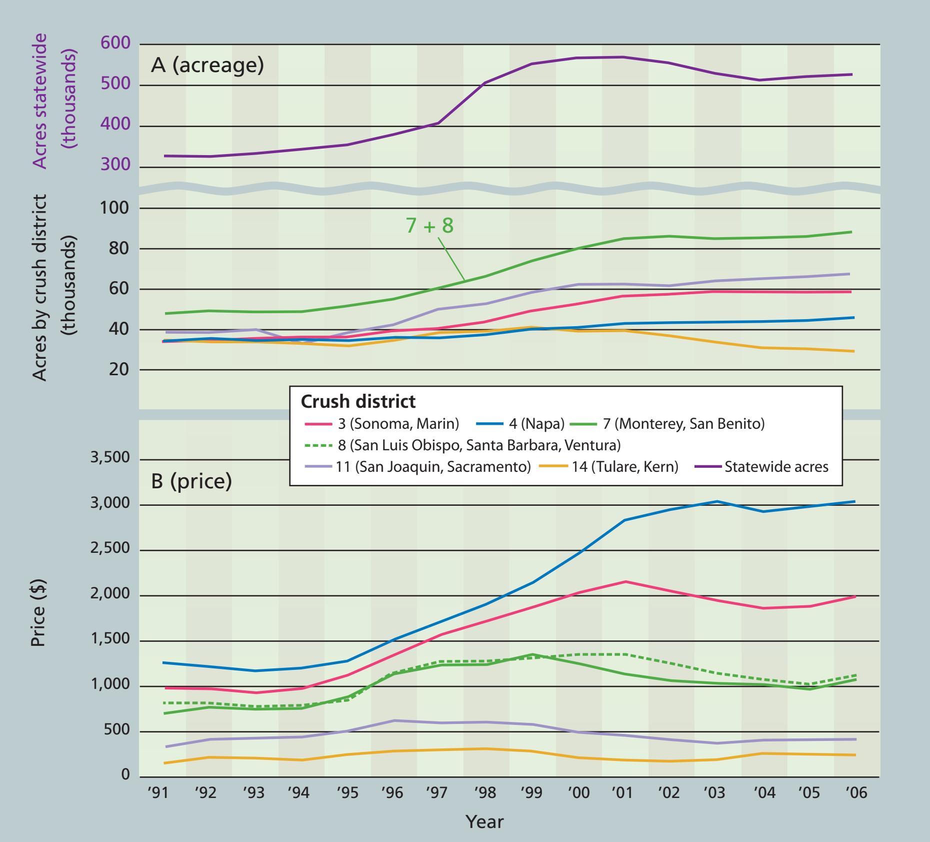


Fig. 3. (A) Estimates of California wine-grape acreage (bearing and nonbearing), 1991–2006, for selected crush districts (CD) and statewide. CDs 7 and 8 include counties also in the Central Coast Vineyard Team, and CD 11 is the same as the Lodi Winegrape Commission. Source: USDA NASS 2006a. (B) Wine-grape weighted average of grower returns per ton, 1991–2006. Source: USDA NASS 2006b.

North Coast and other regions

With over 40 regional organizations, California wine-grape growers and vintners are well organized and represented. The North Coast premium wine regions have partnerships that also embrace sustainability and play key roles in the statewide SWP. The Napa Valley Grape Growers Association and Napa Valley Vintners worked with the Fish Friendly Farming water-quality protection program in 2003 to create a local certification program called Napa Green Land. Napa is basing its winery certification program on the SWP and calling it Napa Green Winery. The Sonoma County Winegrape Commission, formed in 2006, will also use the statewide SWP. Mendocino County has been home to early pioneers in organic and sustainable viticulture such as Fetzer, Bonterra and Frey, and over 70% of Lake County growers have contributed assessments to the SWP database.

Quality and place-based farming

California's wine-grape industry has been proactive in addressing sustainability for the past 15 years. Interviews, focus groups and participation in these partnerships suggest a range of explanations (see Warner 2007b for details on methodology). Some individuals were motivated by a personal, deeply held philosophical commitment to the environment, others cited economic considerations and still others hoped to reduce the fallout from bad publicity linked to conflicts over resource use and the environment and/or human health.

Addressing regional conflicts. Wine grapes have been geographically branded or linked to specific regions for almost 40 years in California. Several transitions toward geographic specificity and segmentation in the industry have occurred, from generic table wines, to varietal wines, to appellations and most recently vineyard-designated or *terroir* wines (Lapsley 1996). This means wine grapes are marketed as a product of specific place more than any other agricultural product. This approach has led to tremendous success and acreage growth, particularly throughout the 1990s and reaching a peak statewide of 570,000 acres in 2001, but more recently declining to 527,000 acres in 2006 (USDA NASS 2006a) (fig. 3A).

However, geographic branding has exposed wine-grape growers to greater environmental criticism linked to the place of production (Friedland 2002; Warner 2007b). Conflicts have arisen due to rapid vineyard development, an ever more-restricted land base in the premium coastal valleys, and the growth of ex-urban wealthy populations in rural areas. Long-term solutions will come from dialogue at the community level and improvements to current practices that address equally the community's economic, environmental and social goals.

Economics of sustainability. An important element of sustainability is economics, and for individual growers the price they receive may determine whether they continue to farm. Over the life of these initiatives, prices received by growers increased, especially in the late 1990s, for all the crush districts that we studied (USDA NASS 2006b) (fig. 3B).

However, prices flattened out or declined early in 2000 for most districts. Much of this price decline is likely due to earlier increases in acreage and hence local grape oversupply, as well as global competition, particularly from other New World wines, and reduced leisure and business travel following 9/11. The average crush price growers receive has continued to climb in Napa, while its acreage has remained static due to a planting out of the valley. Napa (crush district 4) currently has an average crush price that is over 10-fold higher than crush district 14 (Kern and Tulare counties).

Lodi (crush district 11) and the two Central Coast crush districts (7 and 8), which cover the CCVT membership area, at first experienced major growth

Interest in organic winegrowing is increasing

by Glenn McGourty

The term "organic" is used both to describe a market niche and a legally defined way of farming. As codified by the U.S. Department of Agriculture's National Organic Program (USDA NOP), organic farming is:

> "An ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain and enhance ecological harmony" (NOSB 1998).

Major objectives of farming organically are to improve soil quality by building soil organic matter; use only naturally occurring fertilizers and crop protectants (no synthetic materials allowed); recycle crop residues and animal waste by composting and/or incorporating them into the soil; emphasize integrated pest management (IPM) to control pests, diseases and weeds; and create a safe and productive environment for crops and people working on the farm.

Certification. In order to legally use the term "organic" on a product label, the grower must become "certified" by a third-party agency (such as California Certified Organic Farmers, Oregon Tilth or Demeter Stellar), which assures that USDA NOP regulations are followed. A 3-year transition period is required, in which an Organic System Plan (OSP) is implemented. Typically, this includes: not using conventional crop protectants and fertilizers; implementing a soil fertility program with cover crops and compost; and developing a pest management program with spray materials approved for organic growing. (The transition period can be shortened with proof that no restricted conventional materials were applied before the certification process started.)

When organic certification is completed, growers must register their production area and processing facility (for winemaking) with the state of California. The cost of certification and registration varies depending on the area farmed and crop value, but usually ranges from one-half to one percent of the crop value.

Crop protection. Organic winegrowers do spray crop protectants such as wettable sulfur, potassium bicarbonate and minerals, but these materials tend to be environmentally benign and not particularly toxic to workers. The materials must be approved by the third-party certifiers and the USDA NOP for use in organic farming. For wine grapes, an important goal is to create "balance," in which vines are adequately cropped so as not to be excessively vigorous — but not over-cropped — so that the resulting wine is of the highest quality. This involves moderate applications of fertilizer and water, as well as careful canopy management to insure that diffused light penetrates and the fruit zone is aerated, while at the same time minimizing conditions that encourage pests and diseases.

Organic wine. Wine created from organic grapes must be made in a facility certified for organic production, in which strict guidelines are followed that prohibit toxic chemicals and synthetic additives. There are two NOP–defined categories of wine made from organic grapes. First, "organic wine" contains no added sulfites (which are used to preserve and stabilize wine from unintended microbial degradation). However, organic wine is notoriously inconsistent and unpredictable in quality, and is mostly consumed by people who are sensitive to sulfites (a relatively small market niche). Second, "wine made from organically grown grapes" allows the use of sulfites at lower levels than conventionally processed wine. The majority of organic wine-grapes in California are used to make the latter.

State and global acreage. Interest in organic winegrowing has grown steadily over the past decade. In 2006, almost 8,000 vineyard acres were certified organic (CDFA 2006). Total global acreage of organic grapes is estimated at just over 228,000 acres in 31 countries (including California acreage), with Italy alone producing 77,000 acres (Willer and Yussefi 2006). Most California acres are in coastal winegrowing districts: Mendocino County has the most with about 3,000 certified acres, and Napa County is next with 1,600 acres. Significant acreage is also certified in Lake, Sonoma, Santa Barbara and San Luis Obispo counties. Oregon and Washington growers are also certifying significant grape acreage in organic production.

Why grow organic grapes?

Growers farm vineyards organically for many different reasons. Most have a strong conservation ethic and want to minimize potential harm to the environment, workers, neighbors and their family, since many growers reside near their vineyards. They also embrace farming with nature, and want to encourage biological diversity on their property. They recognize that their farms can provide other ecological services, such as habitat for beneficial insects and birds of prey; the recycling and sequestering of organic matter; and protection for the overall health of their watersheds. Others are interested in achieving a very high-quality product, and potentially increasing their income. Finally, organic winegrowing is often used to position products in the marketplace. Many consumers and market outlets (such as high-end wine shops and restaurants) actively seek organically grown products, viewing them as hand-crafted, unique and distinctive compared to mass-produced items. Interestingly, organic practices are farm-scale neutral and are used both by large producers (such as Fetzer Vineyards with more than 1,700 acres in Mendocino County) and small producers making less than 500 cases of wine annually.

Organic winegrowers manage their vineyards as mini-ecosystems, striving to increase biodiversity in the soil, for example via the use of cover crops. Organically managed soils have higher biological activity than conventionally managed ones, possibly due to more efficient resource utilization and diverse flora and fauna (Mader et al. 2002; Reeve et al. 2006). As organic matter is added, organisms in the root zone appear to change the dynamics of disease expression on the vine roots. Organically farmed vineyards infested with phylloxera have been shown to last many years longer than conventionally farmed vineyards attacked by phylloxera, although they do need to be replanted eventually (Lotter et al. 1999). Diverse microflora in the soil suppresses pathogenic fungi that attack grapevine roots damaged by phylloxera.

Some growers feel that the quality of both fruit and wine improves after organic winegrowing practices are adopted. Grower experience has shown that under most conditions, organic winegrowing is both cost effective and productive, and does not reduce yields or quality (Klonsky et al. 1992; Weber et al. 2005). There is no specific premium for organically grown fruit, because wine-grape lots are judged on their individual merits and are more affected by region of production (appellation), variety and intended price-point (such as a finished bottle of wine).

Finally, some organic winegrowers don't bother to register and certify their vineyards, because they see no market or competitive advantage to doing so. Rather, they find that farming organically personally satisfies and meets their production objectives.


A. Thrupp/Fetzer Vineyards

Grape growers may choose to farm organically to minimize environmental damage, encourage biological diversity or position their products in the marketplace. *Above*, mixed cover crops at Bonterra Vineyards in Mendocino County.

G. McGourty is Winegrowing and Plant Science Advisor, UC Cooperative Extension, Mendocino and Lake counties.

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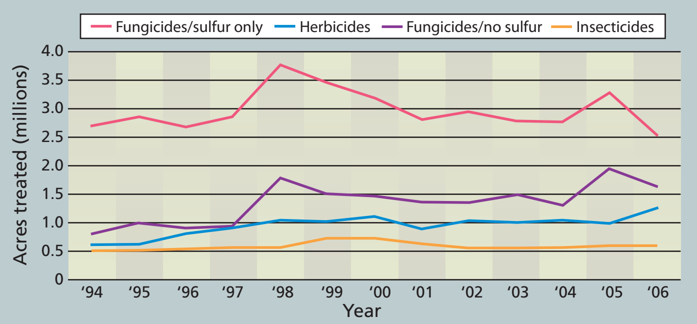

Fig. 4. California wine-grape acres treated with pesticides, 1994–2006. Source: California Department of Pesticide Regulation (DPR) 2006 Pesticide Use Reports.

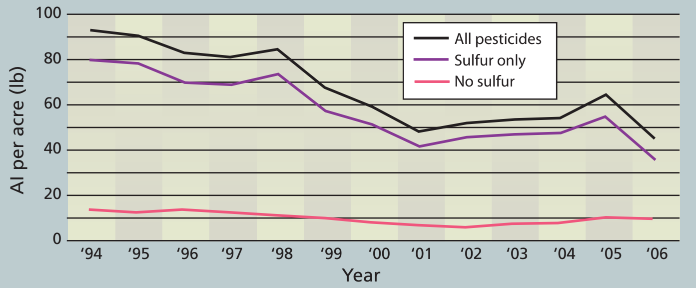

Fig. 5. Pounds pesticide active ingredients (AI) applied statewide to wine grapes per acre planted, 1994–2006, for all active ingredients, those containing sulfur (sulfur only), and all other active ingredients except sulfur (no sulfur). Pesticide data is for "grapes, wine" from DPR Pesticide Use Reports; San Joaquin County includes both "grapes" and "grapes, wine" categories. Sources: DPR Pesticide Use Reports; USDA NASS 2006b acreage data (bearing and nonbearing).

in the mid- to late 1990s in both acreage and prices received for grapes, at the same time that their assessment systems were developed. The Lodi crush price peaked in 1996 at $628 per ton and remained above $500 per ton until the early 21st century. Average crush prices in 1999 and 2001 for Central Coast crush districts 7 and 8 peaked at $1,348 and $1,353 per ton, respectively.

Price differentials. Regional yield differences can make up for price differentials; for example, higher yields in crush district 11 over lower yields but higher prices in districts 7 and 8 can sometimes mean equal or better total returns for district 11 growers. Since the early 21st century, growers in these two regional partnership areas appear to have experienced a drop in crush prices districtwide. Since the average crush prices reported combine prices paid as part of long-term contracts, as well as short-term sales, some growers paid through short-term sales received even less for their grapes.

Providing perhaps a more important measure of sustainability, the Lodi crush district has maintained its price lead over elsewhere in the San Joaquin Valley — such as crush district 14 (Kern and Tulare counties) — while the Central Coast crush districts (7 and 8) received prices more than double those of Lodi. Both regions have created agro-environmental partnerships that recently include third-party certification programs in sustainable viticulture, so as to capture greater recognition and possibly price. The Central Coast and Lodi regions also continue to be recognized and rewarded economically for perceived superior wine quality.

Declining pesticide use

Wine-grape growing practices can affect — both positively and negatively — California water, air and soil quality, human health, and plant and animal habitat. This happens through vineyard development and production practices such as vegetation removal, new plantings, earth moving, tillage and the use of agricultural chemicals, including pesticides. We analyzed pesticide use trends as a proxy for the industry's environmental and human health impacts.

California has a unique tool in its full-use reporting of pesticides applied to agricultural products, called Pesticide Use Reports (PUR). All agricultural applications are required to be reported to county agricultural commissioners, who submit this information to the California Department of Pesticide Regulation (DPR). Working with DPR, we obtained error-checked summary data for pesticides used on wine grapes as county and statewide totals from 1994 through 2006. These data reside in an MS Access database and were manipulated using MS Excel and pivot tables.

We analyzed and then graphed total vineyard acres treated from 1994 to 2006 for the four main types of pesticides used on wine grapes: fungicides (sulfur only), fungicides (no sulfur), herbicides and insecticides (fig. 4). Sulfur accounted for the bulk of materials used on wine grapes, with peaks in 1998 and 2005. Sulfur is considered a relatively low-toxicity fungicide and some forms are allowed for use in organic certification. Total insecticide and herbicide use has stayed pretty constant despite acreage increases.

Because acreage increased substantially from 1994 to 2006, we then calculated pounds of active ingredient applied per acre planted using National Agricultural Statistics Service/California Department of Food and Agriculture county acreage estimates. Especially in the late 1990s, the pounds of pesticides applied to growing acreage declined statewide (fig. 5) and in all regions (data not shown). Because sulfur is used at such a high rate and so extensively on grapes to control powdery mildew, changes in sulfur use appear to explain much of the total reduction in pesticide use per acre (fig. 5). Changes in the sulfur products themselves (from dust to dry flowable formulations) as well as reductions in use frequency may account for much of this per-acre decline.

During this time, the Gubler-Thomas powdery mildew risk index was developed and implemented (see page 127). Use of the index to time fungicide applications is encouraged in these grape sustainability assessment systems, and it has been adopted by 50% of grape-grower survey respondents (Lybbert and Gubler 2008). Although reductions in sulfur use are important in explaining the downward trend in pesticide use on wine grapes, Daane et al. (2005) also found that insecticide use (total pounds applied per acre as well as broken out by chlorinated hydrocarbons, organophosphates, carbamates and miticides) on grapes declined per acre over this same period.

Long-term benefits

Sustainability programs cost money to create and implement. The CCVT obtained approximately $1.6 million in the past 10 years for the PPS and related programs (K. O'Connor, personal communication). The Lodi Winegrape Commission has secured about $1.5 million in grant funds over the same period (C. Ohmart, personal communication), but also draws on its annual assessment fee. The California Sustainable Winegrowing Alliance has obtained approximately $2.2 million in grant funds over the past 5 years, and its main partners have provided about $1.5 million in direct funds (A. Jordon, personal communication). Matching funds from grower membership payments and in-kind services have substantially added to grant funds. The greatest additional expenses have been borne by growers, who generally recognize that environmental stewardship is necessary for credible community outreach and market reputation.

Faced with increasing population, global competition, environmental protection and input costs, the wine-grape industry's definition of quality and production in place increasingly includes promoting stewardship and sustainability. Other perennial crop commodity groups have witnessed the benefits of the wine-grape industry's agro-environmental partnerships and are selectively adopting their strategies, suggesting that the future is bright for collaborative sustainability initiatives in California agriculture (Warner 2007b).

Only time will tell if an individual grower's bottom line, environmental record or community relationships will benefit. Certainly the industrywide effort to assess itself and establish benchmarks, and then promote a cycle of continual improvement in the adoption of sustainable practices both in the vineyard and the winery, is an historic event.

Goodhue et al. (2008) documented the fragmentation of the California wine industry, finding bimodal expansion of multiwinery corporations with many labels on one end, and small wineries selling directly to consumers, restaurants and final users on the other. Midsize wineries that sell 25,000 to 75,000 cases a year may be forced to get larger or smaller. Regional, sustainable wine-growing branding may allow some of the "ag in the middle" growers to survive the coming challenges by increasing their economic sustainability, creating a more competitive and desirable product labeled as such, and creating greater consumer awareness, and therefore demand, for these place-based, sustainably produced wines.

J.C. Broome is Academic Coordinator, UC Cooperative Extension, Sacramento, Yolo and Solano counties, and K.D. Warner is Lecturer and Researcher, Environmental Studies Institute, Santa Clara University. We thank Allison Jordan, Kris O'Connor and Cliff Ohmart of the wine-grape partnerships for kindly providing data and information to assist in this review, and Karen Ross and Jeff Dlott for additional input. We also thank Larry Wilhoit at DPR for providing the pesticide use data. We acknowledge with gratitude support from the National Science Foundation (award BCS-0302393), the Biologically Integrated Farming Systems Work Group and the UC Santa Cruz Center for Agroecology and Sustainable Food Systems.

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REVIEW ARTICLE

Innovative outreach increases adoption of sustainable winegrowing practices in Lodi region

by Cliff Ohmart

The widespread adoption of sustainable winegrowing practices depends not only on rigorous science, but also on its effective delivery to growers. The Lodi Winegrape Commission (LWC) created a unique self-assessment workbook and implementation program for increasing the adoption of sustainable winegrowing practices. This project was based on results from published research projects — many generated by UC scientists — and on-farm demonstration projects carried out by LWC growers and vineyard consultants. Data from two grower surveys shows that the program led to the increased adoption of specific sustainable winegrowing practices in the Lodi region. It has also served as a model for programs in other wine regions, including in California and New York.

Dale Goff

Growers in the Lodi region have embraced sustainable winegrowing practices since the early 1990s.

Sustainable agriculture and the related but legally codified organic agriculture have been evolving since the 1920s (Francis and Youngberg 1990). Their importance and implementation have increased dramatically in the last 20 years. Organic agriculture focuses on inputs (e.g., pesticides and fertilizers), with growers following specific practices to become certified. Over the last 10 years, sustainable agriculture has received increased attention from academia, in the media and on the farm. Sustainable agriculture, unlike organic, is not codified at a national level and has the flexibility to address important emerging issues for California agriculture such as water use, air quality, energy use, greenhouse-gas production, wildlife habitat and human resources (Ohmart 2004b).

The California wine industry, relative to other U.S. agriculture sectors, has invested a significant amount of effort in encouraging the adoption of sustainable practices in vineyards and wineries (Dlott et al. 2002; Ohmart and Matthiasson 2000; Ohmart et al. 2008; Ackerman et al. 1996) (see page 133). The growers in Lodi have been leaders in this endeavor.

The Lodi Winegrape Commission (LWC) was formed in 1991 by a grower vote. The commission's boundaries are those of California crush district no. 11, in northern San Joaquin County and southern Sacramento County. There are approximately 100,000 acres of winegrape vineyards in this crush district, producing about 20% of California's total wine-grape crush. Part of LWC's original mission was to develop an areawide sustainable winegrowing program. To accomplish this, LWC formed an Integrated Pest Management (IPM) Program in 1992, consisting of regular grower meetings, field days, a newsletter and a Web site.

In 1995, with help from a Biologically Integrated Farming Systems grant from the UC Sustainable Agriculture Research and Education Program, LWC established on-farm demonstration vineyards where a range of sustainable winegrowing practices were implemented and the results tracked. In 2000, LWC published the *Lodi Winegrower's Workbook: A Self-Assessment of Integrated Farming Practices* (Ohmart and Matthiasson 2000), and in 2005 launched California's first third-party-certified sustainable winegrowing program, the Lodi Rules for Sustainable Winegrowing (Ohmart 2008; Ohmart et al. 2006).

Growers interested in practicing sustainable winegrowing face three main challenges: defining it, implementing it in the vineyard, and measuring the impacts of implementation (Ohmart 2004a). Once defined, growers must translate sustainable viticulture into day-to-day farming practices. Ideally, practices are based on research results from studies such as those in this issue of *California Agriculture*. Finally, growers must be able to measure the resulting impacts on farming operations, including on wine grapes and wine quality, farming costs, ecosystem quality and human resources.

The aim of the *Lodi Winegrower's Workbook* was to increase sustainable winegrowing practices by Lodi growers, and establish benchmarks of adoption to track change over time. The workbook and implementation program

the
LODI
RULES
FOR SUSTAINABLE WINEGROWING
CERTIFIED
BY PROTECTED HARVEST

In 2005, the Lodi Winegrape Commission launched California's first third-party certification program for sustainable winegrowing.

were the first of their kind to apply the Environmental Management Systems model (Martin 1998) to wine grapes. They have affected grower attitudes about IPM and increased the adoption of farming practices (Dlott and Dlott 2005). Moreover, the workbook has influenced wine industries in California, Washington state, New York and parts of Australia (Bernard et al. 2007; Dlott et al. 2002; Wise et al. 2007). In 2008, LWC published the *Lodi Winegrower's Workbook* (2nd ed.) (Ohmart et al. 2008), greatly expanding the content of the first edition.

Defining sustainable winegrowing

There is no universally accepted definition of sustainable agriculture, and the paradigm continues to evolve. In 2001, the California Association of Winegrape Growers (CAWG) and the Wine Institute formed a joint committee to develop a sustainable winegrowing program that could be implemented statewide. They crafted the following definition: "Growing and winemaking practices that are sensitive to the environment (Environmentally Sound), responsible to the needs and interests of society-at-large (Socially Equitable), and economically feasible to implement and maintain (Economically Feasible)" (Dlott et al. 2002). This definition is often referred to as the three "E's" of sustainability. These 3 E's are common themes reflected in other proposed definitions of sustainable agriculture (ASA 1989; Francis and Youngberg 1990). This simple but comprehensive definition has been widely adopted within the California wine industry, including by Lodi growers.

Implementing sustainable practices

This definition must be translated into farming practices used to grow wine grapes. In 1998, Lodi growers needed a tool to help them increase the adoption of sustainable winegrowing practices and track the level of adoption over time. An industrywide search identified two promising models. First, the Positive Point System (PPS), developed by the Central Coast Vineyard Team (CCVT), allows winegrape growers to assess the level of sustainability in their vineyards (Ackerman et al. 1998). The second was Farm*A*Syst self-assessment workbooks.

Farm*A*Syst, established in 1991, is a partnership between government agencies and businesses to prevent pollution on farms, ranches and in homes using confidential environmental assessments. It is a national program supported by the U.S. Cooperative State Research, Education, and Extension Service, Natural Resources Conservation Service, and U.S. Environmental Protection Agency (EPA). Farm*A*Syst's approach is based on the Environmental Management Systems (EMS) model as a standard process to develop goals, implement them, measure success and make further improvements (Martin 1998; WCED 1987).

Based on this model, producers in the United States, Canada and Australia developed self-assessment workbooks for dairy, cotton and other crops. The Farm*A*Syst workbooks help growers to identify farming practices that are beneficial from an environmental perspective and those that are having negative impacts; create action plans and timetables to address practices causing environmental concern; and obtain information to help develop and carry out action plans.

The Farm*A*Syst workbook model had two attributes that other self-assessments, such as the Positive Point

Anna Goehring/Lodi Wine & Visitor Center

Lange Twins Winery, based in Acampo, credits the Lodi commission as "a catalyst in shaping our philosophy. We have developed our sustainable techniques through their guidelines."

TABLE 1. Fifty six of 105 issues addressed in the *Lodi Winegrower's Workbook*, providing examples from each of the seven chapters

Viticulture	Soil management	Water management	Pest management	Habitat	Human resources	Wine quality
Canopy management	Plant tissue, soil sampling and analyses	Water-quality monitoring	Pest monitoring	Nest boxes for birds of prey	Grower continuing education	Knowledge of wine quality
Vine balance	Nitrogen management	Offsite water movement	Insect and mite management	Planting of insectary plants	Participation in professional organizations	Knowledge of wine industry
Monitoring canopy microclimate	Nutrient management besides nitrogen	Irrigation system selection	Use of broad-spectrum pesticides	Use of pesticides in relation to wildlife	Regulation compliance	Monitoring fruit maturity
Environmental survey	Water infiltration	Irrigation system performance	Use of reduced-risk pesticides	Wind erosion and offsite water movement reduction	Employee training and education	Monitoring juice chemistry
Rootstock selection	pH management	Irrigation system maintenance	Disease management	Establishing wildlife corridors	Team-building among employees	Tasting wine with winemaker
Clone selection	Organic matter management	Water-use monitoring	Weed management	Farmscaping	Safety reward programs	Viticultural improvements based in wine quality
Trellis selection	Tillage	Water budgeting	Vertebrate pest management	Vernal pool management	Employee meetings	Communication with winery
Habitat conservation	Erosion	Deficit irrigation	Spray-drift management	Riparian area management	Employee professional development	Tasting grapes in the vineyard with winery rep

Source: Ohmart and Matthiasson 2000.

System, lacked. One was that farming issues in the workbook are addressed using a four-category system rather than simple "yes/no" answers. The other encourages growers to develop action plans to address the concerns discovered during the self-assessment. After problems are identified, the action plan puts a grower on the path of continual improvement.

The Lodi growers chose to adopt the EMS/Farm*A*Syst model, then established goals and principles for the program through facilitated discussion (Ohmart and Matthiasson 2000). By doing so they took ownership of the program, helping ensure wide adoption by their peers. They felt growers would be much more likely to use a workbook developed by other stakeholders in their region than one developed by an outside group.

Previous Farm*A*Syst workbooks focused on environmental concerns and placed educational information in appendices. Lodi growers chose to not only address important environmental issues but also focus on farming practices that affect wine-grape quality. Furthermore, they chose to integrate throughout the workbook educational information about the most important topics to aid growers in developing their action plans.

Writing the Lodi workbook

No textbooks are devoted to sustainable winegrowing, and the most recent general viticulture text is almost 35 years old (Winkler et. al. 1974). However, advances have continued since then, as shown in publications by UC researchers and other institutions on specific aspects of wine-grape growing, such as *Grape Pest Management* (Flaherty et al. 1992), *Cover Cropping in Vineyards* (Ingels et al. 1998) and *Deficit Irrigation of Quality Winegrapes Using Micro-irrigation Techniques* (Prichard et al. 2004) (see also Adler 2002; Broome et al. 2000; Petersen et al. 1978; Schwankl et al. 1993; Smart and Robinson 1992). There is also a substantial pool of knowledge about sustainable winegrowing in the collective experience of growers, farm advisors, research scientists and others. To take advantage of this published and collective knowledge, a 17-member committee was recruited to develop the workbook, which included Lodi wine-grape growers, vineyard consultants, UC researchers and farm advisors, wildlife biologists, and representatives of the U.S. EPA, Natural Resources Conservation Service and Farm*A*Syst.

Following the Farm*A*Syst model, the next step was to identify all issues that related to growing wine grapes in the Lodi region, not just those pertaining to inputs such as fertilizers and pesticides. The committee identified 105 issues, which were categorized into seven chapters: viticulture, soil management, water management, pest management, habitat, human resources and wine quality (Ohmart and Matthiasson 2000) (table 1).

The committee then created worksheets for each issue listing farming practices available to Lodi wine-grape growers to address them. Each practice influences one or more of the three E's of sustainability, either positively or negatively. In some cases a practice might be positive for one and negative for one or both of the others. For example, a pesticide may be effective and inexpensive but also highly toxic to workers and wildlife.

After the practices were listed for each issue they were arranged into four categories on each worksheet, with category 1 for least-sustainable practices, getting progressively more sustainable in categories 2 and 3, and ending with the most-sustainable practices in category 4 (table 2). Decisions on what practices to list and the level of sustainability for each were based on research results, as well as on the knowledge and experience of the committee members.

TABLE 2. Worksheet for issue no. 11 in soil management chapter of *Lodi Winegrower's Workbook*

Issue	Category 4	Category 3	Category 2	Category 1
11. Soil erosion	Permanent cover crop maintained **And** Permeability/runoff rates are known, and irrigation is applied accordingly **And** Water diversions are on the longer slopes to transport the runoff safely **And** No tillage is done.	Winter annual cover crop maintained **And** Water diversions are on the longer slopes to transport the runoff safely **And** No tillage is done.	Winter annual cover crop maintained **And** You have developed a tillage plan that minimizes the number of passes per season.	No cover crop **And/or** There are visible signs of erosion on your property.

Source: Ohmart and Matthiasson 2000.

The final step in writing the workbook was to add educational information about specific issues and practices. The workbook was not intended to be a textbook on wine-grape growing, but the committee believed that certain scientific information should be included, either as a stimulus for growers to find out more or as practical guide to create and carry out action plans.

Implementing the workbook program

It takes growers about 3 hours to complete the 105 worksheets. There is a summary evaluation sheet for each chapter on which growers record their level of sustainability based on whether their practices best match category 1, 2, 3 or 4. In the subsequent review of the summary evaluation sheets, issues are identified where improvements can be made and an action plan is created. The most serious concerns are identified by issue scores of 1 or 2.

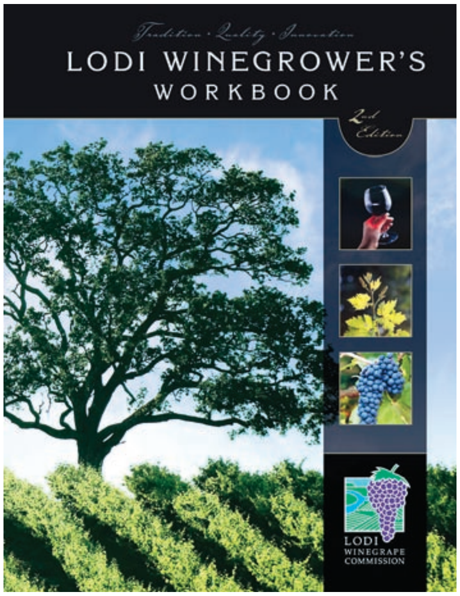
We decided the best way to get busy growers to look at the workbook in depth was to assemble small groups and go through it with them. Key growers in the district were asked to invite 5 to 10 of their neighbors over to fill out the workbooks together. During the first 18 months after the first workbook was published in 2000, 36 workshops were attended by 265 growers managing about 60,000 acres of Lodi vineyards (about two-thirds). Growers took their host role seriously, in some cases trying to out-do each other by serving snacks, wine and coffee; one workshop was held in a pizza parlor.

Measuring adoption

Measuring the level of adoption for sustainable farming practices is difficult, because sustainable agriculture addresses all aspects of farming and encompasses a huge range of practices that fall all along the continuum of sustainability. The four-category worksheet of the Farm*A*Syst workbook model is excellent for dealing with this complexity. The evaluation scores from the workbook can be used to assess the level of adoption for an individual vineyard and grower as well as for a group of growers in a region or larger geographic area.

An individual grower can use the evaluation sheets as a summary of their assessment. If they carry out one or more action plans, their vineyard practices can be reassessed after one or two seasons to track improvements over time. Likewise, a group of growers in a region can pool their evaluations into a common database. For example, LWC created a Microsoft Access database to capture and summarize self-assessments from growers willing to anonymously share their vineyard evaluations.

Assessment data from a group of vineyards and/or growers can be summarized in several ways. One is to calculate an average "score" for each workbook issue. For example, if the average for issue 11 shown on table 2 is a 3, then the average vineyard in the database maintains a winter cover crop, has water diversions on any long slopes and no tillage is done. We have used these data summaries to determine which farming issues require more attention in LWC grower outreach meetings. Likewise, growers can see how they compare to the regional average.



Growers managing more than two-thirds of vineyard acres in the Lodi region have assessed their practices using the *Lodi Winegrower's Workbook*.

Assessing impacts on practices

We attempted to measure the impact of LWC's outreach program on farming practices by conducting grower surveys of more than 700 members of the LWC in 1998 and 2003. The goals were to: assess the quality of LWC's outreach program, including the workbook; identify the sources of educational information used by growers and how important they are; measure the impact of LWC's outreach program on specific farming practices; assess perceptions of IPM; and gather demographic information.

Since LWC's outreach program has focused on IPM — from its inception in 1992 until the publication of the *Lodi Winegrower's Workbook* in 2000 — the 1998 survey questions focused on IPM. The 2003 survey also focused on IPM, including many of the same questions, so that the results would be comparable. As a result, data presented here is primarily related to IPM.

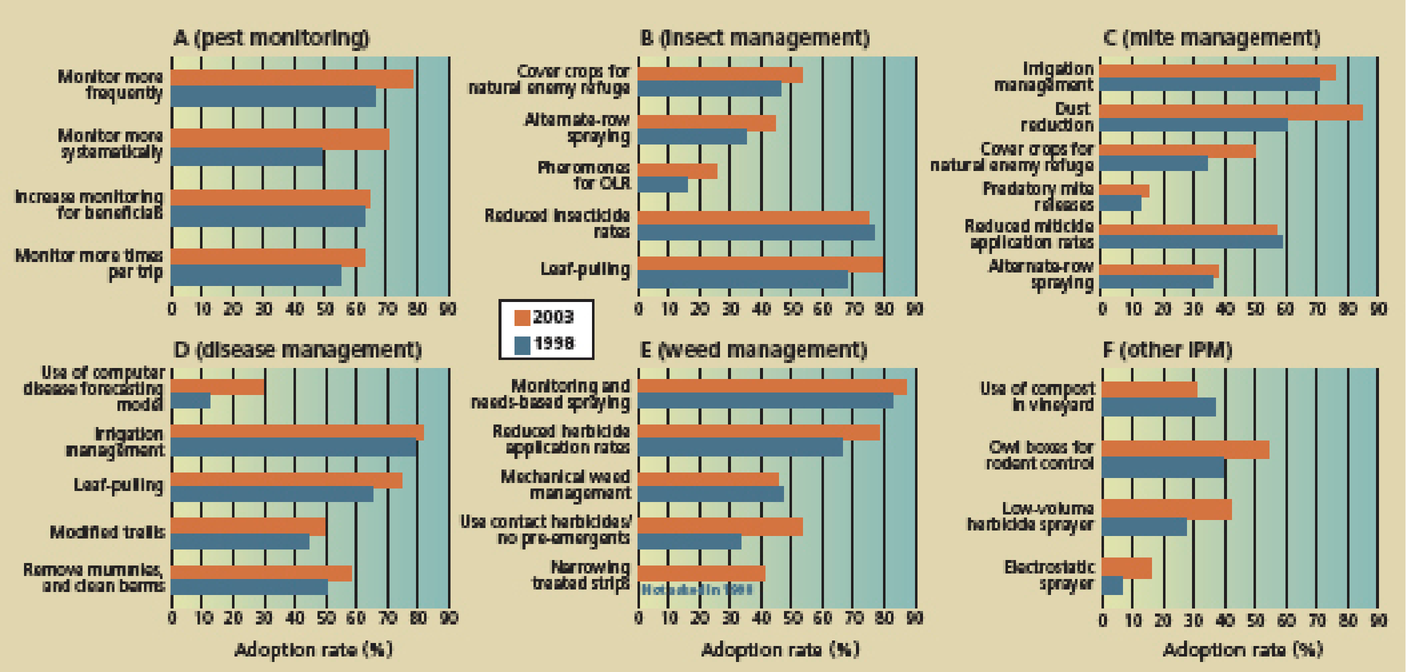


Fig. 1. Percentage of growers using specific practices for (A) pest monitoring, (B) insect pest management, (C) mite management, (D) disease management, (E) weed management and (F) other IPM practices for pest management, based on grower survey results from 1998 and 2003. Source: Dlott and Dlott 2005.

The 1998 and 2003 grower surveys where designed and carried out by Dlott and Dlott (2005), based on the mail and telephone survey Total Design Method (Salant and Dillman 1994; Dillman 2000), with guidance from the LWC Research Committee. Two weeks after the first mailing, a reminder/thank-you postcard was mailed to all growers, managers and pest control advisors (PCAs). Replacement questionnaires were mailed to those who had not returned their questionnaires at 4, 6 and 8 weeks after the initial mailing. The response rate in both years exceeded 44%, making the results statistically accurate to plus or minus 5%.

Since its inception in 1992, LWC's outreach program emphasized the importance of monitoring to manage vineyard pests, so growers were asked how their monitoring practices had changed (fig. 1A). By 1998, a large portion of growers had changed their monitoring practices, and there was a modest-to-large improvement in all categories between 1998 and 2003. For example, in 2003, 78% reported monitoring more frequently, up 12% from 1998; and 70% reported monitoring more systematically, up 21%. Monitoring for beneficial insects did not change appreciably, remaining at just under two-thirds, but 63% of respondents reported an increase in the amount of monitoring time per trip, an increase of 8%.

The percentage of growers using IPM to manage insects, mites, diseases and weeds, as well as other IPM practices, showed a modest-to-large increase in adoption in all but 4 of the 20 practices surveyed (figs. 1B–F). The increase in implementation of several practices exceeded 20% from 1998 to 2003. We hypothesize that growers increased monitoring more systematically (fig. 1A), most likely because when monitoring, one quickly realizes that systematic monitoring provides data that is comparable from one vineyard to another and from one time to another. Growers increased their adoption of dust-reduction strategies because of an increased appreciation for its role in mite outbreaks, as well as increased air-quality concerns in the Lodi region.

The increased use of computer models for disease forecasting (fig. 1D) is most likely explained by a general increase in the use of computers by growers from 1998 to 2003. Finally, the increase in replacement of pre-emergent herbicides with contact herbicides for under-the-vine weed management (fig. 1E) is likely due to an increase in grower appreciation of groundwater contamination by certain pre-emergent herbicides such as simazine.

The small increase in rate of adoption for some practices, such as monitoring more frequently (fig. 1A), reduced insecticide rates (fig. 1B), irrigation management for mites and diseases (figs. 1C and D) and reduced herbicide rates (fig. 1E) is likely due to the adoption rate being so high in 1998 that there was not much room for a large increase in 2003.

By 2002, growers managing over two-thirds of the vineyard acres in Lodi had assessed their practices using the workbook. Since the workbook program was the major outreach effort carried out by LWC between the two grower surveys, the increases in adoption of farming practices can at least in part be attributed to the workbook program.

Shifting the paradigm

The paradigm of sustainable winegrowing continues to evolve. Because it encompasses all aspects of a farming operation and a wide range of practices, it is useful to think of it as a continuum from “not sustainable” on one end to “very sustainable” on the other. A perfectly sustainable vineyard is not likely, in part because what is considered sustainable today may not be rigorous enough tomorrow. Moreover, growing grapes leaves an environmental footprint and there will always be something that can be done to make that footprint smaller. The world of sustainable agriculture is one where the horizon is always receding; this is a source of frustration for some wine-grape growers because it is human nature to want to arrive at an endpoint rather than at some point along a continuum.

A Farm*A*Syst self-assessment workbook is well suited to dealing with this situation. First, it encompasses the complete range of practices for each farming issue, from less sustainable to most sustainable. Second, for every farming issue, it provides a road map of practices, showing growers exactly what their level of sustainability is and what they can do to improve. Third, it encourages them to create and carry out action plans to make improvements. And finally, it provides an objective measurement to help growers track themselves either individually or as a group. In the future, metrics around sustainable winegrowing will need to move past simply tracking practices and include performance measures, such as the amount of energy expended and gallons of water used per ton of grapes produced, as well as balancing multiple factors along with farm-gate income.

Implementing the workbook program through small workshops around the kitchen table in growers’ homes and shop benches was unique and has had numerous positive outcomes. It got growers to open the workbook and discover its value so they would use it. As growers did the self-assessment they would ask the person next to them how they dealt with certain farming issues. Invariably lively discussions ensued, with growers sharing valuable information. Finally, the workbook program gave the Lodi growers a real sense of meeting the challenges of sustainable winegrowing as a community, and led to increased adoption of IPM practices.

C. Ohmart is Sustainable Winegrowing Director, Lodi Winegrape Commission. US EPA Region 9, the CalFed Bay Delta Program and the Great Valley Center provided partial funding for the first edition of the Lodi Winegrower’s Workbook*; the California State Water Resources Control Board provided partial funding for the second edition.*

For more information:

Lodi-Woodbridge Winegrape Commission
www.lodiwine.com

California Sustainable Winegrowing Alliance
www.sustainablewinegrowing.org

Central Coast Vineyard Team
www.ccvt.org

Farm*A*Syst
www.uwex.edu/farmasyst

Sustainable Viticulture in the Northeast
www.vinebalance.com

Washington Guide to Sustainable Viticulture
www.vinewise.org

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RESEARCH ARTICLE

Decision support tool seeks to aid stream-flow recovery and enhance water security

by Adina M. Merenlender, Matthew J. Deitch
and Shane Feirer

In many parts of coastal California, agricultural water needs during the summer are met by tapping riparian and groundwater resources, which has led to documented decreases in stream flow during the dry season. This has consequences for salmon, including sudden drying of habitat, higher water temperatures and changes in the invertebrate prey base. We developed a new, spatially explicit analytical tool to quantify and map human and environmental needs, model daily stream-flow rates, and estimate regulatory flow requirements and cumulative impacts of reservoirs. This tool is part of a decision support system that can be integrated in a Geographic Information System (GIS) with other restoration considerations. This research provides a basis for placing additional reservoir storage where projects are not likely to affect adult salmon passage, while reducing water demand from surface and subsurface flows during spring and summer, ultimately improving both habitat for salmonids and water supply for growers.

Vineyard managers need water for irrigation, as well as other purposes. In areas without reservoirs water often comes from local streams, which may also supply municipal water and provide salmon habitat. Balancing these competing water needs is a critical challenge facing the California wine-grape industry. *Above,* vineyards in the Russian River (top right) basin.

IN 2000 we reported on the expansion of vineyards into upland coastal watersheds (Merenlender 2000). With this expansion came changes in where, how and to what extent water is extracted from these watersheds for agriculture. Like most premium wine-grape-growing regions around the world, coastal California has a Mediterranean climate with most rainfall in the winter months, followed by a dry period of up to 6 months. Stream flow follows a similar trend, with the majority of flow occurring during winter and early spring, mostly as a series of high-flow events separated by lower base flows in winter (fig. 1, page 149). When the rains end, stream flow then recedes gradually to reach or approach intermittence by late summer.

Precipitation is highly variable, seasonally and interannually, leading to an extremely uncertain renewable supply of fresh water. For example, deviations in mean annual flows of 30% or more from long-term annual averages are common, resulting in continual uncertainty about water supply for human use year to year (Deitch 2006).

Moreover, California's coastal regions often have complex geology that can lead to differences in stream flow within and between watersheds. Large, natural freshwater lakes are rare, and groundwater tends to be deep or restricted to bands along river corridors, so that humans rely heavily on streams for fresh water. Because water is not often available at the times when it is needed for irrigation, growers must carefully manage water supplies throughout the growing season. As a result, much of California's water needs are met by disseminating water stored behind large reservoirs. In areas not served by large water projects, including many coastal watersheds where premium wine grapes are grown, water is often diverted from streams or pumped from the ground, and if possible, stored on-site in small private reservoirs that growers establish for use during the dry season.

In addition to irrigation, grape growers may require water for other purposes, such as the protection of young buds from frost in early spring and relief from high summer temperatures. Analyses of seasonal water demand, which describe the fine-scale means through which needs are met, illustrate that direct pumping from streams can cause stream flows to drop by more than 90% locally, and downstream areas are also affected (Deitch et al. 2008).

Water in the Russian River basin

Surface-water diversions may have the most substantial impacts on aquatic biota during spring and summer because stream flow is naturally low. The limited water available is critical for maintaining suitable habitat conditions, yet stream flow at this time is most susceptible to water diversions. In many parts of the Russian River basin, water-rights records predict that the demand for water during the spring and summer growing season exceeds supply, underscoring the imbalance between water need and supply (Deitch et al., in press); yet normal-year discharge (stream flow) during the wet season exceeds annual water removal (diversion) estimates by an order of magnitude (fig. 1).

In watersheds where water demand is high, surface-water diversions may accelerate drying over substantial stream reaches, reducing habitat for juvenile salmon and other aquatic species. Secondary effects of stream drying, such as increased competition, higher water temperatures and increased predation risk may also occur where flows are reduced (Kocker et al. 2008).

The Russian River is home to three species of salmonids: coho salmon, chinook salmon and steelhead trout. All three species have experienced serious population declines and were listed under the federal Endangered Species Act in 2004. Although their life cycles are similar, they are not identical with respect to timing and physiological tolerance; therefore, each species requires special consideration for their recovery. The life cycles of native salmonids are well adapted to the natural hydrologic regime of the region (Moyle 2002) (fig. 1).

Winter floods maintain appropriate sediment distributions and prevent vegetation encroachment, while providing an environmental signal for adults to migrate from the ocean to coastal streams. Lower-velocity winter base flows between storm events allow adult salmon to swim upstream to spawning sites and provide suitable hydrologic conditions for egg laying and incubation. Spring flows maintain in-stream connectivity, allowing juvenile fish to migrate out, aerating eggs until fish emerge, and permitting microinvertebrates — important food for salmonids — to drift downstream. In summer, streams may become intermittent (interupted by dry areas) at which point pools continue to provide over-summering habitat. Flows resume again with the onset of winter rains, triggering the movement of adult salmon downstream (Kocker et al. 2008).

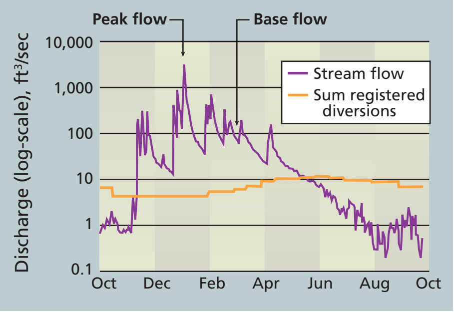

Fig. 1. Mean daily in-stream flows for 2004 from Maacama watershed, below a 43-square-mile catchment with 4.5% of its area in vineyards. Y-axis representing flow magnitude is on a log scale. To measure stream flows, Global Water WL15 pressure transducers were encased in high-pressure flexible PVC hose, attached to solid substrate and operated as stream-flow gauges according to standard USGS methods (Rantz 1982). Flow was measured using Price Mini and AA current meters at biweekly-to-monthly intervals to develop rating curves; instruments recorded stage at 10-minute intervals from November 2003 to September 2005. Arrows show examples of winter peak and base flows.

State water regulation

Since 1990, the State has hesitated to grant new or change existing water rights, in part because of concerns that additional appropriations will affect the in-stream flows necessary to sustain salmonid migration. As a result, there is a backlog of requests for additional appropriative rights, many to increase the storage of winter runoff (SWRCB 1997, 2007). Until recently, the basis for these decisions hinged on draft joint guidelines from the California Department of Fish and Game (CDFG) and National Oceanic and Atmospheric Administration (NOAA) Fisheries Service to maintain winter flows sufficient for adult salmonid migration. In December 2007, the State proposed regulations for storing surface water in northern-coastal California, related

Small reservoirs, such as in the Dry Creek watershed (shown), can help grape growers to store winter rainfall for irrigation. They also safeguard creek flows that are critical for rearing salmonids in the dry season.

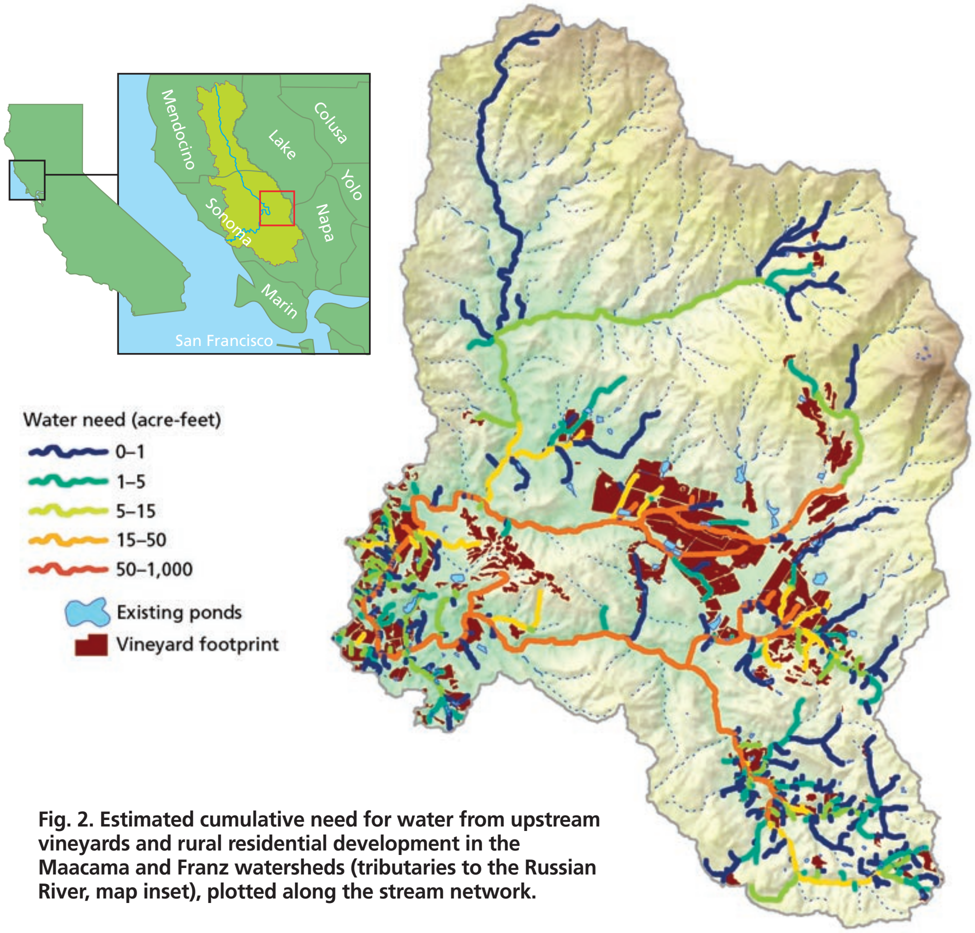

Fig. 2. Estimated cumulative need for water from upstream vineyards and rural residential development in the Maacama and Franz watersheds (tributaries to the Russian River, map inset), plotted along the stream network.

to aquatic ecosystem conservation, as part of its draft "Policy for Maintaining Instream Flows in Northern California Streams" (SWRCB 2007). They are being considered for adoption in 2008.

Because the proposed new policies for surface-water appropriations may not allow growers to meet agricultural water needs, we expect that they will continue to turn to alternative means, including riparian water diversions and groundwater pumping during the growing season, neither of which are subject to the same standards as appropriations (Sax 2002). We theorize that it may be more useful to consider the impacts of small water projects relative to cumulative impacts on discharge through the year, rather than to set a required flow condition that uniformly protects winter flows sufficient for adult salmonid migration at all locations.

We describe spatially explicit models for agricultural and rural-residential water needs, daily stream flow throughout a watershed, proposed environmental stream-flow requirements, and cumulative impact analysis of small reservoirs on stream flow. Integrating this information across entire watersheds where there are no large, centrally controlled reservoirs is essential for evaluating the environmental and social tradeoffs with different water-management schemes widely implemented across coastal California.

Estimating dry-season water needs

A Sonoma County vineyard map based on orthorectified aerial photos from 1993, 2000, 2002, 2004 and 2005, as well as oblique aerial photos from 2006 (59,000 acres in Sonoma County; see *California Agriculture* Vol. 62, No. 1, page 11; and Merenlender 2000), were used to estimate the agricultural water need by multiplying each acre by two-thirds acre-foot. (This estimate does not include additional water needed in areas where overhead sprinkling is required for frost protection [Lewis et al. 2008]). We also added 0.226 acre-foot per rural residential unit to account for outdoor water use by the average home. Rural residential units were mapped based on county parcel and assessor's data, which includes units per parcel. Estimated water need was then summarized for each individual land parcel.

Reservoirs were also digitally mapped from aerial photographs, and the surface area for each reservoir was used to estimate total volume based on an empirical statistical relationship between a sample of recorded volumes and surface area (n = 100) from the State. The estimated volume of winter water storage in existing reservoirs on a given parcel was subtracted from the estimated water need per parcel as described above. We then calculated total water need per parcel not met by winter water storage. Total water need for each land parcel was then summed downstream using a flow accumulation model to determine the cumulative need through the entire drainage network (ESRI 2006) (fig. 2).

In-stream flow thresholds

To compare the amount of water permitted for removal under the new proposed in-stream flow regulations with amounts permitted under existing guidelines, we mapped the regulatory flow thresholds based on these two policies and estimated allowable withdrawals. The new proposed regulations restrict water diversion actions to the winter rainy season, Oct. 1 through March 31. Also, a specific flow threshold must be exceeded before water can be diverted from the stream. This flow threshold is defined as the minimum flow corresponding to a depth that allows salmonids to migrate upstream, preserving the potential for them to find adequate spawning reaches. This standard, the minimum bypass flow, is calculated as:

$$\text{Qmbf} = 9.4\ \text{Qm}\ (\text{DA})^{-0.48}$$

where Qmbf is minimum bypass flow in cubic feet per second; Qm is mean annual unimpaired flow in cubic feet per second; and DA is the watershed drainage area in square miles (for streams with watershed area less than 295 square miles). If the upper limit of anadromy (the point above which the stream is no longer considered salmo-

Aerial photography of vineyards, coupled with stream-flow data, is being used to develop models that will help growers and regulators to better plan for future water needs and salmon recovery. In, *left,* Alexander Valley and, *right,* Dry Creek, vineyards grow on hillsides.

nid habitat, defined as a 12% gradient over a length of 100 meters; SWRCB 2007) is downstream of the point of diversion, the drainage area at the upper limit of anadromy may be used.

Part of the proposed regulation is related to the total amount of water that can be diverted at any time. This is intended to protect peak storm flows, which are important for moving large materials in the stream and reshaping stream channels. This standard, described as the maximum cumulative diversion criterion (Qmcd), is defined as 5% of the 1.5-year instantaneous peak flow at the proposed point of diversion (this peak flow rate is estimated using historical data). We calculated the minimum bypass flow and maximum cumulative diversion in the GIS for every point in the drainage network to examine how the conditions for diversion established by the regional protective criteria vary spatially; where and when stream flow is expected to exceed these threshold levels; and how much water could be diverted when these thresholds are exceeded.

We used the GIS to map the amounts of surface water that would be allowed under these proposed policies for all points across the drainage network, using the following steps: (1) estimating mean daily flow from the normal-year U.S. Geological Survey (USGS) stream-flow data according to watershed area and precipitation differences for all points throughout the drainage network; (2) calculating the Qmbf and Qmcd according to the definitions above; (3) counting the number of days at each point when the expected mean daily flow exceeded the calculated minimum bypass flow threshold over the diversion season, using an average rainfall hydrograph from the historical period of record (1966); and (4) multiplying the number of days by Qmcd (up to the defined Qmbf).

For example, we used stream-flow data at the centrally located Maacama Creek near Kellogg USGS gauge (number 11463900, in eastern Sonoma County, with a 20-year period of record from 1962 to 1981) for a normal-type year (1966, a year with median annual discharge over the period of record), and scaled this stream-flow data by watershed area and mean annual precipitation to create a daily stream-flow value for each point in the drainage. We then counted the number of days for each stream segment where stream flow exceeded Qmbf to determine the number of days during the winter diversion season that water users could divert.

For comparison, we calculated the maximum annual diversion for each point in the Maacama Creek drainage network using a standard of no more than 10% of the winter-season discharge, approximately equivalent to the maximum allowable diversion volume given in the 2002 draft joint guidelines (CDFG/NMFS 2002). This comparison allowed us to quantify the differences between policies relative to the impacts they have on potential appropriators and relative to their location in the watershed.

Cumulative small-reservoir impacts

We also created a model using our GIS to examine the cumulative impact of small surface reservoirs on stream flow through the year, as reservoirs fill from the onset of the rainy season in fall. Estimated reservoir volumes (mean = 28 acre-feet, median = 9 acre-feet; 91% of 1,087 mapped reservoirs are less than 50 acre-feet) in the Sonoma County portion of the Russian River watershed were incorporated into our watershed model, and the upstream catchment area was calculated for each reservoir. We modified the digital elevation model by inserting existing mapped reservoirs so that water flowed from the upper watershed into the reservoirs until they filled and then out the lowest point of the reservoir into the downstream drainage network.

The start of the delineated network began at the reservoir outlets. All segments of the stream network had the maximum flow accumulation value from upstream assigned, and the hydrologic network was then exported from ArcGIS (ESRI 2006) as lines and points into a spatial database. The database files related to the shapefiles were then imported into a Microsoft Access database, which manipulated the stream network created by the GIS. The database was then used to estimate flow across the watershed. The model assumes that reservoirs are empty at the onset of the water year, and that small dams block discharge from up-

Collaborative conservation helps achieve regional water-quantity goals

Land and water conservation in places such as coastal California, which is almost entirely comprised of private land, cannot occur without landowner participation. We are engaged in a collaborative conservation process with a public interest group called the Salmon Coalition, to facilitate landowner participation in transformative restoration. This coalition represents a growing demand for more adaptive local approaches to resource management.

The Salmon Coalition was formed in 2006 to increase communication among the private landowners of Dry Creek, Knights and Alexander valleys (northern Sonoma County); resource agency staff (the National Oceanic and Atmospheric Administration and the California Department of Fish and Game); the Sonoma County Water Agency and their urban clients (nine water districts in Sonoma and Marin counties); environmental interest groups; and other stakeholders. Its goal is to set restoration priorities for salmon recovery while protecting and hopefully improving water security for rural and urban uses, and providing certainty to private landowners dealing with the federal Endangered Species Act (ESA). The coalition is an example of a policy-based initiative that utilizes stakeholder participation to design plans intended to protect habitat as compensation for regulatory protection against potential ESA violations (Cestero 1999).

Collaborative conservation is increasingly popular as decision authority on how to implement species recovery devolves from government to public stakeholders. An increased emphasis on farmer participation in water management planning is now part of the 2008 Farm Bill. The Agriculture Water Enhancement Program changes existing ground- and surface-water conservation programs to allow cooperative agreements between the Secretary of Agriculture, multiple producers, government entities and tribes, with $70 million for each of fiscal years 2008 through 2012. Collaborative conservation will provide the basis for these agreements.

The outcomes of collaborative conservation are generally untested. In an attempt to define a common language and share lessons from case studies, a Sonoran Institute report called "Beyond the Hundreth Meeting" focused on public land issues, offering guidelines for improving the success of public planning processes (Cestero 1999). Place- or community-based efforts are distinguished from those that address a specific policy or interest-based initiatives, like the Salmon Coalition.

Cestero (1999) also reports that place-based efforts work best if they are led by local participants rather than government representatives, and take place in an open and inclusive process that can accommodate a full range of perspectives — including government representatives. It is also better if participants do not try to represent larger interest groups, because confusion can arise when individuals are held accountable for the larger, diverse group, some of whom will feel their interests were not well represented. In addition to completing the desired projects, collaborative conservation increases capacity among community residents to respond to external and internal stresses that will inevitably arise. This capacity can help prevent future problems from becoming crises.

Collaborative conservation groups that focus on smaller areas are more likely to succeed, because those involved can relate to the landscape in question and regular participation from people spread across a large geographic area is not required (Cestero 1999). The Quincy Library Group in Northern California, for example, was a group of approximately 30 people who developed a plan for 2.5 million acres of public forestland. Ultimately, the plan did not adequately address the diverse interests represented in this large and relatively populated area (Duane 1997). Such larger-scale conservation projects are better addressed through a network of local efforts (Cestero 1999).

The Salmon Coalition is primarily focused on two subwatersheds within the Russian River. Equally important, the Salmon Coalition has agreed to a participatory research effort that will greatly increase understanding of the various ways that water is managed across private lands. One way to empower a group early on is to begin collecting and evaluating existing information to increase understanding of the system (Cestero 1999). Wine-grape growers are providing us with information on water management practices, and private landowners will provide access for further stream-flow monitoring. Without this cooperation, local information could not be collected and we would continue to rely on coarse assumptions and management models that are ill-suited for such a complex system. The data will enhance our understanding of human-ecosystem interactions — a necessary step to better inform future water management and policy decision-making.


Mary Ann King

The Salmon Coalition and Trout Unlimited hosted a "Water and Wine" field tour.

We intend for these efforts to help the State and local stakeholders resolve problems over additional requests for appropriative rights to store more water during the rainy season. Our data analysis and models will also be used by Sonoma County to improve its estimates of available flows for ecological processes (including enhancing salmonid recovery efforts) and municipal uses.

— *A.M. Merenlender*

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stream until the reservoir fills (that is, when the cumulative discharge volume from the upstream watershed equals the volume of the reservoir), at which time the upstream drainage network is reconnected hydrologically with the rest of the watershed.

We then used the flow accumulation model to determine the fraction of discharge accumulating from unimpeded parts of the watershed, and adjusted this fraction to reflect flow conditions as reservoirs fill through the winter. In addition to showing local effects of reservoirs (i.e., immediately below the dam), the model is designed to illustrate the cumulative impacts of reservoirs on stream flow anywhere in the drainage network, including flow from unimpaired streams.

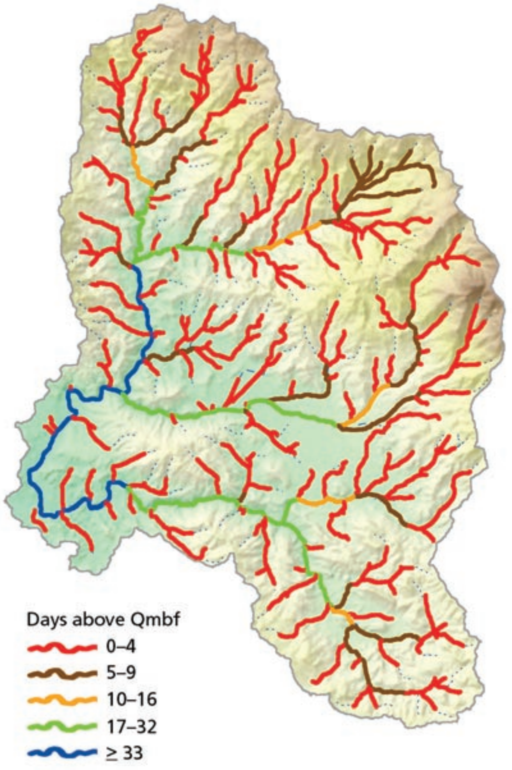
Calculating water needs

Our calculated estimate of total water need ranged from approximately 1,500 to 4,500 acre-feet at the bottom of the major tributaries to the Russian River. This is the estimated demand that is currently unmet by storage ponds and may be extracted during the dry season from surface water, subsurface stream flow and groundwater.

Policy scenarios. Analysis of the new proposed policy restrictions reveals that in headwater streams where new vineyards rely on freshwater resources, surface-water projects would only be permitted to remove water for 2 to 8 days in a normal year during the rainy season in Maacama Creek (fig. 3). Expanding to a broader area, this analysis reveals that an estimated 57% of the drainage network across the Russian River in Sonoma County would be restricted to 0 to 4 days for the diversion of winter stream flow. This is because much (79%) of this area is made up of watersheds less than 0.63 square mile (1 square kilometer) where first-order streams (unbranched tributaries) predominate. We compared the estimated amount of winter surface water allowed to be stored, based on the existing joint policy guidelines, with those proposed by new regulations (table 1). The observed differences for small headwater streams are important because more than 90% of the 1,000 reservoirs in the Sonoma County portion of the Russian River watershed have upstream catchments of less than 0.5 square mile.

Small reservoirs and winter flows. Using normal-year flow data from a time of few dams and diversions (representing unimpaired flow), the model indicates that early-season stream flow in some major tributaries to the Russian River may be reduced by as much as 50% and that these impaired sites are predominately found in small watersheds (fig. 4A). Therefore, we expect that early-season rains may produce only a fraction of the stream flow that would be expected in the absence of small reservoirs.

However, the impact diminishes as the rainy season progresses because



▲ **Fig. 3. Number of days per year that estimated flow exceeds proposed new instream flow policy's minimum-bypass threshold along the Franz and Maacama drainage network. Under the proposed policy, surface-water removal would be allowed in 57% of the continuously mapped drainage area for 0–4 days, 19% for 5–9 days, 7% for 10–16 days and 9% for 17–32 days. Only 8% of the mapped area would allow surface-water removal for 33 days or more.**

TABLE 1. Amount of water allowed to be removed from watersheds under existing joint guidelines, compared with those recently proposed by the State*

Watershed area (square miles)	Joint guidelines	New proposed policy
	acre-feet	
45	5,180	9,100
15	1,835	2,800
5	630	581
1	120	36
0.4	48	7

* Based on calculations from Maacama Creek watershed (Sonoma County) using GIS methods described.

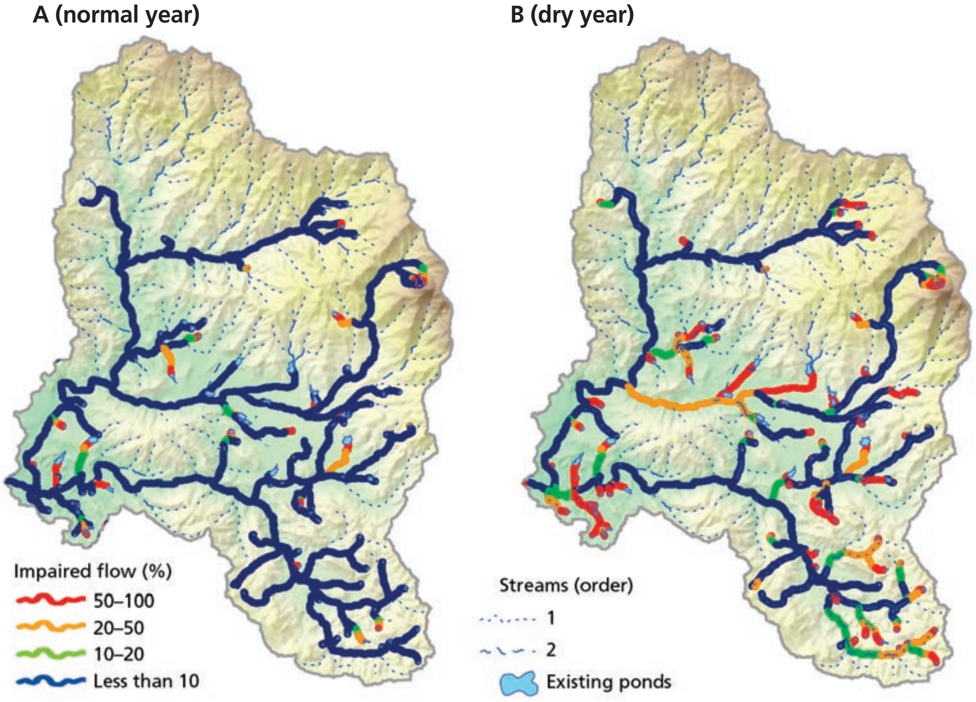


Fig. 4. Levels of flow impairment due to a reservoir's impeding winter flows estimated for week 15 of the water year, based on (A) 1966, a nomal-year hydrograph (median annual discharge) and (B) a dry-year hydrograph (1971, lower-quartile annual discharge, based on historical data). Higher levels of impairment for small reservoirs can be seen for this very dry year. Stream order is also mapped: unbranched tributaries are first order, two first-order streams join together to form a second-order stream, and so on.

reservoirs fill over time: stream flow is reduced by less than 10% by the end of December for most reaches in normal rainfall years because many reservoirs have filled by this point (fig. 4A). Also, 90% of the most-impaired sites are in very small watersheds because reservoirs in the Russian River watershed are commonly focused in headwater streams (table 2). The window for upstream bypass is larger lower in the watershed as compared to upper tributaries, and these reservoirs are less likely to affect the ability of salmon to migrate through lower reaches to find suitable spawning tributaries. The impacts increase when the driest year on record is used to run this reservoir impacts model (fig. 4B). This modeling effort can help reveal where additional reservoirs for storing winter rainfall can be placed to minimize impacts on adult salmon passage and relieve the effects of current management practices on spring and summer stream flow.

A hypothetical example illustrates the tradeoffs between site-level impacts on winter flows from increasing reservoir storage in upland sites for vineyard use, and reductions in water demand over the dry season (figs. 5–7). This upland tributary to Dry Creek in the Russian River basin currently has two upland vineyards requiring an estimated 90 acre-feet of water for irrigation (fig. 5). Reservoirs for winter water storage currently do not exist and the water used is pumped on demand during the dry season, which could reduce intermittent summer flows. To offset impacts on summer flows, small reservoirs averaging 20 acre-feet in size can be hypothetically placed in the upper watershed where they are needed. This reservoir impact model can then be run to estimate the impacts to winter flows (fig. 6), which are limited to just downstream of the storage pond. These small, distributed reservoirs can store sufficient winter water to offset the water needs of these vineyards (fig. 7) and offset the demand for water in the summer.

Water management framework

By quantifying and mapping estimated human needs, environmental

TABLE 2. Percentage of watershed area across entire Russian River basin in Sonoma County that falls within each impairment class, and percentage of those percents that are found in different-sized watersheds

		Upstream catchment area (square miles)				
Impairment (%)	Impaired drainage	< 0.4	0.5–4	4.1–15	15.1–40	> 40.1
			%			
< 10	46	17	41	18	9	15
10–20	17	28	34	18	10	10
20–50	15	37	30	10	3	20
> 50	22	55	26	5	4	10

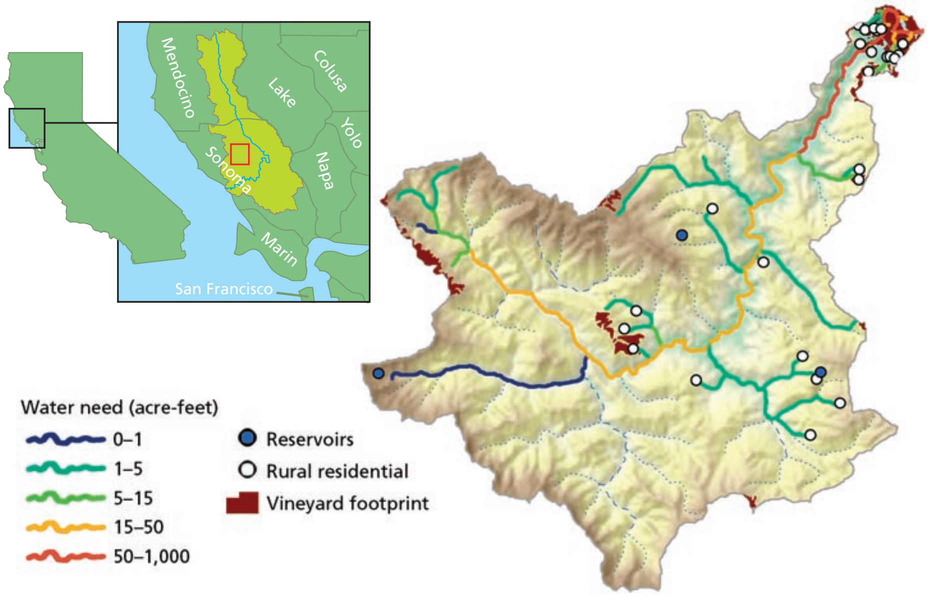
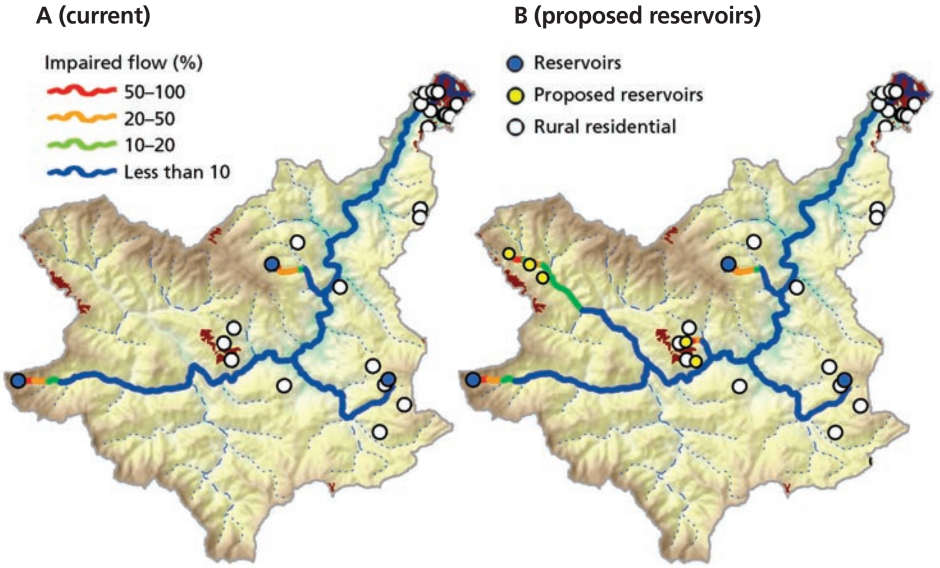


Fig. 5. Estimated need for water not met by existing winter water storage along Pena Creek, tributary to Dry Creek, from residential areas and two upland vineyards.


A (current)

B (proposed reservoirs)

Fig. 6. (A) Impacts of the few existing reservoirs (blue dots) along this creek. (B) Impacts estimated to occur if small, 20 acre-foot reservoirs (yellow dots) were placed on vineyard parcels to meet estimated water needs during the dry season from winter runoff early in the season (day 63 of the water-year based on Pena gauge station data for 1981, a normal rainfall year).

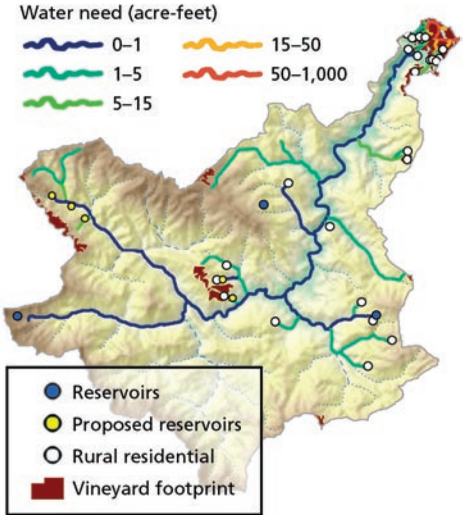


Fig. 7. Greatly diminished water need during the dry season for Pena Creek after the hypothetical placement of several upland reservoirs.

needs and reservoir impacts — and presenting them visually with other restoration considerations — we can provide decision-support for informing water management and salmonid restoration in the wine country of northern-coastal California.

In particular, we demonstrate that these tools can be used to evaluate various water-policy scenarios (i.e., changes to bypass flow thresholds), estimate the cumulative effects of water extraction methods on the natural hydrograph across a large spatial scale (including temporal variation), and provide information for the watershed-level planning required to recover environmental flows for salmonids. Given highly variable year-to-year rainfall patterns it is important that the modeling tools described here allow hydrographs based on low, moderate and high rainfall years to be used to evaluate the impacts of water management. These applications are relevant to the State's water-allocation decision-making process, resource agencies involved in salmonid recovery planning, and private landowners interested in water management solutions and habitat restoration. These models can be compared with existing data on salmon habitat, physical barriers and other mapped information including existing and proposed appropriative water rights, to help prioritize stream-flow restoration needs for salmon recovery.

Our model expresses water needs over a coarse annual scale, while ecological requirements operate at finer scales. However, we are working with the agricultural community to provide increased insight into the timing of water needs throughout the growing season (see sidebar, page 152). Decisions about reservoir management and the amount of water needed during the growing season are currently made based on uniform assumptions, but we believe that better decisions can be made by working with growers to parameterize the models based on their actual water-use practices.

The models presented here quantify the tradeoffs for both wine-grape growers and salmonid recovery efforts, between storing more water in the winter and pumping on-demand year-round to meet agricultural and residential water needs. Environmental flows should be considered across the entire year to improve salmonid habitat. This framework can help to identify potential solutions for ecological and economic interests in the region, helping to prevent future regional environmental and social crises that can arise around salmon and other endangered-species recovery programs.

A.M. Merenlender is Cooperative Extension Specialist, Integrated Hardwood Range Management Program, Department of Environmental Science, Policy and Management (ESPM), UC Berkeley; M.J. Deitch is Senior Environmental Scientist, Center for Ecosystem Management and Restoration, Oakland (formerly Postdoctoral Fellow, ESPM, UC Berkeley); and S. Feirer is GIS analyst, UC Hopland Research and Extension Center. This research was funded in part by the U.S. Environmental Protection Agency (STAR grant G4K10732), and Sonoma County Water Agency. Our colleagues at UC Berkeley have been instrumental in developing some of these ideas: Juliet Christian-Smith, Ted Grantham, G. Matt Kondolf, Ruth Langridge, David Newburn and Vince Resh. We also thank the Salmon Coalition for their interest in applying our research.

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RESEARCH ARTICLE

Leafroll disease is spreading rapidly in a Napa Valley vineyard

by Deborah A. Golino, Ed Weber, Susan Sim
and Adib Rowhani

In the 1930s and 1940s, little was known about viruses, and information on plant diseases caused by viruses was just beginning to appear in the scientific literature. Problems with grapevines in California, first referred to as "red leaf," were initially attributed to inexperience in viticultural techniques and poor growing conditions. However, the problem was later identified as leafroll disease, which causes red leaves, and poor yields and fruit quality. We evaluated its rate of spread for 5 years in a Napa Valley vineyard, and found an average rate of more than 10% per year. Leafroll disease can be vectored by low-level populations of grape mealybugs, and is now spreading rapidly in at least one Napa Valley vineyard for unknown reasons. Using stock for planting vines that is certified as virus-free is a key strategy in preventing the spread of grapevine leafroll disease.

Grapevine leafroll, a viral disease that reduces fruit quality and yield, is diagnosed by the presence of red leaves (shown). The manager of this vineyard had observed low levels of grape mealybug, an effective disease vector, since the early 1990s.

As California's wine industry developed and grapevine plantings expanded during the 1940s, new knowledge and methods of disease detection gradually made clear to scientists just how widespread virus disease problems were in the state's vineyards. A classic case involved leafroll disease in a red table-grape variety from Iran. Called 'Emperor', this variety was reported to be the third-most-important table grape in California in 1941. Often, growers reported low color development and sugar levels, which led to the idea that two varieties actually existed: the normal, red 'Emperor' and the so-called 'White Emperor'. However, in 1943, UC Davis viticulturist Harold Olmo and his colleagues determined that this problem was perpetuated by vegetative propagation and proposed that a virus was involved (Olmo and Rizzi 1943).

In 1946, U.S. Department of Agriculture scientists in Fresno demonstrated that the 'White Emperor' condition was also transmissible via grafts, a method still considered to provide strong evidence that a virus is the causal organism (Alley and Golino 2000; Harmon and Snyder 1946). Grafting a piece of a diseased, infected plant onto a healthy plant can transmit a plant disease caused by a virus. Viruses move from one living cell to another (they are obligate parasites) and will move readily from the grafted piece of the diseased plant into the healthy plant to which it is grafted. This was an important piece of research in grapevine virology because it also linked virus disease with poor vineyard performance. The importance of propagation from healthy stock also became clear to researchers and industry (Alley and Golino 2000).

Significant progress was made in the 1960s and 1970s to reduce the incidence of leafroll disease in California vineyards. The grapevine certification program first proposed by Olmo in 1951 had become a reality, and the material produced in the program became widely available. This successful approach is based on the use of disease-tested grapevine nursery stock, produced at Foundation Plant Services (FPS) at UC Davis through the California Grapevine Registration and Certification Program, which is overseen by the California Department of Food and Agriculture (Olmo 1951; Alley and Golino 2000). Through this program, virus-contaminated stock in commercial propagation is replaced with grape scion and rootstock varieties that are disease-tested, professionally identified and made available to grape growers by participating grapevine nurseries. The program is still active today.

However, many California grape growers continue to use noncertified planting stock, which is often infected with virus. Historically, where the absence of soil-inhabiting pests such as phylloxera or nematodes makes it possible, growers of wine, table and raisin grapes have planted vines that are simple rooted cuttings with no rootstock (known as rootings). Most often obtained from local vineyards, the propagating wood may be heavily infected with viruses. This can save money at planting time but inevitably costs growers money in the long term in reduced yields and quality of fruit. In areas where the insect phylloxera will kill vines unless resistant rootstocks are used, wine-grape growers often buy certified rootstock (free of virus) that is field-budded with scion wood (the fruit-producing top portion of the vine) obtained either locally or from a vineyard with a reputation for producing excellent wines. Much of this scion wood is infected with virus, and even though the certified rootstock is free of virus, the infected scion bud can transmit virus to the entire vine, from top to bottom.

Unfortunately, the use of propagating wood that is not checked for virus (also known as "common stock") has resulted in virus disease problems, ranging from mild to severe, in many California vineyards. Growers continue these practices, despite convincing evidence that modern vineyards do not perform optimally when a virus is present (D. Golino, in preparation). Furthermore, virus-borne diseases can result in significant losses of yield and fruit quality and may also lead to the death of vines (Martelli 2000). More than 50 different viruses are known to infect grapevines worldwide. The most common, economically damaging viruses in California are grapevine fanleaf virus, the grapevine leafroll viruses and the grapevine vitiviruses.

Virus epidemiology

In 1992, enzyme-linked immunosorbent assay (ELISA) tests were put into use at FPS for grapevine leafroll viruses. ELISA is a simple laboratory serological test that can in some cases substitute for field tests taking up to 2 years. (Weber et al. 2002) These tests revealed the presence of "grapevine leafroll associated viruses" (GLRaV) in previously healthy vines in a vineyard block from the 1960s maintained by FPS, indicating active virus spread in recent years (Rowhani and Golino 1995). FPS responded by removing the block from the Grapevine Registration and Certification program, increasing isolation distances from any grapevines that might have virus, and implementing a comprehensive virus-screening program with the new methodology. Since that time, new and increasingly sensitive laboratory tests for grapevine viruses have allowed regular testing of all FPS vines.

The critical remaining problem once these actions were taken was the lack of information on leafroll virus epidemiology. All the previous work had indicated that vine-to-vine spread of leafroll rarely occurred in California vineyards, and no insect vectors had been reported (Goheen 1989). However, when the distribution of infected plants in the old FPS vineyard was mapped, newly infected vines were frequently adjacent to those known to be diseased. Also, contrary to common wisdom at the time, this field spread appeared to have occurred fairly rapidly in just a few years (Rowhani and Golino 1995).

Taking our lead from work done in Europe and New Zealand, which demonstrated that mealybugs could spread leafroll viruses (Martelli 2000), we attempted to transmit California strains of leafroll virus with mealybug species found in California vineyards. At that time, we determined that four species of mealybug were able to transmit GLRaV-3 under experimental conditions. All four are commonly found in California vineyards: the obscure mealybug, *Pseudococcus viburni* (Signoret); the longtailed mealybug, *Pseudococcus longi-spinus* (Targioni Tozzetti); the citrus mealybug, *Planococcus citri* (Risso); and the grape mealybug, *Pseudococcus maritimus* (Ehrhorn) (Golino et al. 2002).

This work, along with the evidence of spread in the FPS vineyard, raised concerns among nurseries and growers about field spread of leafroll disease in California vineyards.

Leafroll in a Napa vineyard

In fall 2002, a viticulture researcher in Napa called to our attention a 12-year-old Cabernet Sauvignon vineyard in which leafroll disease appeared to be spreading. No leafroll disease had been evident in the early years after the block was planted in 1998, and the vines had been propagated with certified rootstock and field-budded with scion wood from a nonsymptomatic vineyard source. At this time, it was unusual for a Napa Valley grape vineyard to be propagated with certified scion wood, but management had made careful observations used to source the scion wood and it appeared to be free of symptoms. By 2002, however, many vines were showing characteristic symptoms of leafroll disease, including dark-red, cupped leaves with green veins and fruit that matures more slowly than on healthy vines. The majority of symptomatic vines were on one edge of the vineyard, close to an older vineyard that had leafroll disease.

Mapping leafroll. That fall, we began mapping disease incidence in a portion of the newly infected vineyard in an effort to determine the rate of spread of leafroll disease. Mapping continued until fall 2006 (fig. 1). The mapped vineyard (block 1) was 'Cabernet Sauvignon' planted in 1989 on several different rootstocks with 6 feet (about 2 meters) between rows and 3.3 feet (1 meter) between vines in the row. The block was budded on several different rootstocks because the winery was beginning to replace blocks planted with AXR-1 with alternative rootstocks. The source of the budwood is uncertain, but no leafroll symptoms were observed for the first 9 or 10 years, suggesting that the original stock was free of virus. Red-leaf symptoms of leafroll appeared in this vineyard in 2000, primarily at the eastern ends of the rows. The number of symptomatic vines was reported to be increasing each year.

Across an avenue from the eastern end of this block was another Cabernet Sauvignon vineyard (block 2) that was

Symptoms of grapevine leafroll disease include red, cupped leaves. Older leaves are the first to show symptoms each summer, and symptoms are strongest just before leaf-fall.

Leafroll symptoms in some vines were mild and showed reddening only at the leaf margin on a few leaves; this plant tested positive using ELISA for GLRaV-3.

Each year, a larger proportion of the vineyard was diseased, reducing yield and quality with each increment of spread.

planted from 1970 to 1972 (fig. 1). This planting was heavily infested with leafroll, as evidenced by the red-leaf symptoms throughout the block reported by the vineyard manager. This vineyard was pulled in 1994 due to leafroll disease and the field was replanted in 1998 after a 4-year fallow. Grape mealybugs were observed in both these blocks most years, but never reached population levels where insecticide treatments were made.

In October 2002, we mapped part of the newly infected block 1 to assess the incidence and pattern of vines with leafroll symptoms. The mapped area included 98 complete rows (approximately 15,680 vines) and covered 7.2 acres (fig. 1, orange section of block 1). When infected with leafroll virus, Cabernet Sauvignon normally produces strong, characteristic visual symptoms that most notably include dark-red cupped leaves with green veins. Vines were individually rated for symptoms of leafroll disease using a scoring system of: 0 = no symptoms; 1 = mild or severe symptoms; Q = questionable (usually difficult to determine due to mite feeding on leaves, which can also cause leaf-reddening); C = canker symptoms masking possible leafroll symptoms; and X = dead or missing vine. Observations were made annually from October 2002 through October 2006.

ELISA testing. To test the accuracy of the 2002 visual-symptom ratings in block 1, 75 petiole samples were tested using ELISA for four grapevine leafroll associated viruses: GLRaV-1, GLRaV-2, GLRaV-3 and GLRaV-4 (Weber et al. 2002). Using our symptom scoring system, 35 of these samples were from vines rated strongly positive for leafroll, 20 vines rated negative and 20 vines rated questionable.

The ELISA testing found only GLRaV-3 in samples from symptomatic vines. The visual-symptom ratings were very accurate, although not in perfect agreement with the ELISA testing. All 35 samples from vines visually rated as positive for leafroll were also positive for GLRaV-3 by ELISA testing. In addition, all of the vines rated as questionable tested negative for virus. However, 2 of the 20 vines (10%) rated negative actually tested positive for GLRaV-3. It is possible that these two positive ELISA tests were examples of vines that were already infected but not yet showing symptoms. Nonetheless, it was clear that visual symptoms were highly correlated with the presence of virus and could be used for large-scale mapping.

With this background information, in subsequent years we eliminated the “questionable” and “canker” categories from the rating system, so that each plant was rated either negative for leafroll, positive for leafroll, dead or missing.

In fall 2007, we repeated ELISA testing on 204 vines to access the accuracy of our visual ratings. Out of 101 vines visually rated as positive for leafroll disease, all but one tested using ELISA were positive for GLRaV-3. Out of 103 vines visually rated as negative, all but three also tested using ELISA were negative for GLRaV-3. It is highly probable that the three latter nonsymptomatic vines represented early stages of infection when there were mild or no symptoms. In our experience, mild symptoms are easily overlooked.

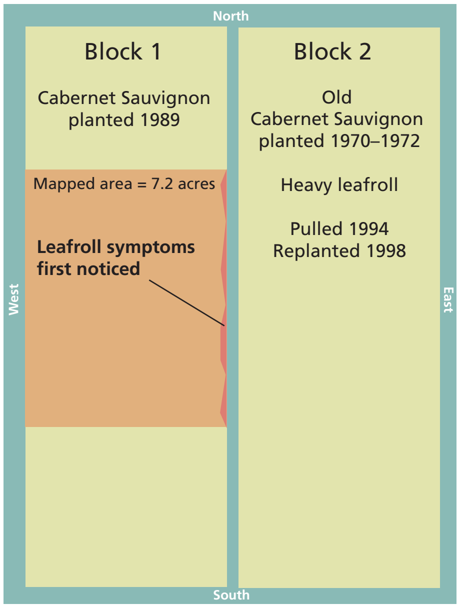

Fig. 1. Leafroll spread was mapped in a Napa Valley Cabernet Sauvignon vineyard planted in 1989, west of an older block heavily infected with leafroll. The two blocks were side by side for 5 years, providing the opportunity for leafroll disease to move from the old block to the new. The red section shows where leafroll symptoms were first noticed. Mapping was conducted each fall from 2002 to 2006 on a vine-by-vine basis in the 7.2 acres indicated by the orange area.

Quantifying virus spread

Our 2002 mapping results showed that leafroll symptoms were present in 23.3% of the vines in the mapped area of block 1 (fig. 2). The distribution of symptomatic vines suggested that leafroll initially spread from block 2 (the adjacent, older, infested block) into the eastern end of block 1, and subsequently spread down the rows toward the west. Nearly all vines on the eastern ends of the rows were rated positive for leafroll, and only a handful were positive on the western end.

The incidence of symptomatic vines in the mapped area increased to 41.2% in 2003 and to 45.8% in 2004, and the distribution of diseased vines continued to show evidence of spread from east to west. We also observed leafroll symptoms in the more recently planted vines in block 2, suggesting that leafroll had now spread back into the new vines in block 2 from the diseased vines in block 1.

In 2004, there was such a difference in fruit quality and ripening patterns that the vineyard was harvested twice — as two separate fruit loads with different harvest dates. Fruit from the healthy vines ripened earlier, was better quality and was used for reserve wines, which command a higher price. Fruit from the diseased vines was picked several weeks later and was not used for reserve wines.

The incidence of leafroll kept increasing, reaching 49.8% in 2005 and 66.1% at the end of our study in 2006 (fig. 3). Due to the inferiority of fruit from the infected vines, the vineyard owner is now faced with the need to replant this block after only 15 years. Most grape growers would expect a much longer vineyard life for their initial investment, quite often twice this long. In 2003, UC cost studies estimated the cost of establishing an acre of vineyard in the North Coast at about $25,000; no harvest would be expected in the first 3 years while the vineyard is being established. It is easy to see that more-rapid replanting of vines due to leafroll spread in vineyards could greatly increase the cost of grape-growing in any part of California affected by this problem.

Role of grape mealybug

The vineyard manager, who is an entomologist, had observed grape

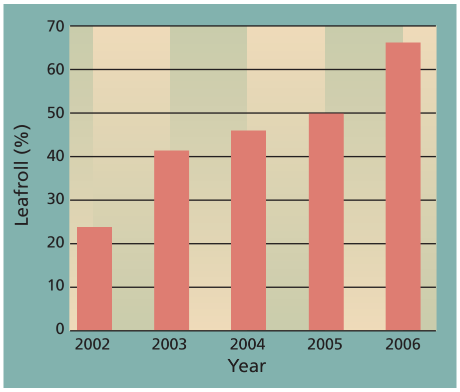

Fig. 2. From 2002 to 2006, the percentage of leafroll-symptomatic vines in a Napa County Cabernet Sauvignon vineyard increased from 23.3% to 66.1%, an increase of more than 10% per year.

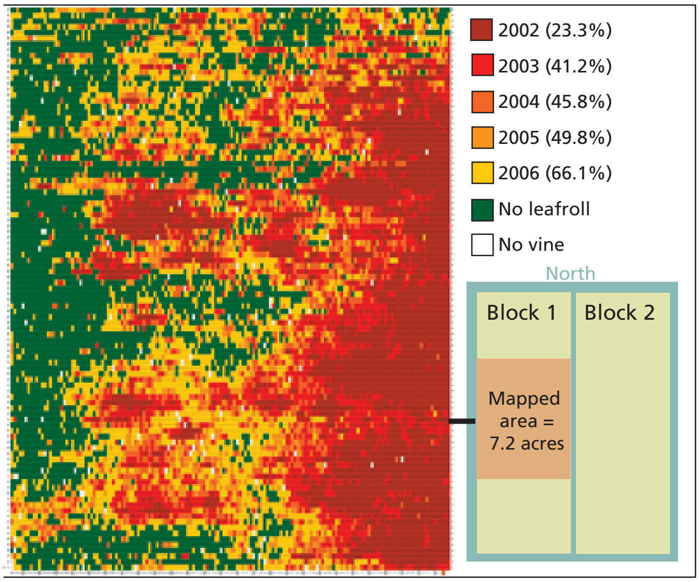

Fig. 3. Spread of grapevine leafroll virus in the mapped area of block 1 (see fig. 1) of a Napa County Cabernet Sauvignon vineyard, 2002–2006.

mealybug in this and surrounding vineyards over many years. The mealybugs were at low populations that were not considered problematic because they did not cause obvious economic damage. However, a low population can still serve as an effective vector for virus diseases in many crop systems without doing direct, significant damage to the plants. Therefore, we believe that the mealybugs were likely responsible for transmitting GLRaV-3 between blocks 1 and 2, and for the spread documented in block 1. The risk of leafroll spread from such small populations had not previously been a consideration when potential damage from grape mealybug was assessed. Similar low populations of grape mealybug are regularly observed in much of Napa Valley (Kent Daane, personal communication).

The steady increase in infection rate seen in our mapping study is the first documentation of significant and rapid field spread of leafroll disease in a California vineyard. The significance of this spread to the grower is clear: each year, a larger proportion of the vineyard was diseased, reducing yield and quality with each increment of spread (figs. 2 and 3).

Possible causes for rapid spread

Several other vineyards in California have been reported recently by growers at meetings to exhibit leafroll spread at rates similar to those documented here. We believe that if such high rates of leafroll spread had occurred in the past in California, the problem would have been described by a number of excellent researchers who have worked on grapevine virus diseases or by observant vineyard managers. That they never did so suggests that something fundamental has changed in these vineyards to allow such spread to occur, such as vector epidemiology, grower rootstock preferences and/or new leafroll strains that are more easily transmitted in California vineyards.

Vector epidemiology. While the possibility always must be considered, nothing has been observed to suggest that a new vector is responsible for the spread of grapevine leafroll disease observed in this study. The vineyard had a history of grape mealybug, which has been in California throughout its grape-growing history. In addition, while the vine mealybug is blamed for rapid spread of leafroll disease in South Africa (Martelli 2000), it was only recently introduced to California and is not yet present in Napa Valley. In the late 1980s, vine mealybug was the first species of this pest reported in the international literature to transmit leafroll virus (Martelli 2000).

Unfortunately, we expect vine mealybug to be an effective vector of leafroll virus in California. First discovered in the Coachella Valley in the late 1990s, the vine mealybug has slowly spread north throughout the state (Daane et al. 2006). This serious pest is difficult to control, and control is even more critical because the insect is known to be a vector of leafroll viruses. Thus if vine mealybug becomes established throughout California, leafroll could spread even more aggressively (see pages 167 and 174). We do not, however, believe it caused the leafroll disease spread that we saw in the study vineyard.

The population dynamics of the vector could also have been affected by changing pest-management practices in the vineyard, and possibly linked to changes in the number of parasites and predators of the leafroll virus vector. Detailed monitoring of many species of arthropods that inhabit vineyards would be needed to determine whether this played a role in leafroll spread.

Rootstock preferences. Today's California rootstocks are less tolerant of leafroll infection than own-rooted vines or vines grafted on the rootstock AXR-1, which was used by the majority of grape growers until it succumbed to an epidemic of type B phylloxera in the early 1980s. AXR-1 rootstock (also known as Ganzin 1) is a cross between the variety 'Aramon' and *Vitis rupestris*; it is generally believed that the *Vitis vinifera* in 'Aramon' led to its failure. (Golino 1993; Golino et al. 2003). The previous generation of Napa Valley vineyards was planted primarily on AXR-1, which is much more tolerant of leafroll infections than many rootstocks currently in use (D. Golino, in preparation). A vine propagated on AXR-1 rootstock and infected with leafroll disease can show mild or little symptoms. Today, 10 to 15 different rootstocks are commonly in use and many of them are extremely sensitive to viruses.

Perhaps leafroll viruses have always spread among vines in our vineyards, but the symptoms simply were not evident in most cases because the rootstocks were more disease-tolerant and showed fewer symptoms. This could account for at least part of the apparent change in epidemiology. Given the greater susceptibility of today's rootstocks, choosing both rootstocks and scion wood free from leafroll infection is far more critical than in the past.

New leafroll virus strains. At this writing, there are at least 10 different species of leafroll virus, each in a taxonomically distinct group. Most have the genetic fingerprint of a group of viruses known to be transmitted by mealybugs. In fall 2006, we tested for all these leafroll species in our study vineyard, but only GLRaV-3 was found, and this species is known to be mealybug-transmitted. All of the vines that became symptomatic of leafroll disease and were tested had this type of leafroll. We believe some strains of GLRaV-3 were present in California when grapevines were first introduced — it is often found in our oldest vineyards, even in isolated locations. However, plant viruses are highly mutable and within-species severity may vary greatly. Is it possible that a strain of GLRaV-3 was inadvertently introduced with grape cuttings smuggled into California from Europe or elsewhere? With the number of illegal importations known to have occurred in the past 20 years, this is a distinct possibility.

In memory of Ed Weber

Ed Weber, a co-author of this article, was a longtime Napa County Cooperative Extension Advisor. He knew Napa vineyards well and was among the first viticulturists to observe an apparent increase in the grapevine leafroll infection rate. Weber died unexpectedly on Dec. 31, 2007, at the age of 51. This article is dedicated to him.

Weber attended UC Davis, where he earned a B.S. in plant sciences and an M.S. in horticulture, with an emphasis on viticulture. He worked as viticulturist for Joseph Phelps Vineyards from 1983 until 1988, when he joined UC Cooperative Extension in Napa County. Weber served as a liaison between the University and its researchers, winemakers, and state and local regulatory agencies.

In the wine industry, Weber was known as a great educator, communicator and problem-solver. His exceptional talent for speaking and writing was accompanied by an ability to take complicated data and information and convey it in a straightforward and logical way that could be understood by industry professionals as well as the general public.

In addition to his research and expertise in viticulture, Weber provided administrative leadership as Napa County Director and served as chair of the ANR Communications Advisory Board.

Research needs

Additional research is urgently needed to help us better understand our observation of rapid spread of leafroll disease in the vineyard. Related ongoing UC projects include work on the transmission biology of leafroll viruses by mealybugs, mealybug management and the impacts of 10 known species of leafroll viruses on grape scions and rootstocks. At this time, specific recommendations for mealybug controls to prevent virus spread are still under development. If leafroll virus spread also occurs across other grape-growing regions of California, as has been observed in this study of a Napa Valley vineyard, the disease will have a far greater impact than ever on vineyard productivity. Therefore, breeding programs should also be initiated to develop resistance in both scion varieties and rootstocks using traditional breeding strategies and possibly molecular biology techniques. This would be the ultimate sustainable approach to controlling this disease.

In the meantime, grape growers are strongly advised to plant their vineyards using only certified planting material that has been screened for virus. Where that is not possible due to winemaker preferences or other factors, propagating stock should be carefully screened for virus using laboratory tests (Weber et al. 2002), and only the healthiest possible stock should be used for propagation. Maximizing the distance between new plantings and virus-infected old plantings should reduce the rate of spread. Care should be taken to ensure that equipment, personnel and pomace moving between vineyards (see page 172) are not contaminated with mealybugs that might be carrying leafroll virus.

D. Golino is Cooperative Extension Plant Pathology Specialist, Department of Plant Pathology, UC Davis; E. Weber was County Director and Farm Advisor, UC Cooperative Extension Napa County (deceased; see box); and S. Sim is Staff Research Associate, and A. Rowhani is Plant Pathology Specialist, Department of Plant Pathology, UC Davis.

This project was initiated with funding from the American Vineyard Foundation and the California Competitive Grant Program for Research in Viticulture and Enology. We acknowledge the invaluable help of Joshua Chase, Justin Jacobs, Judy Lee, Laurel Leon and Yvonne Rasmussen in the survey work and laboratory testing.

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Botryosphaeria-related dieback and control investigated in noncoastal California grapevines

by Lynn Epstein, Sukhwinder Kaur
and Jean S. VanderGheynst

Dieback, or "dead arm," in noncoastal California grapevines is most commonly caused by Botryosphaeria spp. Using Koch's postulates, we demonstrated that isolates of B. obtusa *are pathogenic on grapevines. We initiated studies to investigate the life cycle of* B. obtusa *and ways to control it with cultural practices. Fungal spores disseminated by rainstorms were collected in traps in an Arbuckle vineyard from December 2006 through spring 2007. The data suggests that* B. obtusa *was rain-disseminated throughout winter and spring, and that pycnidia on deadwood in the vines is a major source of inoculum for new infections. Transmission may also be possible via vegetative propagation, pruning shears and insects. Durable latex paints were investigated for protecting pruning and surgical wounds; a self-priming latex paint was shown to be an effective barrier and was nonphytotoxic.*

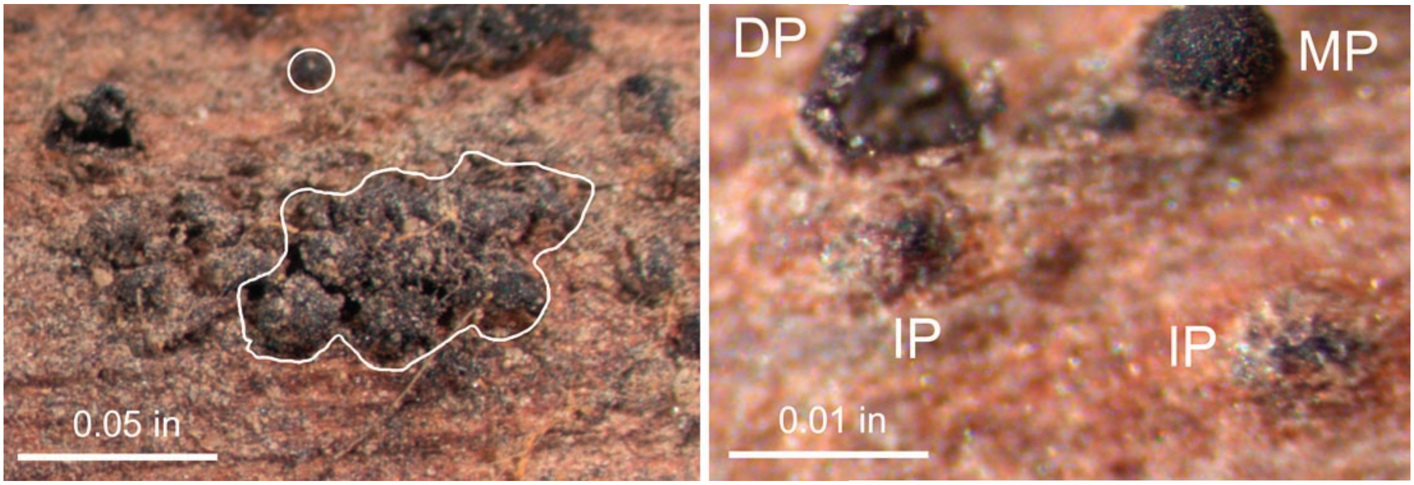
Trunk and cordon cankers that cause vine dieback are serious economic problems in vines 12 years and older. Vines are infected, at least primarily, through pruning wounds. Historically, dieback in California vineyards was attributed to the fungus *Eutypa lata*, but many of the vines, particularly in the Sacramento and San Joaquin valleys, are actually infected by fungi in the genus *Botryosphaeria* (Urbez-Torres et al. 2006); cankers caused by *Botryosphaeria* spp. are called "Bot canker."

Signs of disease on grapevines

Between fall 2004 and spring 2007, we monitored 'Zinfandel' grapevines in Arbuckle, Calif., in an approximately 18-year-old vineyard with many dead spurs and cordons (arms of a grapevine). Our sampling included the extensive dissection of 36 vines in decline. There were two predominant signs of disease in woody tissue: a brownish, often wedge-shaped necrosis (dead tissue) in cross-sections of cankered regions, and dark brown to blackish streaks in longitudinal sections of wood adjacent to pruning wounds. *B. obtusa*, identified by a combination of microscopy and DNA sequencing of a portion of the ribosomal DNA (called ITS), was routinely isolated from the margins of cankers in woody tissue in all parts of the vines. *B. dothidea*, *B. stevensii* and *E. lata* were also occasionally isolated.

Except for a loss of vigor in shoots adjacent to cankered regions, the vines were relatively free of foliar symptoms. Nonetheless, in springtime some vines with multiple dead spurs had deformed, chlorotic (yellow) leaves consistent with symptoms of *Eutypa* dieback. In all 21 vines with foliar symptoms sampled, only *B. obtusa* was isolated from the margins of discolored woody tissue.

B. obtusa pycnidia were observed, generally infrequently and at low density, on the surface of completely dead wood on vines. (Pycnidia are flask-shaped structures that contain conidia, which are asexual spores.) In contrast, pycnidia were observed frequently on prunings and detached wood on the vineyard floor. Individual pycnidia are black and approximately 0.01 inch (0.25 millimeter) in diameter. They are generally aggregated but sometimes separate. When first formed, the pycnidia are submerged in wood, but as they mature they erupt above the trunk sur-



Pycnidia of *Botryosphaeria obtusa* form on prunings on the vineyard floor. *Left, B. obtusa* pycnidia are primarily clustered in aggregates (white outline) with some separate individual pycnidia (circle). *Right,* immature pycnidium (IP) are still partially buried in the plant tissue; mature pycnidium (MP) before spore release; and discharged pycnidium (DP). Microscopic examination of spores is required to identify pycnidia as *B. obtusa* rather than other *Botryosphaeria* spp.

In a pathogenicity test, *Botryosphaeria obtusa* caused a wedge-shaped lesion.

Stands were used to collect fungal spores disseminated in rainstorms. *Left*, each stand had a funnel under the cordon for estimating available inoculum within the vine, and a plate on the ground (2.5 inches high by 20 inches wide) at a 45° angle to collect splash from debris; *right*, stands also had two tented plates (8 inches high by 12 inches wide), which were designed to collect wind-blown rain.

face. After conidia are released during rainy weather and disseminated via wind-blown rain, the empty pycnidial cavities remain on the plant surface. *B. obtusa* pycnidia were never observed on grape berries, and no sexual spores of either *Botryosphaeria* spp. or *E. lata* were ever observed.

Pathogenicity of *B. obtusa*

When we started our work, the literature was unclear on whether *B. obtusa* isolates are pathogenic or saprophytic (living on dead tissue). To test for pathogenicity, own-rooted 'Cabernet Sauvignon' with stems approximately 0.7 inch in diameter were inoculated in the greenhouse with a disc of fungal mycelium (a mass of fungal hyphae) into a wound 5 inches above the soil. After 1 year the plants were examined, Koch's postulates were completed and the experiment was repeated with similar results. (Koch's postulates are a process that allows one to conclude that a particular organism causes a particular disease.)

The greenhouse pathogenicity test produced the two major symptoms that we had observed in the field in infected wood: a brownish, wedge-shaped necrosis in a cross-section and brownish to black streaks in a longitudinal section. *B. obtusa* isolates are pathogenic, and *B. obtusa* grows more quickly in woody tissue than *E. lata* (table 1). Our results are in agreement with other reports in which *B. obtusa* and other *Botryosphaeria* spp. are identified as important grapevine pathogens (Leavitt and Munnecke 1987; Phillips 1998, 2002; Savocchia et al. 2007; van Niekerk et al. 2004, 2006).

Life cycle of *B. obtusa* in a vineyard

Spore dissemination. Rain is critical in the life cycle of *Botryosphaeria* spp. at several stages, including the oozing of conidia out of the pycnidia and then the dissemination of conidia in wind-blown rain. To monitor spores (the reproductive cells) quantitatively in the vineyard, we used funnels under the vines and constructed plates to collect wind-blown rain. Four replicate spore collectors were placed in each of two fields on Dec. 1, 2006, and removed on May 8, 2007. In order to inhibit germination during collection, the receptacle bottles contained sufficient acetic acid for a final concentration of 12% or more. Rainwater (figs. 1D-G) and prunings on the ground (figs. 1B-C) were collected. After rainwater was filtered through membrane filters with grids, conidia were quantified microscopically at 100×. Weather data were obtained from an on-farm monitoring station and the Nickel's Soil Laboratory in Arbuckle (fig. 1A).

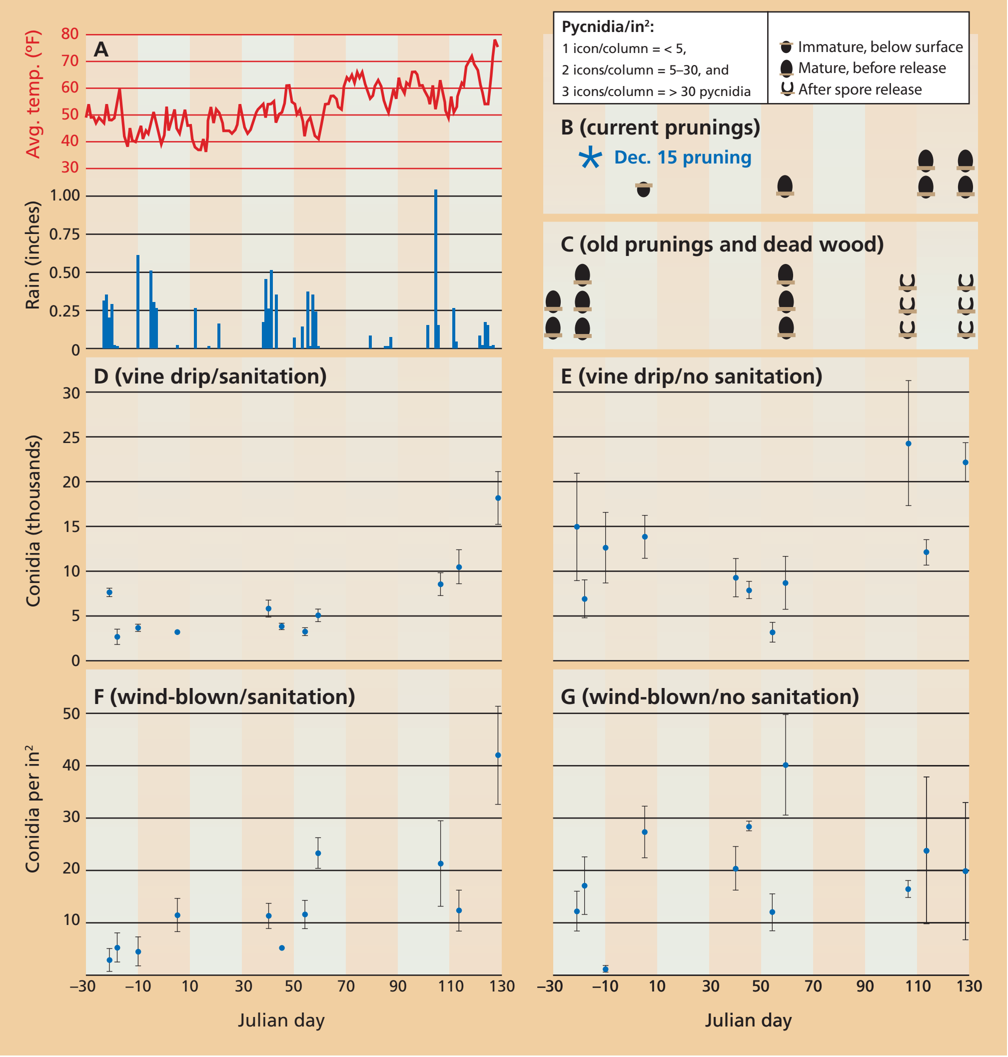
B. obtusa was observed in all rainwater collections; other *Botryosphaeria* spp. and *E. lata* were occasionally observed. The most spores were trapped

TABLE 1. Pathogenicity of *Botryosphaeria obtusa* isolates from Arbuckle, Calif.

Inoculation*	Mean lesion length ± SEM†	Replicate isolates
	inches	*no.*
Botryosphaeria obtusa	20 ± 0.8 a	3
Eutypa lata	14 ± 0.8 b	2
Mock-inoculated control	7 ± 0.8 c	2

* 'Cabernet Sauvignon' own-rooted cuttings were inoculated on June 2, 2005, and examined 1 year later.

† Six determinations per isolate and three determinations for each mock-inoculated control, each on a separate vine. The F-test *P* value = 0.0009. Means followed by the same letter are not significantly different by Tukey's HD, α = 0.05.



▶ **Fig. 1. Biological and meteorological data from a vineyard in Arbuckle, Calif., between Dec. 2, 2006 (Julian day –30), and May 8, 2007 (Julian day 128) (Julian dates start with 1 on Jan. 1 of each year). (A) Daily precipitation and average air temperature. (B, C) Development and abundance of pycnidia on (B) current prunings (* indicates Dec. 15 pruning); and (C) old prunings and dead wood on the vineyard floor. Prunings were partially submerged in soil and partially exposed; examinations occurred each day that spores were collected. Icons are not shown on examination dates when there were no changes from the previous date. New pycnidia were produced on older prunings and wood in multiple years. (D–G) Means ± SE of rainstorm-disseminated spores retrieved in various collectors in a field trial with (D, F) surgical removal of deadwood in the vines, painting of all surgical and pruning wounds and sanitation of pruning debris on the ground, and (E, G) without these measures. (D, E) Total number of *Botryosphaeria obtusa* conidia collected in a 7.25-inch-diameter funnel below the vine. (F, G) Wind-blown *B. obtusa* conidia collected on plates facing north, south, east and west.**

in collectors designed for within-vine drip under an infected cordon in a "no sanitation," area; that is, with neither surgical removal of infected wood, painting of pruning wounds or burial of prunings (fig. 1E). Conidial dissemination occurred throughout the pruning period and into the springtime (May 8) in 2007, in apparent contrast to winter-only dissemination of *E. lata* in California.

Our collection plates for wind-blown rain in the "no sanitation" field (fig. 1G) similarly showed conidial dissemination throughout the December-to-spring observation period. We monitored the development of pycnidia on the current season's prunings from Dec. 15 and on older prunings and wood debris, partly because pycnidia on deadwood in the vine are hard to see and partly because debris on the ground may provide inoculum. Prunings from December 2005 and before, and deadwood on the ground (fig. 1C), primarily released conidia between March 20 and April 14, when it rained on 6 days (fig. 1A). Pycnidia from the current season's prunings matured during 2007, but conidia were not released; release presumably occurred sometime during the 2007-2008 rainy season (fig. 1B). *B. obtusa* conidia also were collected in angled plates designed to determine if the wind could pick up debris from the soil, although the densities were lower than shown in figs. 1F-G (data not shown).

The sanitation treatment consisted of surgically cutting vines to the trunk, painting surgical and pruning wounds, and burying pruning debris (figs. 1D, 1F). Because there were no pycnidia on these regenerated vines, both the vine drip (fig. 1D) and wind-blown (fig. 1F) are estimates of wind-blown inoculum from outside of the sanitation area. Inoculum concentration in the wind was higher later rather than earlier in the season (fig. 1F, slope of linear regression $P = 0.0002$).

Infections through wounds. In addition to observing conidial release from pycnidia (fig. 1C) and conidia in all of our traps in springtime (figs. 1D–G), we also had evidence of infections introduced into wounds made when suckers were yanked out of the trunks in springtime. After surgically cutting vines that had at least one infected cordon down to the trunk in December 2004 and allowing them to regenerate for one season, we completely removed 14 vines in December 2005. *B. obtusa* infections were observed in yanked sucker wounds in 9 of the 14 (64%) vines. Copes and Hendrix (2004) reported faster conidiation of *B. obtusa* at 64°F and 72°F than at 54°F and 86°F. Given temperatures in California (fig. 1A), spring rains may facilitate the most important *B. obtusa* infection events.

Wood discoloration, a grapevine response to infection, appears to occur approximately 1 year after fungal invasion. Both the patterns of wood discoloration and the recovery of *B. obtusa* — from incremental segments of shoots from pruning wounds to the shoot terminus — indicate that *B. obtusa* primarily infects through pruning wounds. In contrast to *E. lata*, *B. obtusa* grows into shoots. In infected vines, we isolated

Vine surgery tested as management strategy for *Botryosphaeria*

by Hal Huffsmith, Robert Abercrombie, Todd Berg *and* Bernardo Farias

The Sutter Home Vineyard in Arbuckle (Colusa County) was planted in 1988 and 1989 with a high-yielding selection of 'Zinfandel' (for white 'Zinfandel' production) on 'Freedom' and 'Harmony' rootstocks at 7-foot-by-12-foot spacing, with an 18-inch cross-arm. The vineyard encompasses 1,082 planted acres and has historically been pruned sequentially (by block) starting with block 1 around mid-December and finishing block 6 in early February. In 2000, we began noticing erratic budbreak and stunted spring shoot growth in the blocks that were pruned early. These symptoms were visually identified as *Eutypa lata* infections. When Russell Molyneux with the U.S. Department of Agriculture's Agricultural Research Service in Albany was unable to extract *Eutypa* metabolites via high-pressure liquid chromatography (HPLC) from cane samples taken at Arbuckle, we began questioning this diagnosis.

At about that time, the American Vineyard Foundation (AVF) Eutypa Research Project released a study by Epstein and VanderGheynst indicating that *Botryosphaeria* (Bot), not *Eutypa*, was the primary cause of spur dieback in some Central Valley vineyards. This work was later confirmed in vineyards located throughout California (Urbez-Torres et al. 2006). In 2004, the Sutter Home Vineyard management group teamed up with Epstein's UC Davis lab to identify and evaluate the organisms causing dieback at Arbuckle and to develop a management strategy to deal with diseased vines.

Epstein, VanderGheynst and Kaur made numerous visits to confirm that *Botryosphaeria* was the organism causing spur dieback, evaluate potential sources of infection, conduct wound treatment trials and monitor spore release. They observed that deadwood on the cordon and prunings left under the vine (on the berm and between the vine rows) were covered with *Botryosphaeria* pycnidia and were the likely source of spore release and continuing *Botryosphaeria* vine infection. The Epstein group initiated a vineyard sanitation trial (see page 161) to quantify *Botryosphaeria* spores in vineyards with minimal and recommended sanitation. Recommended sanitation includes the removal of deadwood from the vine and either burial or removal of prunings from the vineyard floor. Sanitation appears to be useful for suppressing the initiation of new *Botryosphaeria* infections. The removal of *Botryosphaeria*-infected wood from the vine was approached in a couple of ways. The first trial consisted of removing the cordon near the first healthy spur on either side of the stake and switching from spur to cane pruning (see photo A). This approach involved severing the cordons, painting the wounds, disconnecting the cordon wire from the stakes, removing the cordons and cordon wire from the vineyard (burning is an acceptable vine disposal method in Colusa County) and installing a cane wire. This strategy allows for continuous cropping (see photo B) and may be a good way to deal with a mild *Botryosphaeria* infection.

Severe *Botryosphaeria* infections may require a different approach. We have successfully left the infected cordons in place and utilized cane pruning with the remaining healthy and productive wood. However, when the per-acre yield per block falls below an economically viable level, severe vine surgery (as opposed to vineyard replanting) will allow vines to stay in the ground and most of the trellis and drip irrigation system to remain intact. The cost for cutting vines above the graft union and about 12 inches from the ground (see photo C), removing and disposing of the upper portion of the vine and the cordon wire, painting the wound, reinstalling a new cordon wire, retraining and tying the vine, repairing trellises and conducting standard farming activities was about $4.20 per vine or about $2,200 per acre. This method should yield almost a full crop in the second year (see photo D). We are currently evaluating several training practices with the use of either two trunks to reestablish bilateral cordons or quadrilateral cordons, or training the vine for cane pruning (see photo D).

In 'Zinfandel' vines mildly infected with *Botryosphaeria obtusa*, (A) infected cordon wood was removed, and cane pruning replaced spur pruning and (B) regrowth was treated by removing the cordon portion with dead spurs; in severely infected vines, (C) almost all of the scion was removed and new canes were trained and (D) most of the cordon was removed.

Time will determine if severe vine surgery is successful in reestablishing vineyards infected by *Botryosphaeria*. RH Phillips vineyard managers initiated this approach to vineyard revitalization several years ago at a planting about 10 miles south of the Arbuckle vineyard with vines apparently suffering from *Botryosphaeria* infection, and the retrained vines still seem to be vigorous and productive.

H. Huffsmith is Senior Vice President of Vineyard Operations, R. Abercrombie is Vice President of Vineyard Operations, T. Berg is Viticulturist and B. Farias is Arbuckle Vineyard Manager, all with Sutter Home Vineyards, St. Helena.

***Top*, Duration paint is being tested as a treatment for surgical cuts on grapevine trunks; *lower*, an untreated vine.**

B. obtusa in 28% of asymptomatic shoots and 90% of symptomatic 1-year-old shoots (n = 54) 3 inches from the cordon. Symptomatic shoots that were surface-disinfected and incubated in a humid chamber at 74°F for 3 weeks produced *B. obtusa* pycnidia. Overall, our data are consistent with a life cycle in which *B. obtusa* grows asymptomatically within grapevine shoots and woody tissue. We postulate that damage to the vine occurs primarily by the grapevine's release of self-defense compounds that kill its own cambium.

Other means of spread. Although we postulate that pruning wounds are primarily infected by *B. obtusa* conidia disseminated in wind-blown rain, some inoculum may also be disseminated by other mechanisms. Pruning cuts through mature pycnidia can release conidia onto shear blades. Even in cases with only mycelium and no spores, transmission is possible via pruning shears. We made pruning cuts on 25 shoots that we knew, retrospectively, were infected. After making the cuts, we wiped the blades onto sterile paper and then cultured the paper; *B. obtusa* was recovered on 24% of the wipes.

TABLE 2. Two trials in progress on effect of applying Duration paint on pruning and surgical cuts for disease caused by *Botryosphaeria* spp.

Trial no.* (start date)	Extent of sanitation†	Painting of surgical and pruning cuts?	Vines with weaker growth‡	Vines with dead shoots or spurs‡
			%	
1 (2005)	Minimal	No	15	10
1 (2005)	Minimal	Yes	15	6
2 (2006)	Recommended	No	2	0
2 (2006)	Recommended	Yes	3	0

* Each trial was designed for categorical data analysis with approximately 100 replicates in a randomized complete block design with one replicate per block. No statistical differences ($P = 0.05$, Fisher's exact test) between painted and unpainted vines in each trial as of 2007.

† Recommended sanitation includes surgical removal of all deadwood within the vine and either burial or removal of prunings.

‡ Symptoms consistent with infections by *B. obtusa* were evaluated in October 2007.

In preliminary experiments, in which duct tape covered with the sticky product Tanglefoot was placed over pruning wounds, we recovered rove beetles (Staphilinidae) infested with *B. obtusa*. We also detected *B. obtusa* in material that could have been used for vegetative propagation. As indicated above, we isolated *B. obtusa* from asymptomatic shoots. *B. obtusa* also was isolated from the internal tissue of buds that were surface-disinfected, in 13% of the buds (n = 60) of symptomatic shoots and 9% of the buds (n = 57) from asymptomatic shoots on infected vines.

Strategies for cultural control

Surgical removal. Several options are available for surgical treatment: (1) the terminus of the affected cordon(s) can be removed, or (2) most of the scion can be removed, retaining only sufficient wood for the regeneration of new canes (see sidebar). In either case, the retention of a mature root system allows rapid regeneration of the scion. The best location for the surgical cut is not always clear. Certainly, cuts should be made below all necrotic and symptomatic tissue. We have isolated *B. obtusa* in wood up to 4 inches in front of the discolored margin. Although dieback symptoms often appear to be most severe at the ends of the cordons, multiple infection foci can be distributed across the length of asymptomatic portions of the cordon (data not shown). Consequently, we favor cutting down to the trunk.

However, trunks can be infected too. Of the 36 sampled vines, 28 (78%) had infections on the trunk that emanated from wounds on the trunk; wounds were made either when suckers were yanked out or when the mechanical harvester injured the trunk. Moreover, sampling of the wood just above the surgical cut indicated that 10 of the 36 vines (28%) had infections of *B. obtusa* at the surgical cut, of which only three had any indication of discoloration. Although in some cases the mechanical harvester appeared to have damaged the vines, we never had evidence that *B. obtusa* in the trunk per se caused vine debilitation. Based on patterns of discoloration in the trunk, infections of *B. obtusa* appear to grow primarily toward the base of the stem. While we observed infections in the rootstock, we never observed infections in the roots. A long-term study is needed to determine whether over time, *B. obtusa* in the trunk leads to a reduction in yield.

Protection with durable paint. We are investigating two strategies for integrated pest management of Bot canker: (1) the protection of surgical wounds and new pruning wounds with a durable paint and (2) the reduction of inoculum sources. Two field trials are in progress to test wound protection (table 2). In 2005, we surveyed paints for use as protectants and selected candidates with the following properties: high elasticity (reduced likelihood for cracking); breathability (presumably less likely to mold under the painted surface); durability to exposure to ultraviolet light and rain; and fungal resistance. After preliminary trials, we selected Duration (Sherwin Williams K34T154) paint, a self-priming exterior latex with an ultradeep base that was stained with 6 ounces of N1 Raw Umber per gallon.

Duration paint forms an impenetrable and stable physical barrier on grapevine surgical cuts and pruning wounds. Experimental treatments in which the paint was applied onto pruning wounds and over buds indicated no phytotoxic or inhibitory effects on foliage or bud out-growth (data not shown). The California Department of Pesticide Regulation stated that Duration paint can be used as a physical barrier on grapevines without fungicide registration. Possible advantages of paint over fungicide include that the paint is extremely long-lasting, will not wash off during repeated rains and is not phytotoxic. Nonetheless, painting is labor-intensive for a large vineyard. We were not successful in delivering Duration paint using a modified pruner due to Duration's high viscosity, particularly under the cooler weather conditions when pruning is typically done.

In collaboration with Sutter Home Vineyards, Zinfandel vines with dieback symptoms — at least one dead spur — were surgically cut on the trunk approximately 12 inches above the soil in February 2005 (table 2). The surgical cuts were either treated with Duration or not. In the paint-treated vines, all pruning cuts were painted. In 2006, an additional trial with surgically treated vines was started in an area with sanitation. Paint coverage was good in both trials, except when there were heavy rains and sap pushed up a new coating of paint. In this case, paint was reapplied. In both trials, new growth and the establishment of new cordons have been excellent. However, we cannot recommend Duration until data on disease incidence and yield are collected in the next several years. Currently, there is no statistical difference between the incidence of vines with *B. obtusa* symptoms in paint-protected versus nonprotected vines (table 2).

Inoculum reduction. Our and others' data is consistent with the hypothesis that *Botryosphaeria* spp. may infect vines via multiple avenues. The presence of *B. obtusa* pycnidia on deadwood on vines and the collection of conidia in funnels below infected wood suggest that the surgical removal of deadwood should reduce inoculum. Because prunings and deadwood on the vineyard floor can produce large quantities of conidia, we recommend ground sanitation, such as the burial or removal of prunings. Further research is required to determine the contribution of this inoculum to vine infections.

B. obtusa may be transmitted by pruning shears. In a study on the potential transmission of grapevine pathogens in infected propagation material, Aroca et al. (2006) detected *Botryosphaeria* spp. and *Phomopsis* along the length of some plants, but mainly at the graft union. Consequently, grafting tools may transmit inoculum. Gimenez-Jaime et al. (2006) identified *B. obtusa* and other *Botryosphaeria* spp. in grapevine nurseries. Our isolation of *B. obtusa* in shoots and buds also suggests that *B. obtusa* might be spread in propagation material.

We monitored rainstorm-disseminated spores over the period when grapevines are pruned, from December to May. Our data indicates that *B. obtusa* conidia are disseminated during the entire season, including and perhaps especially in spring when temperatures are more conducive for sporulation. Consequently, while later pruning will avoid exposing wounds to early-season rain events and is a worthwhile component of an integrated pest management strategy, it may not provide sufficient control in an infected vineyard.

Research questions

The development of a cost-effective, sustainable Bot canker management program will require additional knowledge. Answers to the following questions will be useful: How long are pruning wounds susceptible to infection by *Botryosphaeria* spp.? What training and pruning strategies minimize the area of susceptible wounds? How does the timing of conidial release vary in different weather conditions? In different vineyards, how important are various modes of pathogen dissemination, and in particular, are *Botryosphaeria* spp. initially disseminated in vegetatively propagated material that is infected but not symptomatic, and if so, how often? How long are vines productive after major surgery? And do infections occurring below the surgical cut affect the longevity of the vines?

Surgery is being tested in some vineyards as a means to revitalize vines with Bot canker (see sidebar, see page 164). We postulate that a combination of sanitation and surgery will allow sustainable control of Bot canker.

L. Epstein is Professor of Plant Pathology, and S. Kaur is Staff Research Associate, Department of Plant Pathology, UC Davis; and J.S. VanderGheynst is Professor, Biological and Agricultural Engineering, UC Davis.

This research was partially supported by a grant from the American Vineyard Foundation. We thank Hongyun Guo, Romil Benyamino, Gurdev Dhahan and Burt Vanucci for technical assistance; Frank Zalom for insect identification; and our fantastic collaborators and their crew at Sutter Home Vineyards.

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REVIEW ARTICLE

Vineyard managers and researchers seek sustainable solutions for mealybugs, a changing pest complex

by Kent M. Daane, Monica L. Cooper, Serguei V. Triapitsyn, Vaughn M. Walton, Glenn Y. Yokota, David R. Haviland, Walt J. Bentley, Kris E. Godfrey *and* Lynn R. Wunderlich

Mealybugs have become increasingly important vineyard pests — a result of their direct damage to the vine, their role in transmitting grapevine leafroll viruses, and the costs for their control. Numerous mealybug species are found in vineyards, and each has different biological traits that affect sustainable control options. We review the mealybug pests and their natural enemies to provide some clarification about current trends in biological control tactics and needed directions for future work.

In an uncontrolled vine mealybug infestation in a San Joaquin Valley raisin-grape vineyard, mealybug and honeydew accumulate on the fruit, canes and leaves.

An obscure mealybug infestation in a Central Coast wine-grape vineyard shows growth of sooty molds that are often associated with mealybug excretion (honeydew), especially in cooler grape regions.

Over the past 100 years, a series of different mealybug species have been found in California vineyards, with five species currently causing damage and a sixth posing a threat. Mealybugs have needlelike mouthparts that feed on the plant's phloem, which contains the nutrients needed for mealybug development. As mealybugs digest their food, they excrete a sugar-rich fluid called "honeydew." All vineyard mealybugs can feed on the vine's trunk, canes, leaves or fruit, and some species feed on vine roots. Crop loss occurs when mealybugs infest fruit or excrete honeydew that covers fruit and leaves, often resulting in sooty mold growth, defoliation and sunburned fruit. Continuous high levels of infestation over successive years may also lead to the deterioration of vines. And many mealybug species transmit viruses such as grapevine leafroll (see sidebar, page 174). However, these mealybug pests can be controlled, to some extent, by natural enemies that are often present in sustainable management programs.

Mealybug pests

Most of California's vineyard mealybugs are invasive species — although some of them have been here for nearly 100 years. For newly invasive species, eradication should be the first response. If eradication is not feasible, then an integrated program that includes classical biological controls should be considered. For native mealybug species, resident natural enemies often provide substantial control or can be manipulated to improve their effectiveness. The history of each mealybug species in California and its distinctive biological characteristics affect the level of economic damage and potential effectiveness of biological controls.

Pseudococcus. The grape mealybug, *Pseudococcus maritimus* (Ehrhorn), is one of the oldest California vineyard pests (Essig 1914). It was first described from specimens collected on coastal buckwheat in California in 1900 and was the only vineyard mealybug thought to be native to North America (Miller et al. 1984) until the arrival of *Ferrisia gilli* Gullan. Grape mealybugs can be found throughout California's Central Valley and coastal grape regions, as well as in Oregon and Washington vineyards. Typically, there are two generations per year (Geiger and Daane 2001). For most of the year, grape mealybugs are found under the bark, but during the second generation (beginning in June) they move into grape clusters, especially clusters in contact with the trunk or spurs. The population overwinters as eggs or small nymphs under the bark, with a required diapause that helps to synchronize generations each year.

The longtailed mealybug, *Pseudococcus longispinus* (Targioni Tozzetti) is believed to be of Austro-Oriental origin

Common mealybug species in vineyards are (A) grape mealybug, with orange-to-red ostiolar secretion near the head and anus (the fluid is often a defensive tactic to ward off predators); (B) obscure mealybug; (C) longtailed mealybug; (D) vine mealybug approaching a grape berry; and (E) Gill's mealybug with glasslike rods brushed aside to show adult wax pattern.

(Ben-Dov 1994). This cosmopolitan species has been resident in California since at least 1933 and is best known as a pest of ornamental plants. Longtailed mealybug has been limited to Central Coast vineyards, where it has three generations yearly. Unlike the other *Pseudococcus* species discussed, longtailed mealybugs give birth to live crawlers (1st-instar mealybugs, which disperse before they settle and feed) rather than depositing eggs.

The origin of the obscure mealybug, *Pseudococcus viburni* (Signoret), is unknown, and both Australia and South America have been suggested. While known to be in North America since the early 1900s, its history is poorly documented due in part to earlier taxonomic confusion — it is a close relative of the grape mealybug and was often misidentified (Miller et al. 1984). The obscure mealybug is primarily a pest of ornamental plants but is also found in coastal vineyards, especially in association with the Argentine ant, *Linepithema humile* (Mayr) (Phillips and Sherk 1991). Biological traits that make obscure mealybug more damaging than grape mealybug are that it readily feeds on leaves (causing leaf damage and raining honeydew down onto grape clusters), it can survive on common weeds such as malva and burclover (Walton and Pringle 2004b), it has three or four overlapping generations per year, and it excretes more honeydew. It is limited, however, to the cooler grape-growing regions, and is most commonly found in Central Coast vineyards.

***Planococcus*.** The vine mealybug, *Planococcus ficus* (Signoret), is a relatively new invasive species to Californian and Mexican vineyards (Daane et al. 2006). In 1994, it was found in Coachella Valley table grapes, although it probably entered the state years before. Vine mealybug has always been associated with vineyards and was first identified as a new species in the Crimea on grapes in 1868. It has since spread and is now a key pest in the vineyards of Europe, northern Africa, South Africa, Argentina, the Middle East and Mexico. In California, crawlers blown by wind or carried by animals and farm machinery aid its spread. Infested nursery stock (Haviland et al. 2005) and pomace from the wine-grape crush (see sidebar, page 172) can also harbor this pest.

Vine mealybug has a number of traits that make it particularly damaging and difficult to control. Most notably, there are four to seven annual generations in much of California's grape-growing regions, resulting in rapid population growth. Vine mealybug also feeds on all parts of the vine throughout the season, resulting in a portion of the population protected under the bark. It can feed on a number of plant species; however, while it is common in Europe on fig (*Ficus* sp.), there are no reports on this host from California. The closely related citrus mealybug, *Planococcus citri* (Risso), has been found on vines but has never been recorded as an economically important pest in vineyards.

***Ferrisia*.** *Ferrisia gilli* Gullan is a close relative of the striped mealybug (*F. virgata* Cockerell), which is probably native to southeastern North America. In fact, until recently the California population was considered to be the striped mealybug, but differences in its adult morphology and economic importance in pistachios and almonds prompted studies that led to its new species description in 2003 (Gullan et al. 2003). Damaging vineyard populations have only recently been found in the Sierra foothills. Because *F. gilli* — commonly called Gill's mealybug, after Raymond Gill — is so new to scientists, research on its seasonal occurrence has, to date, only been conducted on pistachios grown in the Central Valley (Haviland et al. 2006). There, the mealybug has three annual generations. In fall, adult females produce crawlers that overwinter in protected crevices of the trunk and scaffolding branches. During bud-break, the overwintering nymphs migrate to buds to feed; they become adults between late May and mid-June and give live birth to crawlers, the first of two in-season generations. Currently, studies are ongoing in El Dorado County to determine this mealybug's seasonal occurrence on grapes.

Maconellicoccus. The pink hibiscus mealybug, *Maconellicoccus hirsutus* (Green), is an excellent example of an invasive species that presents a significant threat to California grapes but has been limited by a successful classical biological control program (Roltsch et al. 2006). Pink hibiscus mealybug is probably native to Southeast Asia or Australia. It invaded Egypt in 1912, Hawaii in 1984, the Caribbean islands in 1994, Florida in 2002, and reached northern Mexico and Southern California in 2003. It has a wide host range of more than 200 plant species. Under optimum temperature conditions, this mealybug can have explosive populations with more than 600 eggs per ovisac and up to 15 generations per year.

Natural enemies

Hundreds of natural enemies can attack mealybugs, making this brief review incomplete. Here, we catalog the more common natural enemies and their potential impact.

A number of predators contribute to mealybug control; a few specialize on mealybugs, while most are generalists that prey on any small, soft-bodied arthropods. For many of these natural enemies, there are no studies of their impact on mealybug populations.

Mealybug destroyer. One of the more effective and specialized predators is the "mealybug destroyer," *Cryptolaemus montrouzieri* Mulsant. This lady beetle was imported to California from Australia in 1891 to help control the citrus mealybug (Bartlett et al. 1978). Both adults and larvae kill mealybugs. The larvae are mealybug mimics. They have waxlike filaments similar to those of mealybugs and this "camouflage" allows beetle larvae to feed amongst mealybugs without too much disturbance from mealybug-tending ants (Daane et al. 2007). One drawback is the predator's poor tolerance to winter temperatures (Smith and Armitage 1920). In 1996, a "cold-hardy" strain of the mealybug destroyer was collected in southern Australia and released in California (K.S. Hagen, unpublished data). Material from these releases appears to have established and, currently, the mealybug destroyer is found throughout the coastal wine-grape regions (Daane, personal observation).

Common mealybug predators include lady beetles. (A) An adult *Scymnus* species feeds on a grape mealybug. (B) A large mealybug destroyer larva near the smaller obscure mealybug; the larvae of many of these lady beetle species have waxy filaments to mimic mealybugs and reduce interference from mealybug-tending ants. (C) A cecidomyiid larva prepares to feed on grape mealybugs. (D) A third-instar green lacewing (*Chrysoperla carnea*) larva attacks a grape mealybug, prompting it to secrete a ball of red ostiolar fluid in defense.

Other beetles. Other lady beetle species also attack mealybugs. Many beetle larvae in the subfamily Scymninae are covered with wax, similar to the mealybug, and are often mistakenly identified as the mealybug destroyer. These include species of *Hyperaspis*, *Nephus* (=*Scymnobius*) and *Scymnus*, commonly the most abundant mealybug predators in infested vineyards. Some of these beetles, such as *Nephus bineavatus* (Mulsant), were imported for mealybug control from South Africa in 1921; others are thought to be native to North America. These species may not be as dependent on high mealybug pest populations as the mealybug destroyer and therefore, may be more important predators in vineyards with lower mealybug population densities. However, because the taxonomic keys for these Scymninae beetles poorly differentiate among species, many of the observed beetles are never properly identified. Migratory lady beetles, notably those in the subfamily Coccinellinae, are often attracted to large mealybug infestations and their honeydew; these include some of the large and recognizable species such as the convergent lady beetle (*Hippodamia convergens* Guérin-Méneville) and transverse lady beetle (*Coccinella transversoguttata* [Falderman]). There are no studies of any of these beetles' impact on California mealybugs.

Lacewings. Lacewings have long been associated with mealybugs. In fact, Doutt and Hagen (1950) first reported that the golden-eyed green lacewing (*Chrysoperla carnea* [Stephens]) suppressed grape mealybugs in pears. Surveys of coastal vineyards infested with mealybugs found *C. carnea*, *Chrysoperla comanche* Banks and an unidentified *Chrysopa* Leach (Daane et al. 1996). Lacewing larvae are effective predators of smaller mealybugs, although they have a more difficult time feeding on eggs in the mealybug ovisac, where waxy secretions provide some protection from the lacewing larva's mouthparts, or on larger mealybugs, which excrete ostiolar fluid that can act as a defensive mechanism. Often overlooked, brown lacewings may be important mealybug predators in spring because they are present and active at cooler temperatures (Neuenschwander and Hagen 1980). Common brown lacewing species are *Hemerobius pacificus* Banks, *Sympherobius californicus* Banks and *S. barberi* Banks. No studies docu-

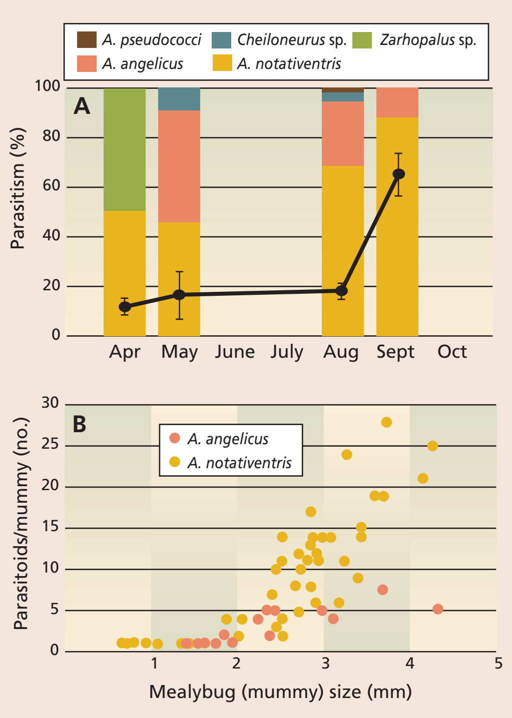


Fig. 1. (A) Percentage parasitism (●) of grape mealybug collected in three San Joaquin Valley vineyards, with bar graphs showing species composition of parasitoids reared on each sample date (*Cheiloneurus* is a hyperparasitoid). (B) Number of *Acerophagus angelicus* and *A. notativentris* reared from mealybugs increased with increasing mealybug size. Source: Daane et al. 2001.

ment the impact of green or brown lacewings on mealybugs in California vineyards.

Flies/midges. Cecidomyiid flies — predaceous midges — are another common mealybug predator. One midge species documented in California vineyards is *Dicrodiplosis californica* Felt (Geiger and Daane 2001). The adult fly, which is not predatory, deposits eggs in or near the mealybug ovisac and the maggotlike larvae feed, primarily, on mealybug eggs and small larvae. The fly larvae typically pupate in the ground. Unfortunately, little is known about these predators in California vineyards. In New Zealand, Charles (1985) reported that *Diadiplosis koebelei* (Koebele) reduced longtailed mealybugs by about 30%.

Other predators. Minute pirate bugs (*Orius* spp.), damsel bugs (*Nabis americoferus* Carayon), big-eyed bugs (*Geocoris pallens* Stål), European earwigs (*Forficula auricularia* Linnaeus) and predaceous mites have all been observed to feed on mealybugs, but are not commonly found in large numbers in vineyards. Spiders are the largest group, often comprising more than 90% of arthropod predators found in vineyards (Costello and Daane 1999). Some spiders, such as *Theridion* spp., have been observed feeding on mealybugs in vineyards. These generalist predators are assumed to play a secondary role behind the more specialized predators and parasitoids.

Parasitoids — tiny wasps

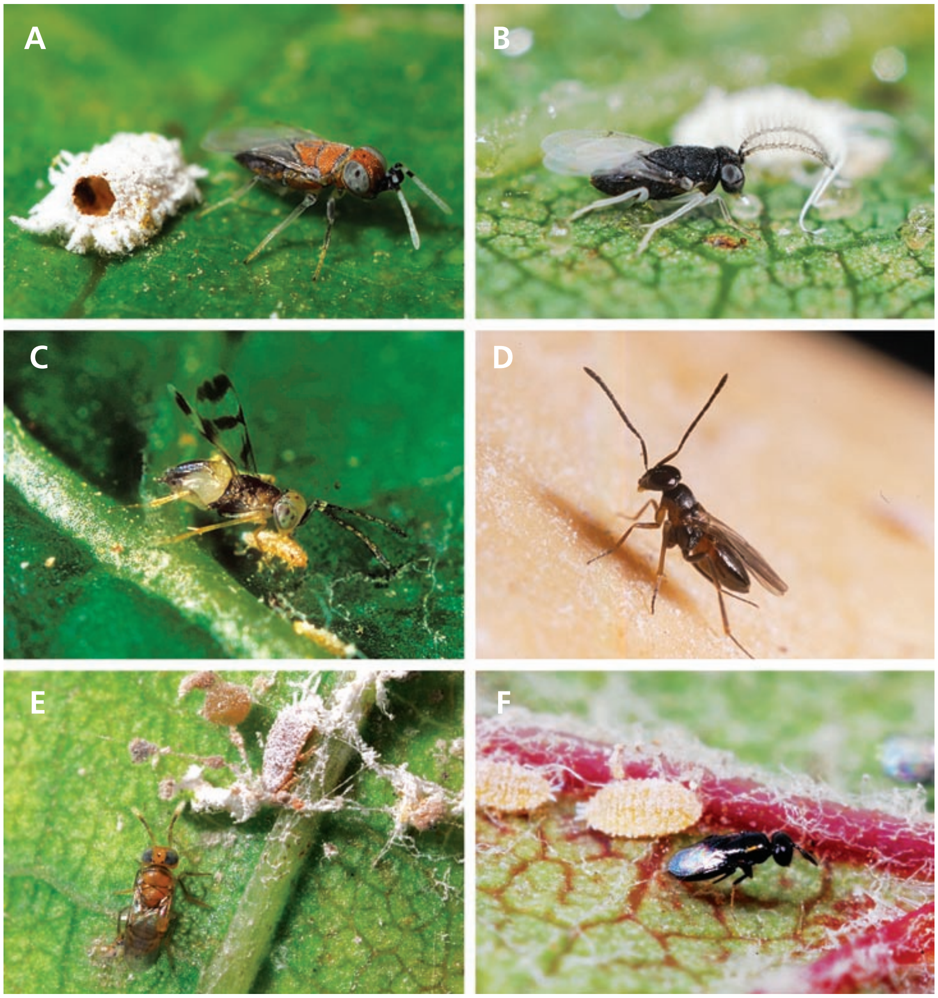
Some of the most important mealybug natural enemies are Hymenoptera, or more specifically, tiny encyrtid and platygastrid wasps (Noyes and Hayat 1994). Depending on the species, these "internal parasitoids" deposit one (solitary) or many (gregarious) eggs inside the mealybug. The parasitoids are classified as "koinobionts" because the parasitized mealybug is, initially, active (still feeding and moving). As the parasitoid larva grows internally the mealybug becomes sluggish and eventually does not move, producing no new wax filaments and forming a golden-brown "mummified" mealybug. The mummy helps protect the developing larval parasitoid(s) inside. The larvae pupate inside the mealybug and the adult parasitoid emerges by chewing a hole through the mummy. Because mealybug parasitoids can be quite specialized, we discuss the complex present in California for each mealybug group.

Grape mealybug. Parasitoids thought to be native to North America have long been credited with grape mealybug control, although the species composition has changed over the years. Smith (1916) and Clausen (1924) reported up to 80% parasitism of grape mealybugs collected in the Central Valley. In these pre-1930s surveys, *Zarhopalus corvinus* (Girault) was the dominant parasitoid; others were *Anagyrus yuccae* (Coquillet), *Acerophagus notativentris* (Girault), *Anagyrus clauseni* Timberlake and *Pseudleptomastix squammulata* Girault. More recent surveys found lower parasitism levels and a change in the parasitoid species complex.

Surveys in the 1970s found that *Acerophagus* (=*Pseudaphycus*) *notativentris* was the dominant parasitoid (Flaherty et al. 1982), and later surveys found *Acerophagus angelicus* (Howard) and *A. notativentris* were common while *Z. corvinus* was less important (fig. 1A). Both *Acerophagus* species are gregarious, depositing more eggs in larger mealybugs (fig. 1B); these are the same key parasitoid species found on grape mealybug in Oregon and Washington (Grimes and Cone 1985; Grasswitz and Burts 1995). In the 1940s, a number of parasitoid species were imported from Africa to control grape mealybug (Bartlett et al. 1978). The fact that none of these parasitoids established provided further evidence that the grape mealybug is native to North America and that the parasitoid species found here may be the most specific to this mealybug pest.

Longtailed mealybug. Soon after longtailed mealybug was found infesting California citrus in 1933, a number of parasitoid species were imported. The most important were *Tetracnemoidea sydneyensis* (Timberlake) from Australia, *Anagyrus fusciventris* (Girault) from Hawaii and *Tetracnemoidea peregrina* (Compere) from Argentina. DeBach et al. (1949) suggested that parasitoids helped suppress longtailed mealybug in Southern California, but that predators, especially the mealybug destroyer, were more important. Recent surveys of longtailed mealybug in coastal vineyards reared a number of parasitoid species including *T. sydneyensis*, *T. peregrina, A. angelicus, Anagyrus pseudococci* (Girault), *Leptomastidea abnormis* (Girault), *Leptomastix dactylopii* Howard and *Coccidoxenoides perminutus* Girault (Daane et al. 2008). Most of these were imported to control other mealybug species, such as the citrophilus (*Pseudococcus calceolariae* [Maskell]) or citrus mealybugs. Despite a long list of natural enemies, outbreaks of longtailed mealybug still occur in Central Coast vineyards, primarily in the Santa Maria appellation.

Obscure mealybug. Prior to 1993, there were no effective parasitoid species of the obscure mealybug in California. For this reason, *Acerophagus flavidulus* (Brèthes) and *Leptomastix epona* (Walker) were imported from Chile in 1996. Both *L. epona* and *A. flavidulus* were initially recovered; however, foraging ants diminished the success of these natural enemies (fig. 2A), resulting in higher mealybug densities (fig. 2B). Currently, only *A. flavidulus* is reported as established



Many parasitoid species attack mealybugs, including: (A) a female *Anagyrus pseudococci* (ca. 2 mm) near a vine mealybug mummy showing the round parasitoid exit hole; (B) the smaller (ca. 1.3 mm) male *A. pseudococci*, which has a different color pattern and hairy antennae, feeds on a drop of honeydew; (C) a female *Leptomastidea abnormis* host-feeds on a vine mealybug crawler; (D) *Leptomastix epona* was imported for obscure mealybug biological control but did not establish because of Argentine ant interference; (E) the small (ca. 1 mm) and fast-moving *Acerophagus flavidulus* closes in on an obscure mealybug; and (F) *Coccidoxenoides perminutus* (ca. 1 mm) near a vine mealybug first instar.

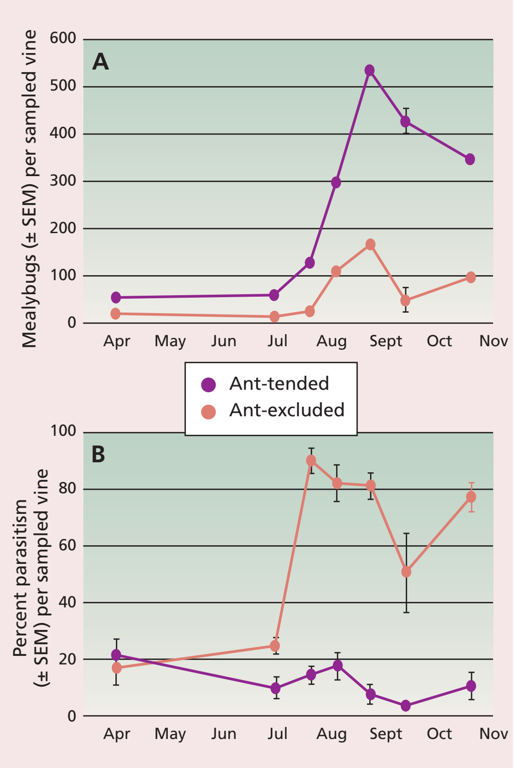


Fig. 2. Mealybug and parasitism levels per vine, based on 3 min. timed counts, in ant-tended and ant-excluded treatments for (A) obscure mealybug density and (B) percentage parasitism of obscure mealybug. Source: Daane et al. 2007.

(Daane et al. 2008). *Acerophagus maculipennis* (Mercet) was recently imported from New Zealand, where it effectively controls obscure mealybug, and is currently undergoing nontarget host evaluation in the UC Berkeley quarantine.

Vine mealybug. The newly invasive vine mealybug has become the most serious mealybug pest in California vineyards (Daane et al. 2006). From 1995 to 1999, parasitoids were imported from Argentina, Spain, Israel and Turkmenistan, and included *A. pseudococci, L. abnormis, C. perminutus* and *L. dactylopii* (González 1998). These species were already present in California, brought in to control the citrus mealybug; however, the newly imported material may have biological characteristics better suited to environmental conditions in California vineyard regions. Currently, *A. pseudococci*, a solitary parasitoid, is the dominant natural enemy of vine mealybug throughout the state, and has a development rate and temperature tolerances that most closely match those of the vine mealybug (Gutierrez et al. 2008).

However, two biological traits reduce levels of natural control. First, overwintered *A. pseudococci* remain in an immature stage inside the mealybug until late April to early May (fig. 3A), delaying their period of activity until after the mealybug is active. Second, the parasitoid does not effectively forage under the vine bark (fig. 3B), where the mealybug finds refuge. An ongoing program is evaluating the biology and molecular identification of *A. pseudococci* populations collected in Europe and the Middle

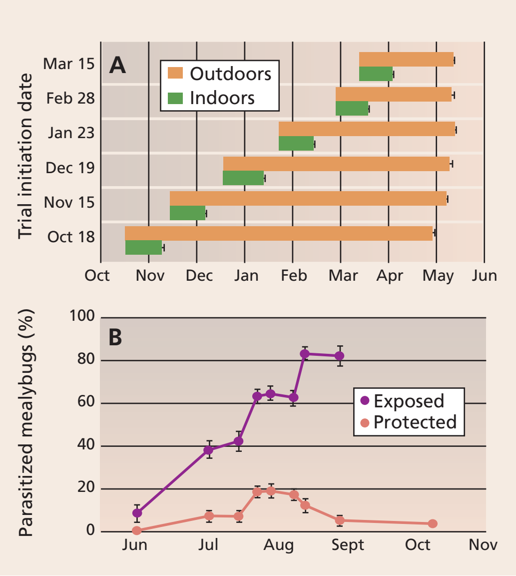


Fig. 3. (A) Average emergence periods for *Anagyrus pseudococci* on vine mealybug that were exposed to the parasitoid from October through March, and then stored either inside at room temperature or outside at ambient air temperatures for Fresno County. Source: Daane et al. 2004. (B) Percent parasitism of vine mealybugs (collected during a timed count) separated by location where mealybugs were collected as exposed (e.g., on leaves) or protected (e.g., under bark). Source: Daane et al. 2006.

Pomace management reduces spread of vine mealybugs

by Rhonda J. Smith *and* Lucia G. Varela

Pomace piles were covered with clear plastic or remained uncovered to evaluate vine mealybug survival.

After vine mealybug was first identified in North Coast wine-grape vineyards in 2002, growers and wineries needed answers to reduce the movement of this pest between vineyards. We investigated the potential for vine mealybugs to survive in one type of winery waste (or pomace) that is often spread over the vineyard floor during the harvest period.

The pomace we investigated contains unfermented berry skins, seeds and cluster stems. This fresh material is produced by pressing hand-harvested whole clusters or mechanically harvested berries; the juice is then fermented. Alternatively, clusters are processed by a destemmer-crusher, after which skins and seeds are fermented with the juice, producing sediment also known as pomace. Because insects do not survive the fermentation process, we focused on the survival of vine mealybug in fresh pomace collected from the winery press after whole clusters were pressed, as well as in piles of fresh pomace placed on the vineyard property.

Mealybug survival after whole-cluster press. Two trials were conducted in wineries located in Sonoma County to determine if vine mealybug survived whole-cluster pressing. In the first trial, a 6-ton load of infested 'Grenache' grapes underwent a press regime ranging from 0.2 to 1.8 bars of pressure. Before pressing, we found an average of 47 live vine mealybugs per cluster. After the press was completed, there were an average of 0.04 live vine mealybugs per cluster (0.085% survival). In the second trial, single infested clusters were placed inside mesh bags and added to a 12-ton load of 'Chardonnay' grapes that underwent a similar press regime. Before pressing, we found an average of over 4,800 vine mealybug crawlers (the small immature stage) per cluster. Afterward, this dropped to an average of 192 crawlers per cluster (4.0% survival).

These trials showed that vine mealybugs can survive whole-cluster pressing. As a result, fresh pomace can be a source of vine mealybug contamination for wineries or growers who traditionally spread this harvest residue directly in the vineyard or who stockpile unmanaged piles of it near the vineyard.

Controlling mealybugs in pomace. Another experiment evaluated vine mealybug mortality in static pomace piles that were either uncovered or covered with clear plastic. Infested cluster stems were placed inside mesh bags that were then inserted 1-foot (0.3 meter) and 3-feet (0.9 meter) deep into pomace piles that were 4 feet (1.2 meters) tall and 15 feet (4.5 meters) across, approximately the size of piles created by dump trucks commonly used by wineries. Initially, the clusters had an average of 1,211 live vine mealybugs per stem.

Results showed that vine mealybug mortality was higher when pomace piles were covered for 1 to 4 weeks with clear plastic than when piles were left uncovered (table 1). When uncovered, more vine mealybugs survived in piles consisting of mostly stems discarded from the destemming process than in the denser, moister piles composed primarily of berry skins and seeds from the whole-cluster press. Uncovered piles composed primarily of stems had greater survival of vine mealybug over time because these piles did not generate high enough temperatures to kill vine mealybugs.

In contrast, when pomace piles were covered, vine mealybugs were reduced by nearly 100% in both "stemmy" and nonstemmy piles. In addition, when covered there was no difference in mortality at different depths in either type of pile. Fresh pomace piles generate heat as organic material degrades. Temperature loggers recorded significantly lower fluctuation at higher temperatures of 120°F to 130°F (50°C to 55°C) in pomace piles with fewer stems and more moisture, than at temperatures of 68°F to 130°F (20°C to 55°C) in piles with a greater mass of cluster stems, which are slower to break down (data not shown).

Recommendations. To reduce the risk of contaminating vineyards with mealybugs, growers should avoid spreading pomace in vineyards unless it has been

TABLE 1. Reduction in vine mealybug on cluster stems after 1 and 4 weeks in two depths, in covered and uncovered pomace piles

Treatment	Pile composition	Infested stem position in pile	Reduction in vine mealybug	
			Week 1	Week 4
			%	%
Uncovered piles	Mostly stems	Top	67.6	89.4
		Bottom	60.7	87.5
	Mostly skins and seeds; few stems	Top	99.9	> 99.9
		Bottom	99.9	100
Covered piles	Mostly stems	Top	>99.9	100
		Bottom	100	100
	Mostly skins and seeds; few stems	Top	100	100
		Bottom	> 99.9	> 99.9

covered with plastic for at least 1 week. Optimally, pomace piles should be located away from vine rows and securely covered as soon as feasible, so heat that is generated remains inside the pile. To help increase temperatures inside stemmy piles and decrease vine mealybug survival, cluster stems collected from a winery's destemmer should be mixed with dense material, such as pomace from either whole-cluster or mechanically harvested press loads. Front-end loaders, which are commonly used in many wineries, may be used to mix pomace piles to some degree.

We did not evaluate the survival of vine mealybug in composted pomace. At facilities required to obtain a Compostable Materials Handling Facility Permit from the California Integrated Waste Management Board, regulations require that the windrow composting process under aerobic conditions maintain a temperature of 131°F (55°C) or higher for 15 days or longer to reduce pathogens. During that period, the windrow must be turned a minimum of five times. Given these rigorous requirements, this process is likely to result in similar or increased mortality of vine mealybugs compared to static, covered pomace piles.

Sanitation practices are recommended to avoid spreading any species of mealybug. Many wineries, regardless of size, find it challenging to cover pomace with clear plastic as it is generated. During the harvest period, pomace may be produced daily at a rate of approximately a ton of pomace for every 3 to 6 tons of grapes, so the lack of space to store and manage this material away from grapevines is a critical problem. Bins and dump trucks that are used to move pomace during the production process may potentially contaminate subsequent loads of fresh grapes with mealybugs. Containers used to haul grapes and pomace should be cleaned with a high-pressure sprayer before they are moved offsite.

R.J. Smith is Viticulture Farm Advisor, UC Cooperative Extension (UCCE), Sonoma County; and L.G. Varela is Integrated Pest Management (IPM) Advisor, UC Statewide IPM Program and UCCE Sonoma County. This study was funded in part by the USDA Exotic/Invasive Pests and Diseases Research Program.

East, noting that this parasitoid is probably a complex of more than one species (Triapitsyn et al. 2007) and other "strains" may be better suited for California.

Gill's mealybug. Very little is known about parasitoids of *F. gilli,* as this species was only described in 2003. From collections of *F. gilli* in El Dorado County vineyards, as well as San Joaquin Valley almonds, it appears that *Acerophagus* sp., *Chrysoplatycerus* sp. and *Anagyrus pseudococci* will attack *F. gilli*. High levels of parasitism have been recorded by *Acerophagus* sp. nr. *meritorius* (Gahan) or *A.* sp. nr. *mundus* (Gahan) (the species cannot be determined because of indecisive species descriptions and poor type specimens [Daane et al. 2008]). The *Acerophagus* sp. was most likely present in California as a parasitoid of the closely related striped mealybug, *Ferrisia virgata.* Currently, research is investigating parasitism levels of *F. gilli* in Sierra Foothill vineyards.

Pink hibiscus mealybug. In India, the pink hibiscus mealybug is a major pest of grapes, reducing yields 50% to 100%. That it is not a pest in California vineyards may be the direct result of a successful biological control program that has limited its spread in the state. After the mealybug was found in the Caribbean in 1994, a cooperative classical biological control project was established for that region, and later extended to California when the pink hibiscus mealybug was found south of the Coachella Valley table-grape region. The parasitoids *Anagyrus kamali* Moursi, *Gyranusoidea indica* Shafee, Alam & Agarwal and *Allotropa* sp. nr. *mecrida* (Walker) were released and, over a 5-year period, mealybug density progressively declined to noneconomic levels (Roltsch et al. 2006). Currently, pink hibiscus mealybug populations are maintained at low levels by these natural enemies, and the pest populations have been contained in the very southern portion of the state — currently out of vineyard growing areas.

Manipulating natural enemies

Insecticides. Vineyard mealybugs are often controlled with insecticides. Prior to the 1990s, most insecticides were not compatible with biological controls. For example, early grape mealybug controls included fumigation with potassium cyanide (Essig 1914), and later materials included DDT and organophosphates (e.g., parathion) (Stafford and Kido 1955). Eventually it became evident that the insecticidal materials disrupted the relatively good control provided by parasitoids. Flaherty et al. (1982) stated that "extensive use of DDT and other synthetic insecticides used to control grape leafhopper disrupted natural control of grape mealybug." Currently, there are many effective materials, such as systemic neonicotinoids, insect growth regulators and tetronic acids that inhibit lipid biosynthesis, which can be used with reduced impact on natural enemy populations. Use of these more narrow-spectrum materials may have a less disruptive effect on biological controls.

Ant controls. Ants can exacerbate mealybug pest problems by disrupting natural enemy activity in vineyards (Daane et al. 2007). Unfortunately, insecticide controls for ants are often more disruptive than materials applied for the mealybugs. For that reason, researchers have developed protein and sugar baits for ant control in vineyards, which can be effective alternative practices (see page 177).

Augmentation. There are few reports of successful augmentation — when natural enemies are reared in an insectary and released into the targeted habitat — for mealybug control in vineyards, in part because this has not been adequately studied.

In fact, one of the first commercial insectaries in North America was developed in 1916 to rear the mealybug destroyer for the citrus mealybug (Smith and Armitage 1920). Today, this beetle is commonly released in vineyards, but release rates, timing and expected outcomes have not been scientifically evaluated. Until those studies are conducted, understanding the biology of the mealybug destroyer may help improve release effectiveness. Beetles are sold as adults and when released into the vineyard they typically begin searching for mealybug ovisacs, where they will deposit eggs. If no ovisacs are found, many of the beetles may fly away; therefore, releases should be timed to coincide with the presence of ovisacs (or females depositing crawlers in the case of the longtailed mealybug).

Studies needed of vectors spreading leafroll disease in California vineyards

by Deborah A. Golino *and* Rodrigo Almeida

Leafroll, a common disease of grapevines caused by a large group of related viruses, reduces the yield and quality of fruit from infected vines. Yield losses of 10% to 20% are fairly typical. Leafroll damages the phloem of infected vines, delaying sugar accumulation and reducing anthocyanin production. Fruit from infected vines is low in sugar, poorly colored and ripens late. In some varieties, fruit maturity is delayed so that fruit on the affected vines may be pale or even whitish at harvest, while fruit on healthy vines is ripe and well colored; late ripening may also expose the fruit to autumn rains that cause rot.

In the past, researchers observed little natural field spread of leafroll disease in California vineyards. Unfortunately, this situation seems to have changed. In the early 1990s, field spread was observed in the UC Davis Foundation vineyard (Rowhani and Golino 1995). More recently, the mapping of leafroll distribution in a 'Cabernet Sauvignon' vineyard in Napa County documented an increase in infection rate of approximately 10% per year over 5 years (see page 156).

Grapevine leafroll viruses. There are currently nine recognized, serologically distinct viruses associated with grapevine leafroll disease. These are unique, closely related viruses, not strains of the same virus. Taxonomically the nine "grapevine leafroll associated viruses" (abbreviated GLRaV-1, and so on) are classified in the virus family *Closteroviridae*, which is characterized by large, flexuous, rod-shaped particles ranging from 1,250 to 2,200 nanometers in length.

Many of these leafroll viruses are transmitted by mealybugs and soft scales. The obscure, longtailed, citrus, grape and vine mealybugs are commonly found in California vineyards and can transmit one or more forms of the virus (Golino et al. 2002; Martelli 2000). In Europe, soft scales such as the vine scale (*Pulvinaria vitis*) have been shown to transmit GLRaVs (Belli et al. 1994); this insect is also found in California vineyards, although the more common soft scale is the European fruit lecanium scale (*Parthenolecanium corni*), which has been implicated but not yet shown to vector GLRaV. Little is known about the biology of leafroll transmission by mealybugs or scales, a research gap we are currently working to fill.

Research goals. Control of insect-borne plant diseases such as leafroll depends upon a solid understanding of pathogen transmission biology. This knowledge could help explain the efficiency, or lack thereof, of certain insecticides in reducing disease spread. It might be the basis for the development of roguing strategies (i.e., the removal of infected vines to prevent virus from spreading), and it should result in improved and vector sampling practices. The newly invasive vine mealybug may result in increased rates of leafroll disease in California, a situation similar to the invasive glassy-winged sharpshooter and Pierce's disease. Our research groups are working to understand how mealybugs transmit leafroll to grapes, with the goal of providing growers with short- and long-term information that can be incorporated into disease management practices.

We have recently determined that first-instar vine mealybugs are more efficient in transmitting leafroll (GLRaV-3) than adult insects. First instars may be dispersed by wind, causing them to travel farther than adults. As a result, virus spread may match these patterns of mealybug movement, which in this case could be reasonably random. We are now working to identify specific periods of the year with high risk of disease spread. The rationale is that large numbers of first instars are not present in vineyards year-round and spread may be increased when crawler populations are high; disease control approaches could be developed to target these times. The incorporation of such knowledge, when available, into management practices may also reduce the undesirable environmental impacts of certain insect-control strategies.

Understanding leafroll transmission. We have focused our efforts on the transmission of leafroll by the vine mealybug, primarily due to its invasiveness and present threat to the grape industry. Other mealybugs, however, may be at least as efficient in transmitting leafroll, so they, too, must be assessed. In addition, the current leafroll epidemic in Napa Valley is probably driven by another factor and not the vine mealybug, as this insect has a limited spatial distribution in that area. Factors behind the epidemic may include a large-scale change of rootstocks over the last decade or the emergence of a virus strain that is transmitted more efficiently by vectors than previously established isolates.


Sue Sim

A leafroll-infected grapevine.

Grapevine leafroll viruses are of economic importance worldwide. Until recently this viral disease complex was assumed to be largely graft-transmitted under California conditions. The finding that mealybugs transmit leafroll was a breakthrough that explained observations of disease spread under field conditions. We are still at the early stages in understanding the most basic aspects of the biology and ecology of leafroll transmission by mealybugs.

D.A. Golino is Director, Foundation Plant Services, and Cooperative Extension Specialist, Department of Plant Pathology, UC Davis; and R. Almeida is Assistant Professor, Department of Environmental Science, Policy and Management, UC Berkeley.

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The beetle is most commonly found in vineyards with many mealybugs and may not be as effective at low mealybug densities. This suggests the beetle may be best used by releasing at hot spots where the mealybug density is high.

Green lacewings are one of the more common commercially produced natural enemies. One of their first successful uses in augmentation was against the grape mealybug infesting pears in California (Doutt and Hagen 1950). In vineyards, the only published studies were of green lacewing releases targeting leafhopper pests (Daane and Yokota 1997), and on the performance of mechanically released lacewing eggs into a vineyard canopy (Wunderlich and Giles 1999). Daane and Yokota's work suggested that a critical shortfall of this program was the release methodology, which subjected the lacewing eggs and neonate larvae to 60% to 80% mortality. Wunderlich and Giles (1999) developed a mechanical technique to safely release eggs in liquid suspension; however, adhesion of eggs to the vineyard canopy was an issue, and carriers have not yet been developed that improve "stick" while maintaining egg viability. Today, insectaries can produce lacewing adults, and this may be a more effective stage for release, especially when combined with an attractant to stimulate the adults to remain in the vineyard and deposit eggs on stalks — where they are not prone to predation by vineyard ants and spiders. Most insectaries produce *Chrysoperla* spp. because the adults are not predatory and can be reared on an artificial diet. Other common vineyard species include green and brown lacewings, which are predatory as adults and therefore more costly to rear.

Other generalist predators that are commercially available for augmentation include predaceous mites, minute pirate bugs and praying mantis. No information on their potential against mealybugs is known, and for that reason, they are not yet recommended for mealybug control.

Parasitoids may be a more effective natural enemy group for augmentative programs, but there are few studies of their use in California vineyards. Experimental release of *A. pseudococci* in a San Joaquin Valley raisin vineyard showed that vine mealybug abundance could be reduced by 50% with releases of 10,000 *A. pseudococci* per acre from June to July (fig. 4). Similar success has been reported in Israel using *A. pseudococci* for vine and citrus mealybugs (Daane, personal communication). The major limiting factor has been the commercial production of parasitoids and the cost per acre of release programs. Because many mealybug parasitoids are specialists, there is not one parasitoid species that can be commercially produced and used against all vineyard mealybugs. Recently, a number of commercial insectaries have shown an interest in producing *A. pseudococci*, a particularly good parasitoid for the vine mealybug. Other more specialized species may be good candidates for cooperative insectaries.

Pheromones. Sexually mature female mealybugs may emit a sex pheromone to attract the winged adult male mealybugs. These pheromones can be used to monitor mealybug populations and densities. Sex pheromones have been identified for the vine (Hinkens et al. 2001), obscure (Millar et al. 2005), grape (Bruno et al. 2007) and longtailed (Millar et al., unpublished data) mealybugs. Trials with the vine mealybug found that the parasitoid *A. pseudococci* was also caught in pheromone-baited traps (Millar et al. 2002). It was later observed that parasitism levels of vine mealybug were higher in vineyards with experimental mating disruption (Walton et al. 2006). Ongoing studies are screening the attractiveness of different parasitoid species to mealybug sex pheromones, to test the hypothesis that some parasitoid species spend more time searching for mealybugs in vineyards using a mating disruption program, thereby increasing parasitism rates.

Mealybug pests can be controlled, to some extent, by natural enemies that are often present in sustainable management programs.

Role of vineyard characteristics

While we presented information on biological controls for vineyard mealybugs, other sustainable control tools were not highlighted. For example, mealybug infestation levels may depend upon vine growth and fruiting characteristics, fruit maturation date and the type of pruning. Therefore, early-harvested varieties are much less likely to have serious fruit damage than late-maturing varieties because mealybug populations tend to increase with each new generation. Vigorous vines are more likely to be infested than weak ones, because mealybug egg production is lower on stressed vines (Daane et al., unpublished data). Most infested grape bunches are those that come in direct contact with the head or cordons of the vine, because most mealybug species find some refuge on the vine trunk for oviposition sites. Therefore, removing grape bunches in contact with the woody portion of the vine will reduce the infestation level.

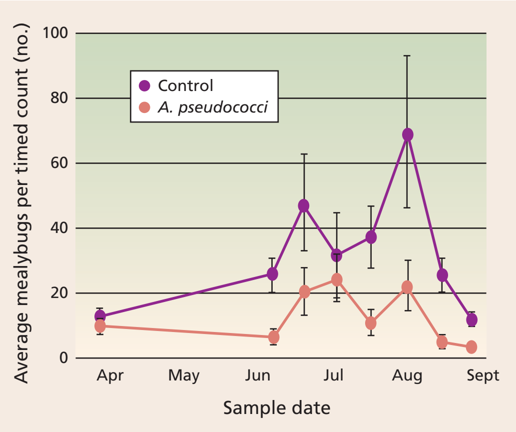

Fig. 4. Season-long average density per vine (for timed counts) of vine mealybugs was lower in treatments with *Anagyrus pseudococci* release, as compared with no-insecticide control plots. Source: Daane et al. 2004.

For these reasons, vineyard characteristics should be taken into account when considering which blocks to transition toward more sustainable programs via the enhancement of biological controls. All of these management tools work in concert with biological controls by lowering mealybug densities or crop damage, which can enable the natural enemies to kill a greater portion of the damaging mealybug population.

K.M. Daane is Cooperative Extension Specialist, and M.L. Cooper is Staff Research Associate, Department of Environmental Science,

Policy and Management, UC Berkeley; S.V. Triapitsyn is Principal Museum Scientist, Department of Entomology, UC Riverside; V.M. Walton is Assistant Professor, Department of Horticulture, Oregon State University; G.Y. Yokota is Staff Research Associate, Department of Environmental Science, Policy and Management, UC Berkeley; D.R. Haviland is Cooperative Extension Farm Advisor, UC Cooperative Extension (UCCE), Kern County; W.J. Bentley is Areawide Advisor, UC Kearney Agricultural Center; K.E. Godfrey is Research Entomologist, Biological Control Program, California Department of Food and Agriculture (CDFA); and L.R. Wunderlich is Cooperative Extension Advisor, UCCE El Dorado and Amador counties.

We thank CDFA for funding this review; and the America Vineyard Foundation, California Table Grape Commission, California Raisin Marketing Board, Viticulture Consortium, Lodi Winegrape Commission (in cooperation with EPA District 9), Central Coast Vineyard Team, UC Statewide IPM Program, California Department of Pesticide Regulation and Western Regional SARE Program for funding mealybug research.

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REVIEW ARTICLE

Liquid baits control Argentine ants sustainably in coastal vineyards

by Monica L. Cooper, Kent M. Daane,
Erik H. Nelson, Lucia G. Varela, Mark C. Battany,
Neil D. Tsutsui *and* Michael K. Rust

Liquid ant baits are an alternative to broad-spectrum insecticide sprays conventionally used to control Argentine ants. We review the development of liquid ant baits, which capitalize on the ants' sugar-feeding requirements and social structure to deliver small doses of toxicant throughout the colony. The ant bait program described here, developed for commercial vineyards, also has the potential to facilitate the use of biological controls for mealybug and scale pests. The implementation of an Argentine ant bait program will enable grape growers to target other pests more selectively with insecticides, further contributing to their sustainable viticulture practices.

Alex Wild

An Argentine ant tends an adult mealybug. A drop of honeydew, the sugar-rich mealybug excretion, can be seen in the ant's mouthparts.

The Argentine ant is an invasive pest that has spread throughout California since it was first reported from Ontario, Calif., in 1905. Though popularly recognized as a household pest (Vega and Rust 2001), the Argentine ant (*Linepithema humile* [Mayr]) also causes severe problems in natural systems by displacing native ants and other insect species, and even some vertebrate and plant populations (Holway et al. 2002). In addition, in agricultural systems the Argentine ant is associated with outbreaks of phloem-feeding insects such as mealybugs, scale and aphids, which the ants protect from natural enemies; in exchange, the ants collect the sugar-rich food source (honeydew) excreted by the phloem-feeders (Buckley and Gullan 1991).

In California vineyards, the Argentine ant has been implicated in outbreaks of three mealybugs species: grape mealybug (*Pseudococcus maritimus* [Ehrhorn]), obscure mealybug (*P. viburni* [Signoret]) (Daane et al. 2007; Phillips and Sherk 1991) and vine mealybug (*Planococcus ficus* [Signoret]), a particularly severe pest that recently invaded California (Daane, Bentley, et al. 2006). Mealybug feeding may partially defoliate vines, and crop damage results when mealybugs infest bunches and excrete honeydew, which promotes the growth of sooty molds and bunch rots (Godfrey et al. 2002). Mealybugs also indirectly damage vines by vectoring leafroll viruses (Golino et al. 1999) (see page 156).

To reduce vineyard damage from mealybugs and promote their biological control (see page 167), the Argentine ant must be suppressed. We review the development of liquid ant baits, which capitalize on the ants' sugar-feeding requirements and social structure to deliver small doses of toxicant throughout the colony. We also discuss future avenues of study to further control Argentine ant populations.

Argentine ant biology

In agricultural systems, Argentine ants are most commonly found in areas with disturbed habitats and some soil moisture. Their nests are composed of reproductive females (queens), sterile females (workers), winged reproductive males and immature ants (eggs, larvae and pupae). Outside the species' native range, the social structure and biology of the Argentine ant have increased its pest status. In its introduced range, Argentine ant nests are unicolonial, forming massive "supercolonies" characterized by the absence of aggression among workers across large geographic areas (Tsutsui et al. 2000). The main European supercolony has been reported to extend up to 3,700 miles (6,000 kilometers), en-

Alex Wild

Argentine ants are aggressive and social. ***Above*****, three Argentine ants attack the native harvester ant (*****Pogonomyrmex subdentatus*****)** ***en masse*****.**

compassing millions of nests and comprising billions of workers (Giraud et al. 2002). In the absence of aggression and territoriality, more resources can be directed to colony growth, the domination of food and nesting resources, and the displacement of native ants in direct, aggressive encounters (Holway et al. 1998).

However, the ants' biology can also be used against them. The Argentine ant diet is composed mainly of carbohydrates (sugars) in a liquid form, such as honeydew (Rust et al. 2000). Therefore, while granular protein baits are not heavily foraged by Argentine ant workers, sugar water laced with insecticide is an excellent method for delivering small but lethal amounts of toxicant to the colony (Silverman and Roulston 2001). Liquid baits exploit the social behavior of ants to distribute toxicant to colony members, including larvae and queens (Silverman and Roulston 2003). Argentine ants also use persistent trail pheromones to recruit colony members to food resources, resulting in fidelity to bait-station locations (Aron et al. 1989; Vega and Rust 2001). Because bait is exchanged among colony members via trophallaxis (i.e., ants feeding other ants), baits have the potential to affect the nest population and provide season-long control (Forschler and Evans 1994; Klotz et al. 2006).

Liquid baits reduce undesirable environmental impacts because they require a relatively small amount of insecticide, and the dispenser design can minimize insecticide delivery to nontarget insects including predators and pollinators (Taniguchi et al. 2005). In contrast, broad-spectrum insecticide sprays targeted at ants may disrupt integrated pest management (IPM) programs by suppressing populations of beneficial insects. While these sprays may also kill foraging ants, unlike baits they have little effect on ants in nests and so allow for an eventual resurgence of the population (Klotz et al. 2002; Rust et al. 1996).

Developing liquid baits

Ant control in vineyards has been investigated using granular protein baits for *Formica* species (Klotz et al. 2003; Tollerup et al. 2004) and liquid sugar baits for Argentine ants (Daane, Sime, et al. 2006; Daane et al. 2008; Nelson and Daane 2007). The liquid bait trials discussed here were conducted either in Central Coast vineyards (San Luis Obispo, Santa Barbara and Monterey counties) populated with obscure mealybug, or in North Coast vineyards (Napa and Sonoma counties) populated with grape mealybug. The initial liquid bait trials were conducted from 2000 to 2002, based on methodologies developed for urban systems by Klotz et al. (2002) and described in detail by Daane, Sime, et al. (2006).

In brief, the liquid baits were composed of 25% sugar water laced with a small dose of one of four different toxicants, and were deployed in approximately 250- to 500-milliliter containers placed on the ground or attached to the vine trunk. Treatments were replicated four to six times in large experimental plots ranging from 0.25 to 0.5 acre (0.1 to 0.2 hectare) to account for the movement of Argentine ants, which forage up to 150 feet from their nests (Ripa et al. 1999).

Ant feeding activity was used to quantify ant densities and was based on the amount of nontoxic sugar water ants removed from 50-milliliter plastic tubes (monitoring tubes). Sugar-water removal rates are related to ant density because each milliliter removed represents approximately 3,300 ant visits to the monitoring tube (Greenberg et al. 2006).

Mealybug densities were assessed using 2.5-to-3-minute visual searches of randomly selected vines (timed counts), based on methodologies developed by Geiger and Daane (2001). Near harvest, crop damage was measured by rating fruit clusters on a scale from 0 to 3: "0" represents no mealybugs; "1" represents 1 to 10 mealybugs and/or honeydew; "2" represents more than 10 mealybugs, sooty mold and/or honeydew; and "3" represents heavily infested, unmarketable clusters.

Because most insecticides are not highly soluble in water, one of the major challenges facing the study group was to find suitable toxicants that can be formulated into sugar water solutions. The first vineyard trials were in 2000 and 2001, and compared a no-bait control to four liquid bait treatments: boric acid (0.5%), imidacloprid (0.0001%), fipronil (0.0001%) and thiamethoxam (0.0001%). These initial trials showed little difference between the no-bait control and the liquid bait treatments.

However, valuable lessons were learned and applied to subsequent trials, in which measurable differences were recorded among treatments (Daane, Sime, et al. 2006). First, bait stations left in the field for longer than 3 weeks, without the addition of preservative, fouled as the sugar fermented. Second, unlike the urban systems tested, the vineyards had incredibly large Argentine ant populations: up to 1.2 ounces (35 grams) of sugar water per day were removed from monitoring tubes, the equivalent of more than 100,000 ant visits!

In a later trial in 2002, researchers refilled and cleaned the bait stations every 2 weeks to reduce bait fermentation, increased the distance between plots to keep the large ant population from spilling over between treatment plots, and increased the number of bait stations deployed from 35 per acre (85 per hectare) to 65 to 250 per acre (160 to 620 per hectare). The researchers also used only one bait formulation (0.0001% thiamethoxam) and deployed bait stations earlier in the season to take advantage of spring foraging activity. With these changes, researchers recorded significant differences in Argentine ant feeding activity and mealybug crop damage between the bait and no-bait treatments with the liquid bait treatment (fig. 1).

The ants' biology can be used against them.

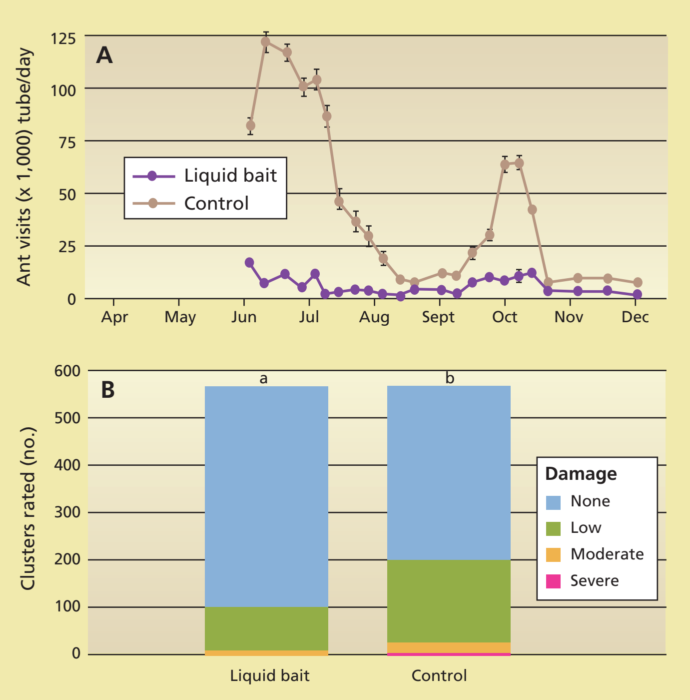

Fig. 1. Comparison of liquid ant bait (0.0001% thiamethoxam in 25% sugar water) and no-bait control in a North Coast vineyard for (A) ant visits to monitoring tubes (F = 28.981, df = 1,6, *P* = 0.002) and (B) crop damage as rated Sept. 17–19, 2002 (Pearson's χ^2 = 44.72, df = 3, *P* < 0.001). Source: Daane, Sime, et al. 2006.

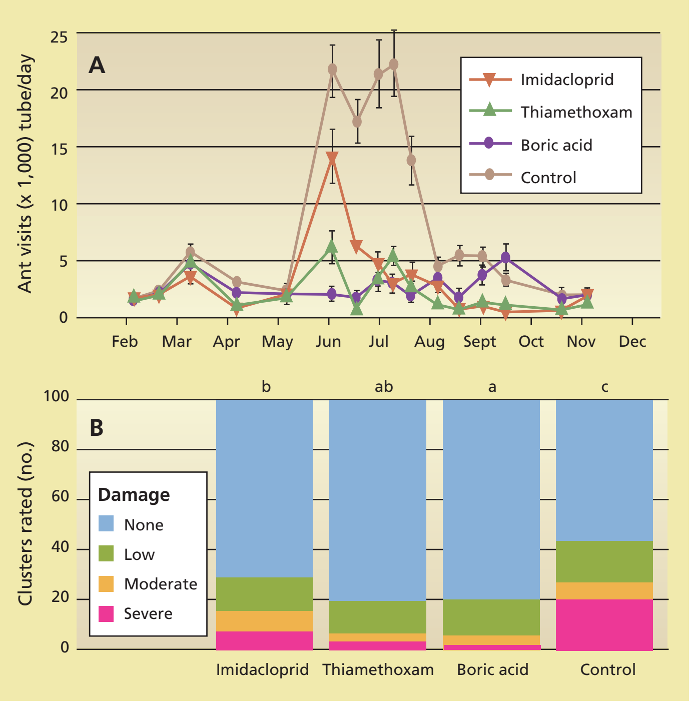

Fig. 2. Comparison of liquid ant baits with different toxicants and a no-bait control in a Central Coast vineyard for (A) ant visits to monitoring tubes and (B) crop damage as rated on Oct. 14, 2003 (letters above each treatment bar indicate a significant difference using pairwise comparisons for Pearson's chi-square test). Source: Daane et al. 2008, where complete statistical description is provided.

Evaluating toxicants

Results from the 2002 trial showed that liquid baits could, in principle, be used to lower Argentine ant densities (Daane, Sime, et al. 2006). However, in practice grower adoption would require answers to the following critical questions: What toxicant would be used, and would it be available as a commercial formulation? What bait station could be used? How many bait stations are needed per acre? At what time of year should baiting begin, and should bait be deployed continuously or seasonally?

Using the improved bait-station deployment methods, researchers reevaluated different toxicants by testing the impact of liquid baits containing either boric acid (0.5%), imidacloprid (0.0001%) or thiamethoxam (0.0001%) against a no-bait control (Daane et al. 2008). As before, large plots were located in commercial vineyards, and liquid baits were delivered in plastic containers deployed at about 50 per acre (160 per hectare). Results showed that the thiamethoxam and boric acid treatments consistently and significantly reduced ant feeding activity measured by monitoring tubes, mealybug density measured by timed counts and fruit damage ratings (fig. 2).

The poor results with imidacloprid were attributed to rapid photodegradation of this toxicant and to the low concentration of active ingredient. Because the imidacloprid concentration in the bait (0.0001%) was below the reported, delayed toxicity range (0.00071% to 0.0092%) (Rust et al. 2004), it may have killed some foraging ants, but did not have the desired colonywide impact.

The formulation of liquid baits can be tricky: the concentration of active ingredient must be great enough to cause ant mortality yet low enough to be slow-acting (killing ants in 1 to 4 days), allowing ample time for bait to spread throughout the colony and remain attractive to foraging ants (Rust et al. 2004). The range of suitable concentrations for a variety of toxicants has been delineated in laboratory trials, and baits with toxicant levels within these ranges are referred to as having delayed toxicity (Hooper-Bui and Rust 2000; Klotz et al. 2000; Rust et al. 2004).

Commercial bait products

The next phase of the bait program was to test commercially formulated bait products, including a liquid bait containing imidacloprid (0.005%), a granular protein bait containing spinosad (0.015%) and a liquid bait containing spinosad (0.015%) (Daane et al. 2008). Researchers used methodologies similar to those described previously, except that the bait stations were shielded from light with Styrofoam containers to protect against degradation of the toxicants. Results again demonstrated the suppressive impact that liquid baits have on Argentine ant and mealybug populations (fig. 3). Granular spinosad bait had no impact on ant populations, while both the spinosad and imidacloprid liquid baits significantly lowered ant densities. This result reaffirmed the need for a liquid sugary bait to target the Argentine ant rather than a granular protein bait (Aron et al. 2001; Rust et al. 2000).

As a result of this research, several liquid ant-bait products are now available for use in agricultural systems, and others may become available in the future. The registered products include Vitis (imidacloprid, Bayer CropScience), Gourmet Liquid Ant Bait (borate, Innovative Pest Control Products) and Tango (methoprene, Wellmark International). During the 2007 season growers began using these products in commercial vineyards and orchards in five California counties, independent of research activities. Ongoing efficacy trials will determine the long-term impacts of these baits on Argentine ant populations (Cooper and Daane, unpublished data).

Liquid ant-bait stations registered for use in vineyards and orchards by the ChemSAC arm of the U.S. EPA (fall 2005) include the UC-designed PVC station, *left* and *center*, with bait reservoir, and, *right*, the KM AntPro station (www.kmantpro.com).

Bait-station design

A commercially acceptable bait station for vineyards should protect the bait from degradation, be easily moved but sturdy, be relatively inexpensive or long-lasting, and hold enough bait so that it must be filled only once per season, provided the bait is formulated with preservative to prevent spoilage. The KM AntPro dispenser consists of a central reservoir that slowly releases bait in response to ant feeding. It has been used successfully in Argentine ant trials in citrus orchards (Greenberg et al. 2006). A bait station developed by UC researchers, which consists of an outer protective PVC housing and an inner disposable bait bottle, has been used in large-scale commercial vineyard trials since 2004. Both bait stations were approved in 2005 for use in vineyards and orchards by the ChemSAC arm of the U.S. Environmental Protection Agency.

Densities for effective control

In urban systems, researchers were able to affect the relatively small Argentine ant populations by placing stations at very low densities (Klotz et al. 2006). In vineyards, however, bait stations were deployed at much higher densities to produce measurable effects on ant populations (Daane, Sime, et al. 2006). To determine how many bait stations are needed, Nelson and Daane (2007) compared a range of densities (0 to 91 per acre, or up to 225 per hectare) in commercial vineyards, and measured the impact on ant density and mealybug fruit-infestation levels.

The results showed that incremental increases in bait-station density had an increasingly suppressive effect on both ant activity and mealybug abundance in fruit clusters (fig. 4). However, the data did not indicate a particular bait density that maximized ant or mealybug suppression. Rather, the results suggest that all investigated bait densities will provide some reduction in ant activity and mealybug damage. This work implies that the optimal bait-station density may depend on the size of the local Argentine ant population. Higher densities may be required to achieve measurable ant control within one or two seasons, particularly in vineyards with higher ant densities. In subsequent seasons, as the ant population declines, continued suppression may be achieved with fewer bait stations per acre.

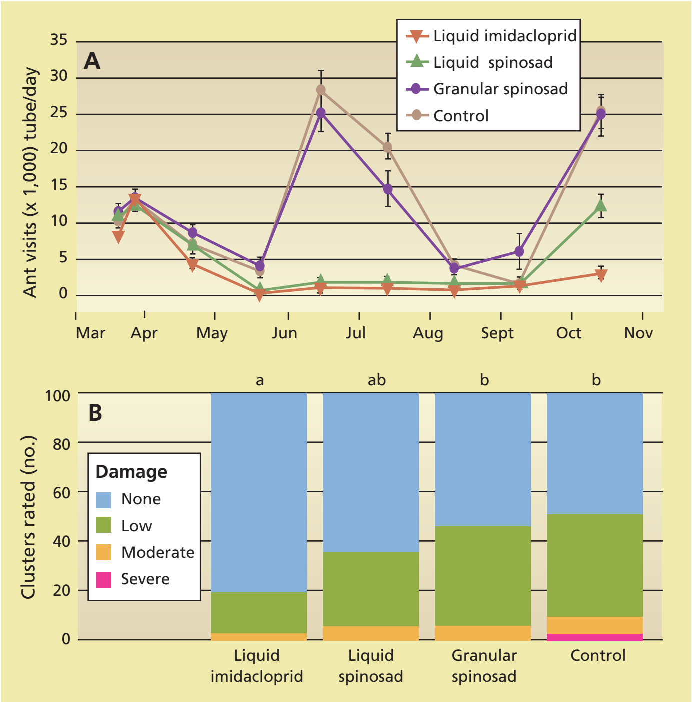

Fig. 3. Comparison of ant baits with different commercial baits and a no-bait control in a North Coast vineyard for (A) ant visits to monitoring tubes and (B) crop damage as rated on Aug. 16, 2004 (letters above each treatment bar indicate a significant difference using pairwise comparisons for Pearson's chi-square test). Source: Daane et al. 2008, where complete statistical description is provided.

The optimal bait-station density is determined in part by the distance that ants travel from the nest to locate food. Foraging distance has been investigated for Argentine ants in urban environments (Vega and Rust 2003) and citrus groves (Ripa et al. 1999). Sugar water labeled with rabbit immunoglobin G protein was used to study ant movement in vineyards (Daane, Cooper, et al. 2006). The percentage of ants carrying protein-labeled sugar water, as determined by a sandwich enzyme-linked immunosorbent assay (ELISA), declined sharply as distance from the bait station increased (fig. 5). In the 6 days following the placement of sugar water in the field, most bait movement was limited to within 66 feet (20 meters) of the stations; beyond 66 feet, fewer than 10% of the ants were carrying the bait. However, a few ants at the most distant sample points did test positive, showing that ants occasionally carried the sugar water more than 236 feet (72 meters). Bait movement appears to be highly localized in the first 6 days after a bait station is placed.

We expected trellising along rows to facilitate bait movement, and row middles to impede bait movement. But surprisingly, the movement of bait

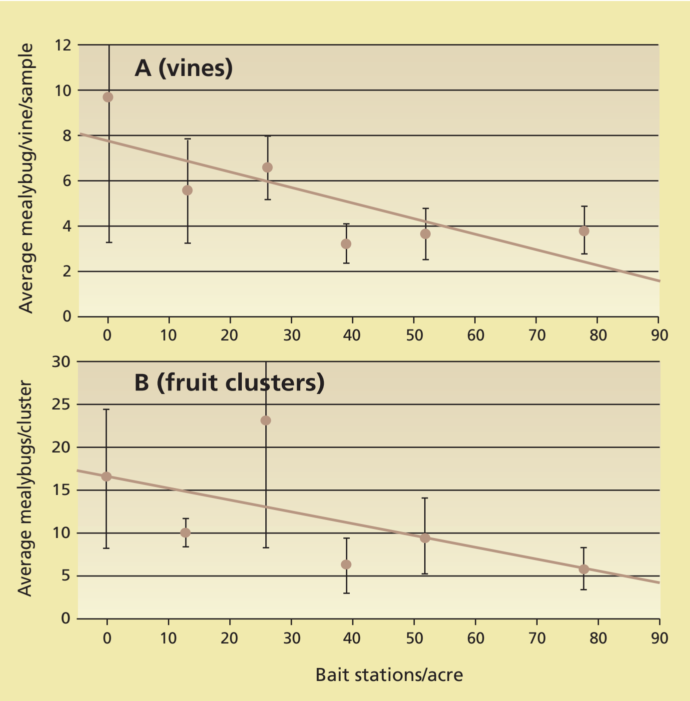

Fig. 4. Bait-station density and grape mealybug abundance (A) on vines during the growing season and (B) in fruit clusters at harvest, showing a significant negative relationship. Bait stations were deployed at 0 to 78 stations per acre. Source: Nelson and Daane 2007.

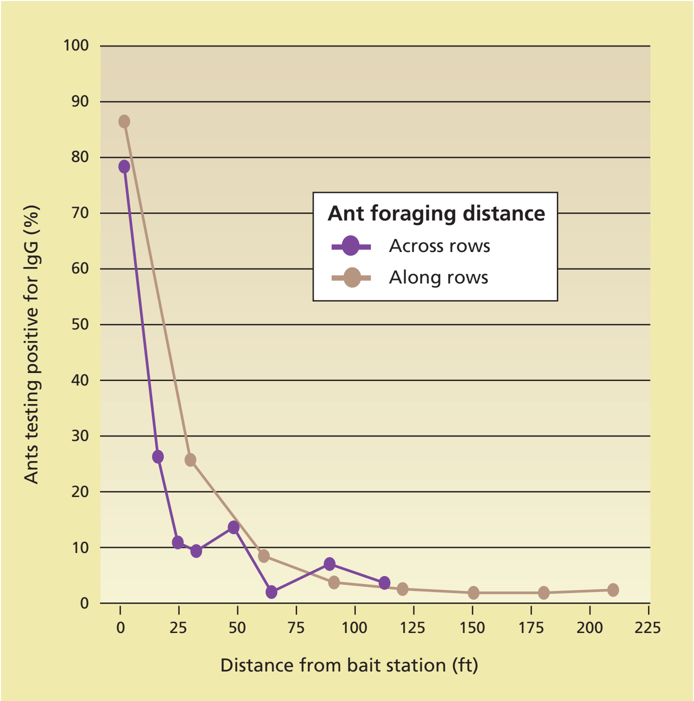

Fig. 5. Movement by Argentine ant of sugar water labeled with rabbit protein (IgG) collected 6 days following initiation of treatment; y-axis shows proportion of ants that tested positive for the rabbit protein. Data are averages of four plots in a Sonoma County vineyard. Movement across and along rows was not significantly different.

across vineyard rows was similar to movement along rows. This result suggests that bait stations do not need to be placed in every row, but may be placed in every second or third row.

Timing and duration

Liquid baits target Argentine ant larvae and therefore, should be deployed during periods of peak larval development and active nest expansion. To delineate these periods, Argentine ant nests were collected monthly from April 2004 to May 2006 at a vineyard in San Luis Obispo County. Using a flotation method, dead ants were separated from small batches of nest soil (1.8 to 3.5 ounces, or 50 to 100 grams) and then categorized into eight recognized life stages: egg, worker larva, worker pupa and sterile adult worker; and reproductive larva, reproductive pupa, male and queen.

This study found that Argentine ant reproductive larvae are most numerous in April, and that worker larvae are present virtually yearround (fig. 6). Therefore, bait deployed during April and May has the greatest potential to affect colony development and expansion by targeting the reproductive larvae. This period is considered essential to decreasing the effective mating population. Although worker larvae continue to populate the nest from July to September, ant foraging activity at bait stations and monitoring tubes declines during this time (figs. 1, 3), due in part to the prevalence of alternative food resources such as mealybug honeydew and ripening grapes in the vineyard.

This foraging shift toward alternative food resources reflects typical Argentine ant behavior in agricultural settings and has been well documented in citrus groves, where the number of aphids and scale insects tended by

Alex Wild

An Argentine ant nest in northern Argentina shows various life stages: egg, larva, pupa and adult.

Above, **mealybug parasitoids are released in experimental plots with ant bait programs. *Right,* a plastic centrifuge tube is filled with 50 milliliters of 25% sugar water to monitor ant populations in vineyard trials. One milliliter of liquid removed is equivalent to roughly 3,300 ant visits to the tube.**

Argentine ants increases dramatically from June to October (Horton 1918; Newell and Barber 1913). Warm weather and favorable foraging conditions after harvest result in a second, shorter, intensive foraging period (figs. 1, 3) in October, which may also be exploited, with toxic bait affecting the remaining larvae and the overwintering adult population. Argentine ants typically constrict their range in the winter months (Markin et al. 1970) in response to cool, wet weather. Therefore, foraging from November to March is extremely light due to these climatic factors and because there are fewer larvae in the nest during this time.

These results suggest that to have the maximum impact on ant populations, baits should be deployed in early spring to target developing larvae — especially those that will become new queens and males — and to coincide with a period of active foraging by ant workers. Ongoing trials investigating the impact of various bait-deployment periods will further elucidate the links between timing and duration of bait deployment as it affects Argentine ant and mealybug populations.

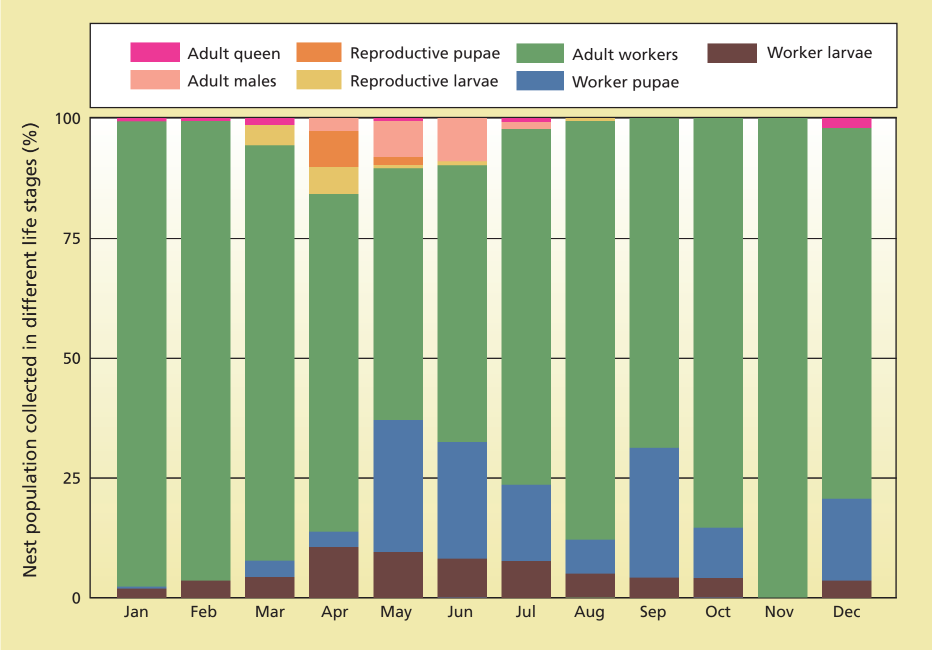

Fig. 6. Argentine ant life cycle in coastal California vineyards, based on averaged data from nest collections in a San Luis Obispo County vineyard, 2004–2006. Data presented as percentage of nest population in recognized life stages.

Future directions

Grape growers now have at their disposal a sustainable Argentine ant management tool that is an alternative or companion to broad-spectrum insecticides. The registered bait products and stations that arose from this work allowed growers to begin implementing this program on a commercial scale in 2007. Continuing research on the density and timing of bait-station deployment has the potential to improve the program's effectiveness and lower costs, thereby facilitating broader implementation.

Concurrently, the expanded production and release of natural enemies will provide better biological control of vineyard mealybugs. Ongoing studies are evaluating the impact of the Argentine ant on developing parasitoids, as well as delineating the mealybug's production cycles of honeydew and attractiveness to tending ants. Future studies in vineyard landscapes where Argentine ant populations are declining in response to bait treatments will examine impacts on the distribution patterns of nontarget ants. Also, data reported here was collected in fields populated with either grape or obscure mealybug; the program has since been expanded to include work in fields populated with the invasive vine mealybug and European fruit lecanium scale, *Parthenolecanium corni* (Bouché).

In the future, the methods described here may be supplemented by the use of semiochemicals, including pheromones, allomones, kairomones, attractants and repellents that modify ant behavior. For example, trail pheromones or other chemical attractants could be used to enhance recruitment to bait (Greenberg and Klotz 2000) or to permit the use of fewer bait stations in a given area.

Alternatively, studies focusing on the chemical ecology of the Argentine ant may reveal methods for disrupting their foraging or inducing aggression among nest mates. These newly explored control methods, combined with the liquid baits described here, hold promise for advancing IPM strategies for the Argentine ant in managed ecosystems. In a broader sense, the ant management system developed and tested in vineyards can be applied to other managed and natural ecosystems that have been disrupted by the presence of Argentine ants. Ultimately, this program has the potential to minimize the use of broad-spectrum chemicals and facilitate the use of sustainable and IPM practices.

M.L. Cooper is Staff Research Associate, K.M. Daane is Cooperative Extension Specialist, and E.H. Nelson is Postdoctoral Researcher, Department of Environmental Science, Policy and Management, UC Berkeley; L.G. Varela is Integrated Pest Management (IPM) Advisor, UC Statewide IPM Program and UC Cooperative Extension (UCCE) Sonoma County; M.C. Battany is Farm Advisor, UCCE San Luis Obispo County; N.D. Tsutsui is Assistant Professor, Department of Environmental Science, Policy and Management, UC Berkeley; and M.K. Rust is Professor, Department of Entomology, UC Riverside. *We thank California Department of Food and Agriculture for funding this review; and the America Vineyard Foundation, California Table Grape Commission, California Raisin Marketing Board, Viticulture Consortium and Central Coast Vineyard Team for funding this research. We gratefully acknowledge the cooperation of growers in Monterey, Napa, San Luis Obispo, Santa Barbara and Sonoma counties.*

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RESEARCH ARTICLE

Vineyard floor management affects soil, plant nutrition, and grape yield and quality

by Richard Smith, Larry Bettiga, Michael Cahn,
Kendra Baumgartner, Louise E. Jackson
and Tiffany Bensen

Management of the vineyard floor affects soil and crop productivity, as well as runoff and sediment that leave the vineyard. In Monterey County, weed control is typically conducted in a 4-foot-wide area under the vines, while cover crops are planted in the middles between vine rows. This 5-year multidisciplinary study in a low rainfall vineyard evaluated the impact of weed control strategies (cultivation, pre-emergence and post-emergence herbicides) in the vine rows, factorially arranged with three cover-crop treatments in the middles. We studied soil compaction, moisture and runoff; vine and soil nutrition; soil microbial biomass and mycorrhizae; and grape yield and quality. The late-maturing 'Trios 102' triticale used more water during the vine growing season than the earlier maturing 'Merced' rye. Cover crops increased organic matter and microbial biomass in the middles and reduced sediment loss. Weed control treatments did not affect crop yield or soil nutritional and microbiological parameters, but cultivation increased soil compaction at 4 to 7 inches deep. Weed control strategies and cover crops must be chosen carefully to maximize benefits and minimize negative environmental impacts.

Cover crops can help reduce runoff from vineyards into nearby surface waters, and they protect soil from erosion and nutrient loss. *Left,* a cover-cropped Monterey County vineyard middle planted with 'Merced' rye; *right,* with no cover crop following a winter rain.

Vineyard-floor management strategies, such as weed control and cover-cropping, have wide-ranging impacts both inside the vineyard, in terms of crop management and productivity, and outside the vineyard, in terms of runoff and sediment movement into streams and rivers. The increasing importance of water-quality issues statewide, including in Monterey County where the Salinas River drains into the Monterey Bay National Marine Sanctuary, highlights the need for management strategies that limit environmental impacts. Growers are interested in alternative weed-control practices and cover crops, but they need information in order to balance benefits with the economic realities of wine-grape production. We established a 5-year experiment in a commercial vineyard in Monterey County with the intent of identifying effective practices that can be integrated into the cropping system without negatively affecting wine-grape production.

The vineyard floor consists of two zones: (1) the rows, a 2- to 4-foot-wide swath underneath the vines, which are managed primarily to control weeds by herbicide applications or cultural practices (e.g., mechanical cultivation); and (2) the middles, interspersed between the rows, which are vegetated by cover crops or resident vegetation in the dormant season, and are tilled or left untilled in spring.

Growers manage weeds in rows to reduce competition for water, nutrients and light (Hembree et al. 2006), and to prevent tall-statured weeds such as horseweed (*Conyza canadensis* L. Cronq.) (Shrestha et al. 2007) from growing or climbing into the canopy, where they interfere with harvest. Growers transitioning to more sustainable production systems need information on how management practices affect the physical properties, health, organic matter and water retention of soil. We monitored soil microbial activity for arbuscular mycorrhizal fungi (AMF) and soil microbial biomass, since weed control and cover-cropping can affect populations of beneficial soil microbes in annual crops (Kabir and Koide 2002).

Dormant-season cover crops in the middles minimize runoff from winter rains (McGourty and Christensen 1998). Many California growers are also willing to plant cover crops because they protect soil from nutrient and sediment loss in winter storms (Bettiga et al. 2006), suppress weeds (Lanini and Bendixen 1992), harbor beneficial arthropods (Costello and Daane 1998), enhance vine mineral nutrition (Patrick et al. 2004) and increase soil organic matter (Ingels et al. 2005).

Competition between vines and cover crops for soil moisture in spring, when both are actively growing, can lead to severe water stress and reduce grape production (Tesic et al. 2007). However, wine-grape production is distinct from other cropping systems (i.e., agronomic crops) because water stress may be imposed to enhance wine composition (Matthews et al. 1990); this practice has been studied mostly in high-rainfall regions of California. The vineyard production region of Monterey County, in contrast, has low rainfall (< 10 inches annually), and growers must weigh the benefits of cover crops with the possible need to replace their water use with irrigation.

In addition, growers must decide on the type of vegetation to utilize in the middles. Resident vegetation is cheap and generally easy to manage. Cover crops can provide specific benefits such as nitrogen fixation (i.e., legumes) or high biomass production and vigorous roots (i.e., cereals). There are many choices for cover crops in vineyard systems, ranging from perennial and annual grasses, to legumes (Ingels et al. 1998). Each species has strengths and weaknesses, as well as associated seed and management costs.

The clear benefits of cover crops were increased organic matter in the middles and reduced sediment loss.

Five-year study in Monterey County

Research site. The trial was initiated in late fall 2000 in a drip-irrigated vineyard near Greenfield, Calif., and continued through the 2005 harvest. The vineyard was established in 1996 with *Vitis vinifera* L. cv. Chardonnay on Teleki 5C (*V. berlandieri* Planch. × *V. riparia* Michx.) rootstock. Vine spacing was 8 feet between rows and 6 feet within rows. Annual rainfall normally ranges from 4 to 10 inches. Soil is elder loam with gravelly substratum. The vineyard was drip-irrigated from April to October.

Experimental design. Row weed-control treatments were: (1) cultivation, (2) post-emergence weed control only (glyphosate at 2.0% by volume [v/v] plus oxyfluorfen at 1.0% v/v) and (3) pre-emergence herbicide (simazine at 1.8 pounds active ingredient/acre [a.i./acre] plus oxyfluorfen at 1.0 pounds a.i./acre), followed by post-emergence herbicide applications (glyphosate at 2.0% v/v plus oxyfluorfen at 1.0% v/v). Cultivations and herbicide applications were timed according to grower practices and label rates.

Cultivations were carried out every 4 to 6 weeks during the growing season using a Radius Weeder cultivator (Clemens and Company, Wittlich, Germany). The cultivator used a metal knife that ran 2 to 6 inches below the soil surface cutting weeds off in the vine row; it had a sensor that caused it to swing around vines. Pre-emergence herbicides were applied in winter with a standard weed sprayer, and post-emergence herbicides were applied in spring through fall as needed with a Patchen Weedseeker light-activated sprayer (NTech Industries, Ukiah, CA).

An early and late-maturing cereal were chosen for the cover-crop treatments; legumes were not considered due to aggravated gopher and weed problems. Cover-crop treatments in the middles were: (1) no cover crop (bare ground), (2) earlier maturing 'Merced' rye (*Secale cereale* L.) and (3) later maturing 'Trios 102' triticale (X Triticosecale Wittm. Ex *A. Camus*). Cover crops were planted with a vineyard seed drill in a 32-inch-wide strip in the middle of 8-foot-wide rows just before the start of the rainy season in November 2000 to 2004 (narrow cover-crop strips are used in Monterey County to minimize competition for water). They were mowed in spring to protect vines from frost, and both cover-crop species senesced by summer. Prior to planting cover crops each November, row middles were disked to incorporate the previous year's cover crop and stubble and prepare a seedbed. Periodic spring and

(Left) 'Trios 102' was compared with (right) bare ground and 'Merced' rye (not shown). The treatments were evaluated for soil qualities; vine nutrients and growth; and grape yield and quality.

The 'Merced' rye cover crop (back) grew faster from December to March, while 'Trios 102' (foreground) grew slowly early in the season but vigorously from March to May.

▲ **A sump pump was used to monitor runoff from storm events, as well as collect water samples for sediment and nutrient analysis.**

The 'Merced' rye cover crop (back) grew faster from December through March, while 'Trios 102' (foreground) grew slowly early in the season but vigorously from March through May.

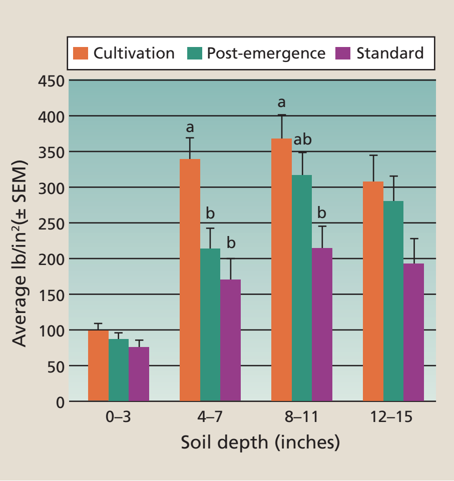

Fig. 1. Soil compaction under vine rows in 2005. Soil compaction with cultivation was significantly greater than the post-emergence and pre-emergence treatments at 4 to 7 inches ($P = 0.0206$) and significantly greater than standard weed control at 8 to 11 inches ($P = 0.0087$). Means within each depth were statistically significant ($P < 0.05$) by pairwise t-tests; differences within each depth are indicated by different letters.

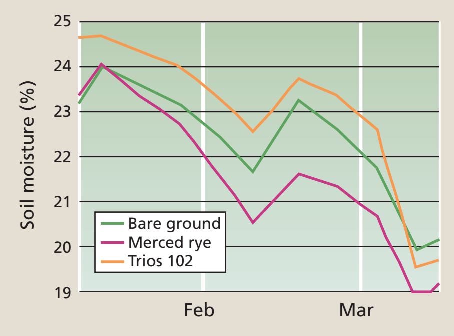

Fig. 2. Average soil moisture in vine rows (middles) at 6 to 42 inches during winter 2002–2003 (date-by-cover-crop interaction, $P < 0.0001$).

summer disking kept bare-ground middles free of weeds.

Weed control (in-row, main plot) and cover-crop (middles, subplot) treatments were arranged in a 3 x 3 split-block design with three replicate blocks covering a total of 23 vineyard rows (7 acres). Each block contained six vine rows and six adjacent middles. Weed control treatments were applied along the entire length of each vine row (300 vines); cover-crop treatments were established along one-third of each middle and were continuous across the main plot treatments in each block. Each replicate main plot-by-subplot treatment combination included 100 vines.

Soil and crop evaluations

Soil compaction. Soil compaction was measured in the vine row in November or December 2003, 2004 and 2005 with a Field Scout Soil SC-900 compaction meter (Spectrum Technologies, USA). Ten sites in each plot were sampled to a depth of 15 inches.

Soil moisture. Soil water storage was evaluated from volumetric soil moisture measurements taken in-row and adjacent middles to a depth of 3.5 feet at 1-foot intervals using a neutron probe. The neutron probe readings were calibrated with volumetric moisture measured from undisturbed soil cores collected at the site.

Rainfall and runoff. A tipping bucket rain gauge with an 8-inch-diameter collector was used to monitor daily and cumulative rainfall at the field site. Runoff was collected at the lower end of the plots into sumps measuring 16 inches in diameter by 5 feet deep. Each sump was equipped with a device constructed from a marine bilge pump, a float switch and flow meter, to automatically record the runoff volume from the plots during storm events. During the second and third years the sampling devices were modified to collect water samples for sediment and nutrient analysis.

Vine mineral nutrition. One-hundred whole leaves opposite a fruit cluster were collected from each plot at flowering in May 2003, 2004 and 2005. Petioles were separated from leaf blades, and tissue was immediately dried at 140°F for 48 hours and then sent to the ANR Analytical Laboratory for nutrient analyses. Petiole and leaf-blade tissue samples were analyzed for nitrate (NO_3), ammonium (NH_4), nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), boron (B), zinc (Zn), manganese (Mn), iron (Fe) and copper (Cu).

Soil mineral nutrition. Composited samples from 10 soil cores taken to a depth of 1 foot were collected from the vine rows and middles at flowering as described above. Samples were air-dried and sent to the ANR Analytical Laboratory for analyses. Soil samples were analyzed for pH, organic matter, cation exchange capacity (CEC), nitrate, Olsen-phosphorus, potassium, calcium, magnesium, sodium (Na), chloride (Cl), boron and zinc.

Soil microbial biomass. Due to the limited capacity of the laboratory, microbial biomass assays were conducted on selected treatments. Ten soil cores were collected to a depth of 1 foot and then composite samples were made from each replicate of the pre-emergence and cultivation weed-control treatments and the adjacent middles of the 'Merced' rye and bare treatments. Samples were collected about four times each year (each season) from November 2001 to November 2005 for a total of 14 sets of samples. Soil samples were immediately placed on ice and taken to the laboratory for soil microbial biomass carbon (C) analysis according Vance et al. (1987).

Mycorrhizae. Roots were collected, stained and examined as previously reported (Baumgartner et al. 2005) on April 16, 2003, May 3, 2004, and June 2, 2005.

Grape yield, fruit quality and vine growth. Fruit weight and cluster number were determined by individually harvesting 20 vines per subplot. Prior to harvest a 200-berry sample was collected from each subplot for berry weight and fruit composition. Berries were macerated in a blender and the filtered juice analyzed for soluble solids as Brix using a hand-held, temperature-compensating refractometer. Juice pH was measured by pH meter and titratable acidity by titration with a 0.133 normal sodium hydroxide to an 8.20 pH endpoint. At dormancy, shoot number and pruning weights were measured from the same 20 vines.

Statistical analysis. Analyses of variance (ANOVAs) were used to test the effects of cover crop, weed control and year on the vine, soil and microbial parameters, according to a split-block ANOVA model in SAS (SAS Institute, Ver. 9.1, Cary, NC). Cover crop, weed control, year and their interactions were treated as fixed effects. The main and interactive effects of block were treated as random effects. Year was treated as a repeated measure. When necessary, data were log-transformed to meet the assumption of normality for ANOVA, although untransformed or reverse-transformed means are presented. Changes in soil moisture among treatments during the winter and the irrigation seasons were determined from significant treatment-date interactions.

Compaction evaluation

We conducted evaluations with a penetrometer each fall to determine the impact of weed-control treatments on soil compaction. Soil compaction was not significantly different at any depth in 2003 ($P > 0.420$ for all depths). However, in 2004 and 2005 soil compaction began to increase in the cultivation treatment compared to the other two weed-control treatments. In 2004, soil compaction at the 4- to 7-inch depth was significantly greater in the cultivation treatment compared to the standard treatment ($P = 0.0178$), but not more so than in the post-emergence treatment ($P = 0.0629$). In 2005, the cultivation treatment had significantly greater soil compaction at the 4- to 7-inch depth than both the post-emergence and standard weed-control treatments ($P = 0.0206$). At the 8- to 11-inch depth, soil compaction was significantly greater than the standard treatment ($P = 0.0087$), but not greater than in the post-emergence treatment ($P = 0.2884$) (fig. 1).

The blade of the cultivator passes through the soil at 2 to 6 inches deep, which may explain why greater soil compaction was measured there. Cultivations often also occurred when the soil was still moist following an irrigation, which may have contributed to the development of compacted layers over time.

Water effects on soil

Moisture. Average, volumetric soil-moisture levels at the 6- to 42-inch depth increased after the first rain events of the season, such as in winter 2002-2003 (this season's data are representative of other years in the trial) (fig. 2). Soil moisture declined most rapidly with 'Merced' rye in the middles during periods without rainfall each year ($P < 0.0001$), presumably due to its greater early-season growth and greater potential evapotranspiration, compared to the 'Trios 102' triticale. Soil moisture levels were similar between the bare and 'Trios 102' triticale treatments until May for all years.

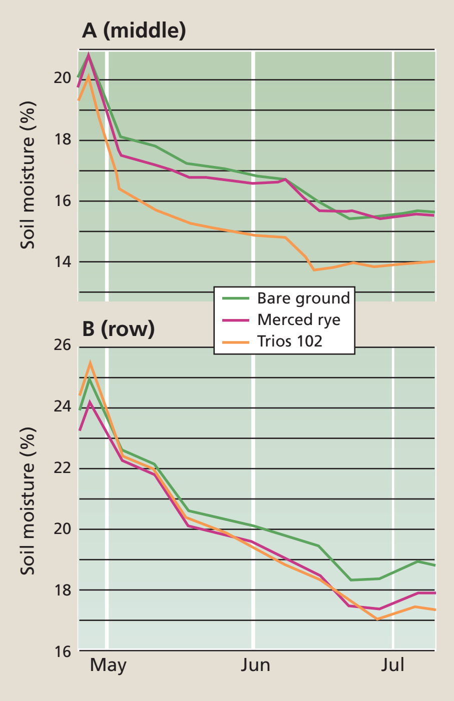

Fig. 3. Average soil moisture at 6 to 42 inches due to cover-crop treatments during the 2004 growing season for (A) middles ($P = 0.09$) and (B) rows ($P = 0.0003$); date-by-cover-crop interaction.

During the irrigation season, average soil moisture levels at the 6- to 42-inch depths were higher in rows than middles. Soil moisture in the rows and middles steadily declined during the irrigation season for all treatments during all years (fig. 3). Moisture levels declined most in middles with 'Trios 102' triticale cover during each irrigation season, presumably due to the later growth of this cover crop ($P = 0.09$). In addition, the row soil-moisture levels also declined the most adjacent to 'Trios 102' triticale for the 2003 and 2004 irrigation seasons ($P = 0.016$ and $P = 0.0003$, respectively), but not during the 2005 irrigation season ($P = 0.97$).

Runoff. Total precipitation at the field trial was 7.4 inches during the 2002-2003 winter, 7.6 inches during the 2003-2004 winter and 9.9 inches during the 2004-2005 winter. A majority of the runoff was collected during December

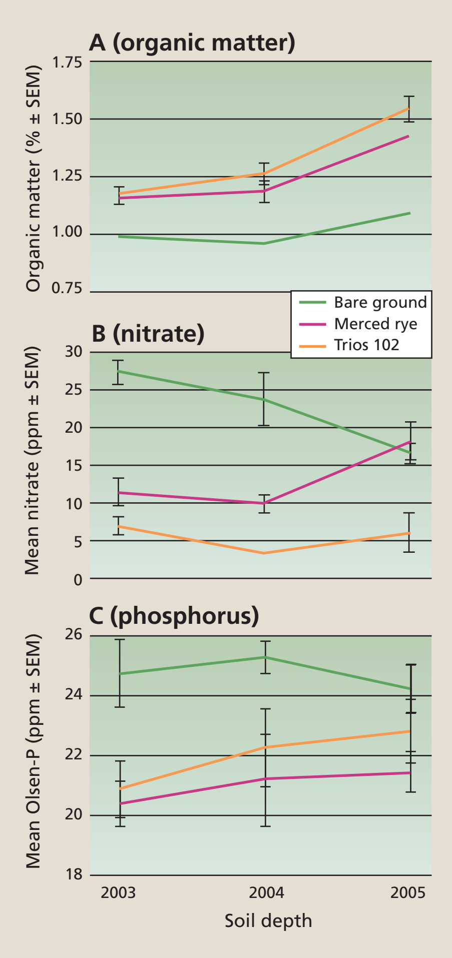

Fig. 4. Levels of (A) soil organic matter (B) nitrate and (C) phosphorus in cover-crop treatments in middles over 3 years. Each point is the mean of three observations and error bars are standard errors of the mean.

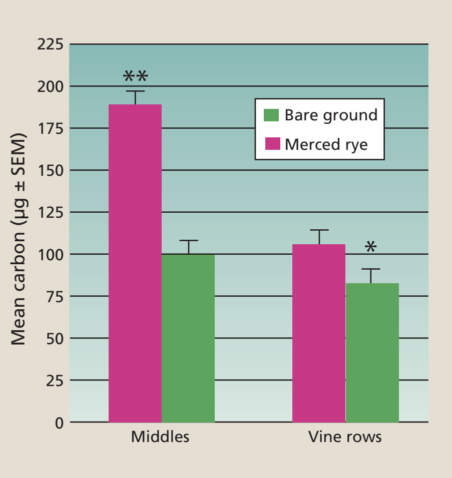

Fig. 5. Cover-crop effects on microbial biomass (ug C/g dry soil ± standard error of the mean) in middles and vine rows at 1-foot deep. In paired t-tests, differences between treatments in middles and vine rows adjacent to rye cover-cropped or bare middles were significant (* = $P < 0.05$; ** = $P < 0.0001$).

TABLE 1. Nutrient and sediment content of composited runoff samples collected from cover-crop treatments, winter 2004

Cover crop treatment	Nitrate-N	Total N	Ortho-P	Total P	Total suspended solids	Turbidity
	. . . .	*ppm*	. . . .		*mg/l*	*NTU*
Bare	1.7	5.6	0.7	2.6	1,735	3,283
'Merced' rye	2.0	6.4	1.3	2.5	952	1,960
'Trios 102' triticale	1.2	4.5	0.8	1.6	508	1,250
Average	1.7	5.4	0.9	2.2	1,064	2,209
LSD$_{0.05}$	NS*	NS	NS	NS	1,046	†

* Not statistically significant.
† LSD could not be calculated due to missing data.

and January for the 2002-2003 and 2004-2005 winters, and February for the 2003-2004 winter.

Cumulative runoff collected from individual plots during the three winters ranged from 0.02% to 3% of seasonal rainfall. Runoff was usually collected during rain events greater than 1 inch per day. Runoff was highest during the second and third years of the trial. During three consecutive winters, runoff was significantly lower in the cover-crop treatments ($P = 0.004$). 'Trios 102' triticale (38.4 gallon/plot) and 'Merced' rye (96.3 gallon/plot) had significantly less runoff than the bare treatment (177.1 gallon/plot) ($P < 0.05$).

Suspended sediment ($P = 0.07$) and turbidity ($P = 0.09$) were also significantly lower in runoff collected from the cover-crop treatments than in bare middles during winter 2004, but nutrient (ortho-phosphorus, total phosphorus, nitrate-nitrogen and total nitrogen) levels were similar ($P > 0.16$) among all treatments (table 1).

Nutrient levels

Vines. Weed control and cover treatments did not have any significant effect on the nutritional status of the grape vines as measured by nutrient levels of the leaf petiole tissues, as determined by ANOVA. Although the nutrient levels by year were significantly different, the interactions of weed control-by-cover and weed control-by-cover-by-year were not significant (data not shown).

Weed control and cover treatment also had no significant effect on blade nutrient content with the exception of boron and phosphate (PO_4-P) content. Vines adjacent to cover crops had significantly lower boron ($P = 0.009$) and phosphate ($P = 0.02$) levels in the leaf blade tissue than vines adjacent to bare row middles. As with the petioles, there was an absence of significance between the interaction of weed control-by-cover and weed control-by-cover-by-year for all nutrients analyzed (data not shown).

TABLE 2. Average crop yield and fruit composition evaluation parameters, 2001–2005

Weed treatment	Yield	Clusters per vine	Cluster weight	Berry weight	Brix	pH	Titratable acidity
	kg/vine	*no.*	. . . .	*g*			*g/l*
Standard practice	6.11	47	130	1.24	24.2	3.40	7.2
Cultivation	5.99	46	133	1.25	24.1	3.40	7.2
Post-emergence herbicide	6.49	48	138	1.25	24.1	3.42	7.2
Cover crop							
'Merced' rye	6.48	48	139	1.26	24.1	3.40	7.2 a
'Trios 102' triticale	5.98	46	130	1.23	24.1	3.40	7.0 b
Bare ground	6.14	47	132	1.25	24.2	3.41	7.3 a
Significance							
	. . . .	. . . .	. . . . . .	*P value*	. . . .	. . . .	. . . . . .
Weed treatment	0.21	0.16	0.54	0.94	0.33	0.09	0.92
Cover	0.11	0.26	0.13	0.33	0.09	0.47	0.003
Year	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Weed trt x year	0.94	0.08	0.27	0.19	0.72	0.48	0.001
Cover x year	0.40	0.67	0.63	0.02	0.28	0.07	0.16
Weed trt x cover	0.21	0.26	0.30	0.61	0.50	0.90	0.38
Weed trt x cover x year	0.84	0.99	0.99	0.76	0.98	0.97	0.96

Soil cores indicated that most of the vine roots at this site were located under the vine row and few of the roots extended out to the row middles. This root distribution probably occurred because irrigation water was applied under the vines, and low rainfall at the site does not facilitate root growth into row middles. Thus, the lower nutrient levels in vines near cover crops may have been accentuated by irrigation effects that reduced vine root exploration of the soil to a narrow band under the vines. Since cover-crop roots probably grew into this zone there may have been competition between vines and cover crops for some nutrients.

Soil. Cultivated rows had significantly lower levels of nitrate-nitrogen ($P = 0.01$). Although the nutrient levels by year were significantly different, there was an absence of significance between the interaction of weed control-by-cover and weed control-by-cover-by-year (data not shown). The differences observed in nitrate-nitrogen in the cultivation treatment may be due to the impact of loosening soil on water movement and leaching. Weed control treatments had occasional impacts on soil mineral nutrition in the middles, but results were inconsistent from year to year (data not shown). Cover-crop treatments had no effect on soil nutrients in the rows (data not shown).

The most significant impacts of the vineyard floor treatments were of the cover-crop treatments on soil parameters in the middles. Soil organic matter in cover-cropped middles ('Merced' rye and 'Trios 102' triticale) was higher ($P = 0.0004$) than in bare middles each year (fig. 4). Cover crops affected key soil nutrients in the middles; for instance, cover crops greatly reduced nitrate-nitrogen ($P = 0.002$), and to a lesser extent, extractable phosphorus ($P = 0.01$) (fig. 4), which may be beneficial in reducing loss of these nutrients in runoff during winter storms, but which also may have reduced the phosphorus content in the vines. In addition, cover crops in the middles also significantly reduced soil boron ($P = 0.001$), extractable sodium ($P = 0.008$) and pH ($P = 0.03$), and increased chloride ($P = 0.009$) and zinc ($P = 0.02$) when compared to bare soil.

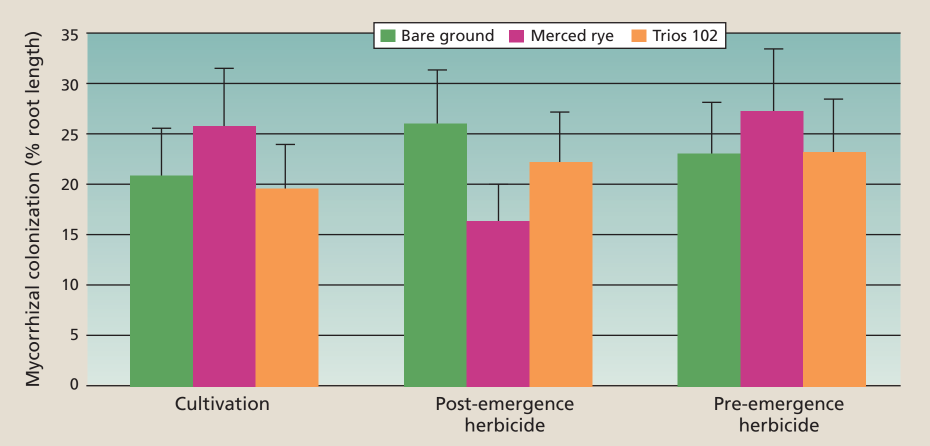

Fig. 6. Interactive effects of cover crop and weed control treatments on mycorrhizal colonization of grapevines, 2003 to 2005. Each column is mean of nine observations, averaged over all three blocks and all 3 years. Simulation-based t-tests were used for mean comparisons. Error bars are 95% confidence intervals; columns without overlapping confidence intervals are significantly different at $P \leq 0.05$.

Soil microbiology

Soil microbial biomass. Microbial biomass varied as a result of both the cover-crop and weed control treatments. In both the middles and vine rows, microbial biomass was higher in rye cover-crop plots compared to bare plots (cover crop-by-sample location, $P = 0.0017$) (fig. 5). These results confirm earlier observations by Ingels et al. (2005) that microbial biomass carbon was higher in cover-cropped middles compared to bare middles. In the vine rows, microbial biomass was greater in plots adjacent to rye cover-cropped plots compared to bare plots. The effect of cover crops grown in the middles on soil in the vine rows may be due to cover-crop roots or tops extending into the vine rows and their subsequent decomposition, providing a food source for soil microbes.

Microbial biomass varied between the weed treatments in the vine rows ($P = 0.0453$) but not middles ($P = 0.1540$). In the vine rows, microbial biomass was significantly higher in the cultivation plots (105.95 ± 7.68 micrograms carbon per gram [ug/g C] of soil) compared to the pre-emergence weed control plots (82.08 ± 8.04 ug/g C). The most likely explanation is the incorporation of greater amounts of weed-derived carbon into the surface soil of the cultivated plots.

Mycorrhizae. AMF can benefit grapevines by improving the nutritional status of the plant and producing a highly branched root system. We quantified AMF reproductive structures (propagules) in grapevine roots to determine if the weed control treatments in the rows and/or cover-crop treatments in the middles had significant effects on mycorrhizal colonization from 2003 through 2005. Based on ANOVA, the effects of weed control on colonization were not consistent among cover-crop treatments (interactive effect of weed control-by-cover crop, $P = 0.04$). Grapevines adjacent to 'Merced' rye had higher colonization compared to those adjacent to 'Trios 102' triticale or bare ground, in both the cultivation and pre-emergence treatments (fig. 6).

In contrast, grapevines in the post-emergence treatment had the lowest colonization when adjacent to 'Merced' rye. These findings were consistent in each study year, based on the absence of significant main or interactive effects of time (data not shown). It is possible that low colonization of grapevines in the post-emergence-by-'Merced' rye treatment is associated with this treatment's weed community. Indeed, weed species vary in their ability to host AMF (e.g., mustards are not mycorrhizal), so their presence or absence may affect mycorrhizal colonization of grapevines. Indeed, reports on the influence of plant community composition on AMF suggest that plant diversity has a strong effect on AMF diversity (Johnson et al. 2004), and this may affect the colonization of individual plant species.

Grape yield and quality

All yield, fruit quality and vine growth parameters varied by year, and this was the only significant effect for these parameters, with the exception of berry weight and titratable acidity (tables 2 and 3). No differences in crop yield or fruit composition were observed from 2001 to 2005 due to weed control treatments (table 2). Cover-crop treatments also had no significant effect on yield or fruit composition, although in 2001 and 2004, there was a reduction in berry size in the 'Trios 102' triticale treatment.

Weed control treatments also had no effect on vine growth (table 3), based on shoot counts and pruning weights taken at dormancy. Cover-crop treatments had no significant effect on vine growth when averaged over 5 years, although in 2001 and 2005 the 'Trios 102' triticale treatment significantly reduced pruning weights. The trend for lower pruning weights may be related to the greater decline in soil moisture in the middles where this cover crop was used. It appears that vine growth, yield and grape quality are more significantly affected by annual precipitation than by vineyard floor management practices.

Choosing the right cover crop

In low rainfall areas the choice of cover crop is critical because of its effect on available soil moisture. We observed that late-maturing 'Trios 102' used more soil moisture during the vine growing season; if irrigation water does not compensate for water used by the cover crop, reduced vine growth and yield losses may result. The clear benefits of cover crops were increased organic matter in the middles and reduced sediment loss.

Microbial biomass was increased in cover-cropped middles and there were indications that this effect extended to under the vines. Although there were no negative impacts of weed control treatments on vine productivity, we observed increased compaction over time from the use of cultivation. This study indicated that the choice of weed control strategy and cover crop must be carefully considered to maximize the benefits and minimize negative impacts of the practices. The benefits of cover crops are concentrated in the middles, and future research should focus on evaluating practices that improve the quality of soil under the vines.

TABLE 3. Average vine growth parameters, 2001–2005

Weed treatment	Shoots per vine	Pruning weight	Fruit: pruning weight ratio
	no.	*kg*	
Standard practice	37	0.52	12.0
Cultivation	37	0.50	12.5
Post-emergence herbicide	37	0.58	11.3
Cover crop			
'Merced' rye	37	0.56	12.1
'Trios 102' triticale	37	0.48	12.7
Bare ground	37	0.56	11.1
Significance			
	. . . . P *value*		
Weed treatment	0.80	0.35	0.43
Cover	0.38	0.07	0.09
Year	< 0.001	< 0.001	< 0.001
Weed trt x cover	0.81	0.56	0.84
Cover x year	0.64	0.32	0.83
Weed trt x year	0.42	0.90	0.08
Weed trt x cover x year	0.92	0.96	0.99

R. Smith, L. Bettiga and M. Cahn are Farm Advisors, UC Cooperative Extension (UCCE), Monterey, Santa Cruz and San Benito counties; K. Baumgartner is Research Plant Pathologist, USDA Agricultural Research Service, Department of Plant Pathology, UC Davis; L.E. Jackson is Professor and Cooperative Extension Specialist, Department of Land, Air and Water Resources, UC Davis; and T. Bensen is Postdoctoral Research Associate, Department of Biology, University of Mississippi. Western Sustainable Research and Education Program and the Viticulture Consortium Program funded this research. Thank you to growers Jason Smith and Daryl Salm, and research assistants Dave Miltz and Pat Headley.

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RESEARCH ARTICLE

Self-reseeding annual legumes evaluated as cover crops for untilled vineyards

by Glenn McGourty, James Nosera,
Steven Tylicki *and* Agnes Toth

Self-reseeding annual cover crops can regenerate in subsequent years without tilling the seedbed and can be part of a strategy to protect vineyard soil from erosion. We compared 22 such cultivars in a 1-year-old 'Syrah' wine-grape vineyard located at 1,400 feet in Lake County. We found significant differences between species in the amount of biomass produced in 2004 and 2005. All of the species studied were relatively low statured and fit well in vineyard middles. Pressure bomb readings taken after the cover crops stopped growing showed that with a dry spring (2004), vines with cover crops were modestly more stressed than those under tillage prior to July irrigations, but after irrigation the cover-cropped vines were slightly less stressed. In 2005, which had rainfall in late spring, there were no differences in vine water status throughout the season. We conclude that water use by the cover crop must have been relatively low and did not result in excessive vine water stress.


Research shows that low-statured, self-reseeding legumes and grasses may be good cover-crop choices for North Coast vineyards. *Above*, baby blue bells (*Nemophila insignis*) and subterranean clover grow in a Lake County organic vineyard.

During the past 15 years, cover crops have become widely used in California as a vineyard floor management practice (McGourty 1994, 2004). Cover crops protect vineyard soil from erosion, improve soil fertility and tilth, serve as habitat and food for beneficial insects and mites, and provide firm footing during wet weather. They are also aesthetically pleasing, especially those with colorful flowers.

Initially, many cover-crop species used in California vineyards were more appropriate for agronomic-crop farming systems (rotation crops). These species — such as oats (*Avena sativa*), common vetch (*Vicia sativa*) and bell beans (*Vicia faba*) — are large biomass producers and grow up to 48 inches high. As a result, they often contribute excessive soil nitrogen, encouraging unwanted vegetative growth. Most also require tillage for seedbed preparation (Bugg et al. 1996). Since the majority of these cover crops are planted in the fall, soil is exposed when rainfall is most likely, increasing the chances of erosion and water pollution in adjacent surface water (streams, rivers and ponds).

Research by the authors and others has demonstrated that under North Coast conditions, self-reseeding annual legumes and grasses are better choices, since they use less tillage and energy inputs than cover crops that require seedbed preparation and annual seeding. With self-reseeding annual legumes, crop residue from the previous growing season protects the soil from erosion in fall and winter, when seedlings emerge and eventually form a new sward in the vegetated area on the vineyard floor between the vine rows (Bugg et al. 1996; McGourty 1994, 2004).

Vineyard acreage expanded rapidly in Lake County during the late 1990s, resulting in new vine plantings in upland areas. Otherwise good vineyard sites, many upland locations are at high risk of soil erosion because they are on sloping ground. Many of these new vineyard sites were formerly dry-farmed (nonirrigated) walnut orchards in which orchard floor vegetation was removed to conserve soil moisture, and soil erosion was common in winter. Typically, these new vineyards were planted above 1,400 feet, where winters can be cold (below 18°F) and wet (rainfall averages 35 inches annually, and can total 60 inches in wet years).

Cover crops planted in upland areas must be able to tolerate more extreme conditions than in more temperate low-elevation areas planted to vineyards on the North Coast. In previous cover-crop trials in Lake County, medic, rose clover, crimson clover, subterranean clover, balansa clover and Persian clover performed well (McGourty et al. 2006). These cover-crop species often have different winter dormancies (chill-hour requirements to induce flowering and vegetative growth) and potential to produce hard seed (a seedbank that allows self-reseeding in subsequent years).

In previous studies, broad groups of cover crops were evaluated, and their regeneration by self-reseeding was followed for up to two seasons (Bugg et al. 1996; McGourty et al. 2006). In most of these studies, plots were reseeded every year into a tilled seedbed for two consecutive seasons. The trials consistently indicated that low-growing,

Twenty-two cover-crop cultivars were compared with an unseeded control. *Left,* subterranean clover; *center,* balansa clover; and *right,* bur medic.

self-reseeding annual legumes such as medic, subterranean clover and other clover species were useful in vineyards as cover crops, even if annual reseeding was required.

This trial was initiated to evaluate the performance of a broader range of cultivars and species of self-reseeding annual clovers. Additionally, we wanted to investigate whether cover crops increased seasonal vineyard water-use. Measurements required to quantify consumptive use were beyond the scope of this work, so we settled on assessing vine water status with pressure chamber measurements to see if vines growing with these cover crops were more stressed than those under tillage. Our goal was to help the many growers who prefer clean tillage (bare soil free of any vegetation) of the vineyard floor during the growing season to determine if the benefits of this strategy, including the conservation of winter rainfall stored in the root zone, were outweighed by potentially increased soil erosion from fall and winter rainfall on the unprotected vineyard floor.

Self-reseeding legumes tested

Experimental design. A randomized complete block experimental design was used with four replications of each selection for 22 annual legume cultivars and an unseeded control, for a total of 92 plots. The experiment was undertaken in a 1-year-old upland vineyard at 1,400 feet, planted in 2002 to 'Syrah' clone 877 on 101-14 rootstock, with vines spaced 5 feet apart in rows 8 feet apart as dormant bench grafts. The site had formerly been planted to walnut trees for 27 years.

Species. The species evaluated were selected to represent a broad range of winter dormancies and hard-seed production. These species have been used successfully in other agricultural regions with Mediterranean climates as self-reseeding forage crops. Species planted included subterranean clover, medic, Persian clover, balansa clover, crimson clover, rose clover and a control of resident vegetation (table 1). In each replicated plot, the selection was hand-seeded at an appropriately high rate so as not to be a limiting factor (at least 25 pounds per acre) on Oct. 22, 2003, in two adjacent row middles four vines long (20 feet) by 5 feet wide.

Site preparation. The site was limed at 5 tons per acre before the vines were planted in 2001, resulting in a soil pH of 6.5. Phosphorus fertilizer with sulfur (0-36-0-20) was applied at 200 pounds per acre to the entire trial to insure that phosphorus and sulfur deficiency would not be a limiting factor to cover-crop growth.

Irrigation. The vines were irrigated with a drip system suspended beneath the vines. Two drip emitters with an output of 0.5 gallon per hour each were spaced 2.5 feet apart beneath each vine. Irrigation was applied uniformly to the vineyard at 4 gallons per vine per week. The grower timed each irrigation set, starting and turning off the irrigation pump after precisely 4 hours. In 2004, the vineyard received 12 weekly irrigations beginning July 2, for a total of 48 gallons per vine. In 2005, the vineyard received 10 weeks of irrigation starting July 14, for a total of 40 gallons per vine.

Harvest measurements. Plots were evaluated and harvested on May 4, 2004. Data taken included percentage of the vineyard-floor plot area covered by each cover crop (visual estimation); height (measured with a yard ruler by taking the average height at four spots); and biomass production (measured by clipping the plant material contained within three 1-foot-square wire frames). Biomass was oven-dried at 120°F and weighed. These measurements were taken again on May 9, 2005. Only percent-cover estimates were made on May 12, 2006.

Data were analyzed with ANOVA and means were compared with Duncan's multiple range test at the 95% confidence interval.

Leaf water potential. In 2004 and 2005, leaf-water-potential measurements were made on cloudless days with a pressure bomb by sampling between 11 a.m. and 1 p.m. (full solar noon) using fully expanded, sunlit leaves. Sampling began early in the season, once the cover crops stopped growing and were drying down. In 2004, one replication of each cover crop was chosen at random and a grape leaf was selected from a vine in the center of the plot that had the same cover crop growing in the two adjacent middles to the vine row. Twenty-two vines were chosen in the cover-crop area, and 22 were chosen in an adjacent clean-tilled area of the vineyard. (This was the practical number of samples that could be taken during the solar noon period.)

Leaves were removed, placed in a small plastic bag, inserted into the pressure chamber and secured as quickly as possible. Pressure was applied slowly until sap was extruded from the end of the emerged petiole. The pressure at this point was noted on the gauge of the pressure bomb and recorded. Sampling areas were rotated weekly so that no specific sampling order was followed (i.e., the cover-cropped area was sampled first one week, and the tilled area was sampled first the next week).

Weekly or biweekly observations were made at the same marked vines. When leaf water potential reached more than −13 bars, irrigation was initiated (week 7, June 24, 2004). Leaf water potential was measured until week 10 after two irrigations. Significant precipitation occurred in June 2005 and irrigation was initiated later, since leaf water potential was lower later into the growing season. The sample sizes were reduced to 12 vines in both the cover-cropped and tilled areas, since fewer plots had successfully regenerated. Monitoring began on July 14, 2005, and the vineyard was irrigated following pressure bomb measurements on July 21. Monitoring continued for 2 more weeks, until Aug. 4.

TABLE 1. Dry weight biomass, height and percent cover of self-reseeding annual legumes in Lake County, 2004–2006

Cover crop	Biomass		Height		Cover		
	2004	2005	2004	2005	2004	2005	2006
	tons per acre		*inches*		%		
Subterranean clovers (dormancy category)*							
Antas (LS)	1.89 efg†	2.08 cde	6.5 ab	10.2 abc	87.5 def	85.0 b	85.0 g
Campeda (MS)	1.13 cde	2.32 def	4.4 a	9.0 ab	73.7 cde	68.7 ab	88.7 g
Denmark (LS)	1.06 cde	2.40 def	4.2 a	10.2 ab	62.5 bcd	70.0 ab	85.0 g
Gosse (MS)	1.25 cde	2.14 cde	4.0 a	11.2 a	75.0 cde	86.2 b	82.5 g
Koala (MS)	0.94 ab	1.96 bcd	4.5 a	7.5 a	57.5 abc	61.2 ab	90.0 g
Mt. Barker (MS)	1.64 def	2.54 ef	4.7 a	11.2 bc	92.5 fg	92.5 c	87.5 g
Nungarin (ES)	1.07 bcd	1.94 bcd	3.7 a	8.7 ab	47.5 a	60.0 ab	60.0 de
Seaton Park (ES)	1.06 bcd	1.66 bc	3.9 a	8.5 ab	60.0 bc	65.0 ab	73.7 ef
Trikkala (MS)	1.07 bcd	2.00 bcd	4.0 a	8.7 ab	55.0 ab	55.0 a	61.2 de
Woogenellup (MS)	0.96 ab	1.86 bcd	3.8 a	9.0 ab	67.5 cde	57.5 ab	70.0 ef
York (ES)	1.10 bcd	2.18 cde	3.8 a	11.2 bc	75.0 cde	85.0 b	83.75 g
Medics							
Jester	1.83 efg	2.06 cde	9.0 bc	10.0 abc	90.0 efg	60.0 ab	35.0 cd
Parabinga	0.87 ab	2.08 cde	5.7 a	10.7 abc	75.0 cde	70.0 ab	70.0 ef
Santiago	1.03 abc	1.50 bc	6.4 ab	10.2 abc	76.3 cde	73.7 ab	40.0 cd
Torreador	0.79 a	1.58 bc	5.6 a	8.5 ab	52.5 a	60.0 ab	86.2 g
Other clovers							
Balansa Bolta	1.53 def	2.20 def	10.8 c	13.2 cd	95.0 fg	82.5 b	80.0 g
Balansa Paradana	1.60 def	2.32 def	11.0 c	12.0 cd	97.5 h	86.2 b	81.2 g
Crimson Flame	2.39 i	2.38 def	17.0 e	16.0 e	97.5 h	93.7 c	50.0 de
Persian Lightning	2.10 gh	2.38 def	13.6 d	12.0 cd	100.0 h	75.0 b	6.2 a
Persian Nitro	1.58 def	2.40 ef	9.5 c	11.0 bc	90.0 efg	62.5 ab	27.5 bc
Rose Hykon	2.15 gh	1.88 bcd	10.5 c	10.7 bc	97.5 h	67.5 ab	11.2 ab
Rose Overton	1.76 efg	2.34 def	9.5 c	12.2 cd	86.2 def	65.0 ab	7.7 ab
Control (resident vegetation)	**0.70 a**	**1.10 a**	**4.1 a**	**7.0 a**	**100 h**	**100 d**	**100 h**
Trialwide average	**1.34**	**2.07**	**6.7**	**10.1**	**74.4**	**68.8**	**59**

* ES = early season; MS = midseason; LS = late season.

† Values followed by the same letter within columns are not significantly different as determined by Duncan's multiple range test at 95% level.

Pests. The plots did not have any pest problems such as diseases, mites, insects or vertebrates, and no interventions or treatments were made.

Cover-crop performance

We found significant differences between many of the cover-crop species in biomass production, plant height and percent cover of the sward (table 1).

Biomass production. Winter 2004 was relatively dry, and precipitation was lower than usual. Rain did not begin until November, and precipitation in March and April was less than 1 inch (23.7 inches for the season). All the cover crops germinated and grew, but overall biomass for the entire trial was lower than in 2005, when precipitation was 2.5 inches in October and almost 5 inches in April and May (26.72 inches for the season). In 2006, total precipitation exceeded 50 inches in the Clear Lake basin.

In 2004, average biomass production was 1.34 tons per acre, ranging from 0.79 ton ('Torreador' medic) to 2.38 tons ('Flame' crimson clover) per acre; by comparison, the resident vegetation (control) produced 0.7 ton per acre. In 2005, average biomass was 2.07 tons per acre, ranging from 1.5 tons ('Santiago' bur medic) to 2.4 tons ('Nitro' Persian clover) per acre, compared to 1.1 tons per acre produced by the resident vegetation.

Biomass is converted into soil carbon over time, which helps to improve soil quality and increase microbial activity, imparting many benefits to the agroecosytem. If a goal of cover crops is to increase biomass grown in the vineyard, then many of the selections performed well compared to resident vegetation. (Nitrogen fertilizer may spur resident vegetation to produce more biomass, but this requires more energy.) Dominant species in the resident vegetation included annual bluegrass (*Poa annua*), shepherd's purse (*Capsella bursa-pastoris*), annual ryegrass (*Lolium multiflorum*), chickweed (*Stellaria media*), scarlet pimpernel (*Anagallis arvensis*) and annual sowthistle (*Sonchus oleraceus*).

Height. All of the cover-crop selections that we studied were low-statured and would not hinder vineyard operations or create high levels of humidity near the vine canopy in late spring (table 1). By contrast, some annual cover-crop species used in vineyards such as oats (*A. fatua*), purple vetch (*V. benghalensis*) and bell (fava) beans can grow up to 4 feet high. In 2004, the average cover-crop height in this trial was 6.7 inches, ranging from 4.0 inches ('Gosse' subterranean clover) to 17.0 inches ('Flame' crimson clover). In 2005, the cover crops grew taller because of increased precipitation. The average height was 10.1 inches, ranging from 7.5 inches ('Koala' subterranean clover) to 16 inches ('Flame' crimson clover).

Cover. Percent cover of the sward measures how successful a species is in germinating and competing with weeds, and how persistent the stand is over time (i.e., how sustainable a planting is). In this trial, cover varied considerably by species (tables 1 and 2). The subterranean clovers increased over time, while medics gradually declined (although 'Torreador' persisted well and increased in percent cover). The other clovers decreased dramatically from 2004 to 2006. Only balansa clover persisted well, with percent covers above 80% for the two selections after 3 years. We believe that our visual estimations were accurate, but since they may vary by 5% to 10%, the means comparisons may be overstated in the ANOVA. Nonetheless, percent cover above 70% indicates that the cover crop has germinated and grown well during that season.

Leaf water potential. Cover-cropping with annual self-reseeding legumes had different effects. In 2004, with its dry spring, there were slight but significant differences between the tilled

TABLE 2. Average percent cover of sward, 2004–2006

Cover crop	2004	2005	2006
	%		
Subterranean clovers	70	70	80
Medics	75	65	60
Other clovers	95	75	40
Trialwide average	75	75	60

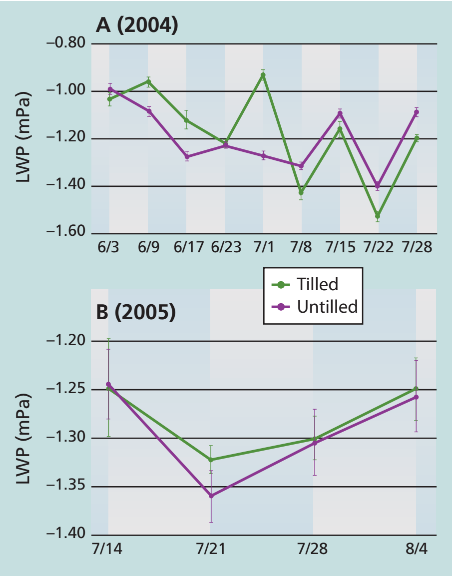

Fig. 1. Leaf water potential (LWP) or vine moisture status in millipascals (mPa), with and without cover crops in (A) 2004 and (B) 2005. "Tilled" means all cover crops were turned under with a disk; "untilled" means the dried aftermath of annual cover crops was left on the surface of the vineyard floor. Tilled, a standard grower practice, is the control. Untilled represents the average of pressure bomb readings taken from all 22 cover crops in 2004. In 2005, readings were taken more randomly within the untilled portion of the trial. In 2004, vines were irrigated during the weeks of July 2 and 22; in 2005, irrigation was during the weeks of July 21 and 28.

and cover-cropped areas (fig. 1). Before irrigation began on July 2, vines in the cover-cropped areas had more negative leaf-water-potential values, indicating that they were under greater water stress. However, after irrigation began, vine water status with the cover crops recovered to a greater extent than with the tilled treatment. The tillage may have caused increased surface evaporation. In 2005 more rain fell in late spring, and there were no significant differences between vine moisture status in the different treatments.

It is not possible to analyze in detail the impact of the different surface treatments on evapotranspiration, since we did not measure the impact of the treatments on the storage of winter rainfall. However, the fact that vine water status with cover crops was only modestly lower than with tillage prior to irrigation, and actually somewhat higher after the 2004 irrigations, indicates that cover-crop water usage did not result in excessive plant water stress. In 2005, there were no significant differences in vine leaf water potential in either the pre- or postirrigation periods (fig. 1). This was likely because there was more rainfall later in the spring and presumably higher soil water levels as the summer progressed in 2005. We conclude that while cover crops certainly consume water, the magnitude of this evapotranspiration must be relatively small and may be offset by improved infiltration and storage of winter rainfall. Additionally, the dried vegetation aftermath in cover-cropped areas offers considerable protection against erosion when fall rains resume, a definite benefit to water quality during winter precipitation.

Choosing cover crops for vineyards

Numerous species performed well in the initial year of seeding. Top performers for biomass production included the crimson, balansa, rose and subterranean clovers, similar to previous studies (Bugg et al. 1996; McGourty 2006). As a group, the medics did not grow as well as subterranean clovers under Lake County conditions. However, they persisted better than some of the others tested, including Persian, 'Flame' crimson and rose clovers.

Persistence is dependent on the production of hard seed that can survive for several years before germinating, as well as successful germination each season. Subterranean clover has a definite advantage, generating a large amount of hard seed. Most importantly, it can actually preplant its seeds into the ground; seedpods develop on pegs (like peanuts) after flowering, and the seed matures in the soil, protected from feeding by birds and rodents. The seed is then ready to germinate when conditions are optimal.

Balansa clover also performed well, although its percent cover of the sward declined somewhat over time. This species is likely to persist and flowers prolifically, making it potentially useful as an insectary plant for generalist predatory and parasitoid insects and mites.

The cover crops that declined over time in this study were usually displaced by annual weeds also found in the control plots. In our practical experience, it is not unusual for subterranean clover and bur medic stands to increase and decrease over time, since rainfall and distribution can greatly affect seed emergence at the beginning of their growth period in the fall.

All of the species tested are suitable as cover crops for vineyards in the North Coast region, and many performed well at our high-elevation test site. While some may not persist for long, they would still be useful as cover crops even if they require annual reseeding. Subterranean clovers persisted the best of the cover-crop species that we evaluated. Subterranean clovers are categorized by the amount of winter dormancy that is required before vegetative growth and flowering will occur in the spring (table 1). These cultivars with short winter dormancy are best for warm winter areas with limited rainfall, because they complete their growth cycles in less time. Cultivars with longer winter dormancies are best suited for areas with longer winters and more rainfall, and they tend to produce more biomass than cultivars with shorter winter dormancies. Selections from all the dormancy categories also performed well, although in practice, most growers are using long-dormancy selections such as 'Antas', 'Koala' and 'Mt. Barker'.

G. McGourty is Winegrowing and Plant Science Advisor, UC Cooperative Extension (UCCE), Mendocino and Lake counties; J. Nosera is Agricultural Technologist, UCCE Mendocino County; S. Tylicki is General Manager, Steele Wines, Kelseyville, Calif.; and A. Toth is former intern, UCCE Mendocino County. The authors appreciate the cooperation of vineyard owner Jed Steele and assistance of custom farmer Lars Crail. Fred Thomas of Cerus Consulting suggested many of the cover-crop selections. Kamprath Seed Company donated seed for the trial.

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RESEARCH ARTICLE

Soil-landscape model helps predict potassium supply in vineyards

by Anthony T. O'Geen, Stuart Pettygrove,
Randal Southard, Hideomi Minoshima
and Paul S. Verdegaal

The Lodi Winegrape District is one of the largest in California and encompasses a wide diversity of wine-grape varieties, production systems and soils, which complicates grape nutrient management. To identify regions within this district that have similar nutrient-management needs, we are developing a soil-landscape model based on soil survey information. Our current model identifies five regions within the Lodi district with presumed relationships between soil properties and potassium-supplying ability. Region 1 has weakly developed, clay-rich soils in basin alluvium; region 2 has weakly developed, coarser-textured soils on recent alluvial fans, flood plains and stream terraces; region 3 has moderately developed soils on low terraces derived from granitic alluvium; region 4 has highly developed soils on high terraces derived from mixed alluvium; and region 5 has weakly developed soils formed on undulating volcanic terrain. Field and lab studies of soils in these regions show that our model is reasonable in concept, but that it must be fine-tuned to account for differing degrees of soil variability within each region in order to make realistic nutrient-management predictions.

The Lodi Winegrape District of San Joaquin and Sacramento counties encompasses a wide range of soil types, on which about 100,000 acres of wine grapes are grown.

The Lodi Winegrape District is one of the largest in California, with approximately 750 growers and about 100,000 acres in production in San Joaquin and Sacramento counties. This district encompasses a wide range of wine-grape varieties, production systems and soils.

Many growers and crop management professionals in this district and elsewhere in California lack confidence in some of the grape nutrient-management guidelines developed by the University of California over the past few decades (Christensen et al. 1978). These guidelines were based largely on research conducted with own-rooted, flood-irrigated 'Thompson Seedless' grapes. Several factors may contribute to the limitations of existing UC nutrient guidelines, but in the Lodi Winegrape District, soil variability appears to be especially relevant.

This district has an incredible diversity of soils that encompass a range of ages, parent mineralogy and physical properties possibly found in no other agricultural area of similar size in the United States. This variability reflects the presence — even within single vineyards — of a mélange of volcanic, metamorphic and granitic alluvial and upland landforms spanning a range of ages, from modern-day stream deposits to ancient geomorphic surfaces among the oldest in the country.

In such an environment, a single set of soil and nutrient management practices cannot reasonably be expected to meet wine-grape yield and quality goals. In particular, it is well known that the chemical and physical properties of soil control a plant's supply of potassium (K).

Potassium and wine grapes

Potassium is an essential nutrient for plant growth and is needed in relatively large amounts by many crops. In grapes, potassium deficiency results in reduced vine growth, premature leaf drop and yield loss (Christensen et al. 1978). During periods of rapid leaf and fruit growth, the rate of potassium uptake by the fruit is high.

Care must be taken not to overapply potassium fertilizers. High levels in the soil can contribute to excess potassium in red grape skins, reducing color. The intensity of wine color is an important sensory component of wine. Excessive potassium uptake by grapes can also lead to an increase in juice pH (Boulton 1980) and a decrease in the yeast-assimilable nitrogen and ammonia of the fruit (Wehmeier 2002). Excess potassium in the wine may precipitate as potassium tartrate during cold stabilization, requiring the winery to adjust pH to avoid losing an important sensory component of the wine. Undesirably high potassium levels are a documented problem in some Australian vineyard soils (Krstic et al. 2003).

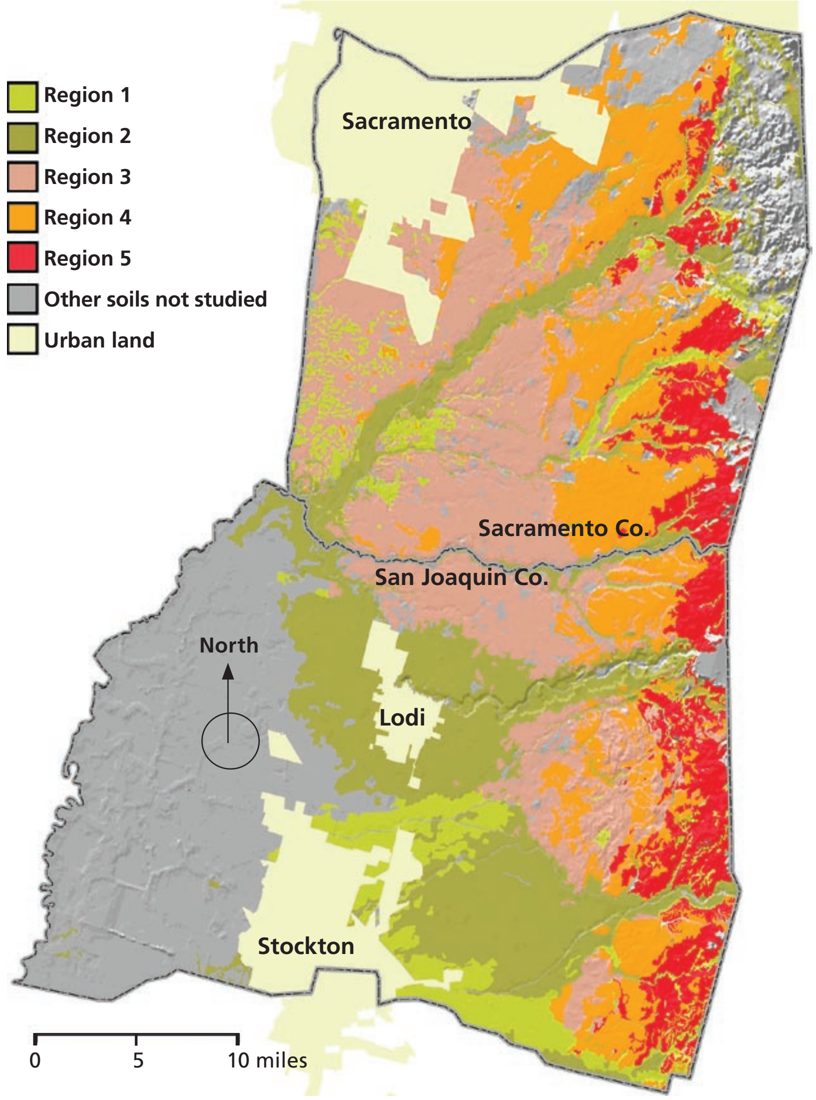


Fig. 1. Modeled soil regions in the Lodi Winegrape District.

Soil controls potassium supply

Plant-available potassium occurs in the soil solution or as exchangeable cations on soil mineral particles and organic matter. Over time, potassium can leach from soils, especially sandy ones, and must be replaced by either fertilization or the slow-release weathering of minerals.

Potassium fixation. Potassium fixation is an important phenomenon in soils derived from granitic parent material. Potassium gets trapped within the crystalline structure of vermiculite (a layer-silicate mineral derived from mica) and becomes less available to plants. Soils with vermiculite are common in granitic alluvium on the east side of the Central Valley, especially in landscapes with moderately weathered soils. Potassium fixation is influenced by soil mineralogy and texture (Murashkina et al. 2007a, 2007b).

Vermiculite is a transitory mineral in most soils. As soils develop, parent materials weather from primary minerals, such as mica, into secondary minerals, such as vermiculite and smectite. In turn, these secondary minerals can be further weathered into new minerals such as kaolinite and iron oxides.

Each mineral has intrinsic differences in the magnitude of potassium fixation and cation exchange capacity (CEC). Micas have low potassium-fixation and low cation exchange capacity; vermiculite has high potassium-fixation and high cation exchange capacity; smectite has low potassium-fixation and high cation exchange capacity; and kaolinite and iron oxides have low potassium-fixation and low cation exchange capacity.

Glossary

Cation exchange capacity (CEC): The sum total of exchangeable, positively charged ions that a soil can adsorb and then release to soil solution. Cation exchange sites serve as a reservoir of plant-available nutrients such as potassium. CEC differs based on the magnitude of negative charge on the minerals, surface area, the nature of the silicate layering and soil organic matter content.

Duripan: A silica-cemented soil layer, also referred to as a hardpan.

Exchangeable potassium: Potassium on cation exchange sites that can be extracted by ammonium acetate.

Horizon: A layer of soil formed parallel to the soil surface and affected by soil-forming processes.

Iron oxides: A group of minerals (e.g., hematite, goethite, ferrihydrite) that impart reddish color in soils, with very low CEC and no potassium fixation potential.

Lithology: The description of rocks on the basis of their physical and chemical characteristics.

Mineralogy: The description of the assemblage of primary and secondary minerals in soil.

Potassium fixation: The adsorption of potassium from soil solution into the crystalline structure of minerals, such as vermiculite, which makes the potassium less available for plant uptake.

Smectite: A layer-silicate clay with lower negative charge than vermiculite; has high shrink-swell capacity and high CEC, but low potassium-fixation potential.

Soil taxonomy: The classification of soil bodies into a hierarchy of groups based on measured soil properties.

TABLE 1. Framework for predicting potassium (K) supply characteristics of soilscapes in Lodi Winegrape District

Soilscape characteristics	Geologic age of parent material*	K-rich weatherable minerals†	Soil weathering intensity†	Exchangeable K‡	K fixation potential‡
	years				
Region 1: Alluvial fans, fine-textured	0–14,000 (post-Modesto and upper Modesto formations)	Moderate	Low	High	None
Region 2: Alluvial fans, coarse-textured, granitic alluvium	0–70,000 (post-Modesto and Modesto formations)	High	Low	Moderate	Moderate
Region 3: Low terraces, duripans, granitic alluvium	130,000–330,000 (Riverbank formation)	Moderate	Moderate	Low	High
Region 4: High terraces, mixed alluvium	> 600,000 (Turlock Lake and Laguna formations)	Low	High	Moderate	None
Region 5: Undulating volcanic terrain	3–10 million (Mehrten formation)	High	Low	High	None

* Geologic ages based on Marchand and Allwardt (1981).

† Weatherable minerals and soil weathering intensity classes are not quantitative, but reflect relative differences based on soil properties.

‡ Exchangeable K and K fixation classes are based on profile-weighted averages for each representative soil. Exchangeable K (mg/kg): high > 200, moderate 100–200, low < 100. Class cutoffs for K fixation potential (mg/kg): High > 100, moderate 0–100, none < 0.

Soil-specific potassium fertilization. Current recommendations for potassium fertilization in California vineyards do not take into account potential differences among soils in fertilizer effectiveness or the maintenance of soluble potassium levels (Christensen et al. 1978).

We propose that the key characteristics of soils that control potassium supply and retention, while not explicitly a part of the soil classification system, can be inferred from soil-survey database information. Rather than providing a regionwide prescription for potassium nutrition, our goal was to develop a landscape-targeted model that predicts the fate of potassium, based on properties of the soil parent material and the degree of soil development.

Lodi soils

The Lodi Winegrape District is located at the confluence of the San Joaquin and Sacramento rivers immediately east of the San Joaquin-Sacramento Delta and west of the lower Sierra Foothills. The average vineyard size is approximately 80 acres, usually in multiple small parcels. The district's principal wine-grape varieties are Zinfandel (comprising 40% of California's total acres), Chardonnay, Cabernet Sauvignon, Sauvignon Blanc, Merlot and Syrah.

Soils of the Lodi district vary spatially as a result of the parent materials' depositional history and subsequent weathering. Soils on the east side of the San Joaquin Valley formed from alluvium (sediment transported by water) that accumulated over thousands to millions of years from erosion of the Sierra Nevada. As a result, the district's soils fall into a systematic spatial pattern: the youngest materials are generally on the west side, the oldest are generally on the east side, and materials of intermediate age are in the center.

Through time, the source material of this terrain has changed. During the initial stages of Sierran uplift, the mountains were capped with metamorphosed sedimentary rock, metamorphosed volcanic rock and volcanic rock. As the uplift continued, the mountain caps were stripped by erosion, exposing the granitic rocks that lay beneath. The lithology and age of parent materials in which the soils formed have changed over time, resulting in a variety of soil mineral assemblages.

Soil-landscape model

Potassium fertilizer requirements are determined by the balance between plant demands for this nutrient and the capacity of the soil to provide it. Our model encompasses three factors: (1) the slow release of potassium by mineral weathering, which determines total potassium supply; (2) the soil's cation exchange capacity, which affects the retention of available potassium; and (3) the soil's potassium fixation potential, which reduces the availability of exchangeable potassium.

The primary datasets for our model were the Soil Survey Geographic databases (SSURGO) for Sacramento and San Joaquin counties. (To view an example of soil survey information see Web Soil Survey at http://soils.usda.gov or Online Soil Survey http://casoilresource.lawr.ucdavis.edu/soilsurvey). In a geographic information system (GIS), attribute tables containing taxonomic information for the dominant soil series of each soil map unit were joined to the soil maps (fig. 1, table 1). The hierarchical framework of soil taxonomy was used to define the degree of soil development and type of parent material (Soil Survey Staff 1999). Each regional soilscape consisted of aggregated soil map units through queries of SSURGO data.

The model groups soils into five regions with differences in parent material and degree of soil development, which serve as a proxy for potassium supply (table 1).

Region 1. This region has weakly developed, smectitic, clay-rich soils with high shrink-swell capacity in basin alluvium. We queried SSURGO for all soils classified as Vertisols and all in the smectitic soil mineralogy family class (Soil Survey Staff 1999).

Region 2. Region 2 has weakly developed, coarse- and loamy-textured soils on recent alluvial fans, flood plains and stream terraces. This region represents such soils formed mostly from granitic alluvium in their initial development stages. First, all weakly developed soils were queried as inferred by their taxonomic classification. We selected all Xerolls at the suborder level of soil taxonomy, and all Xerofluvents and Xeropsamments at the great group level (Soil Survey Staff 1999). These soils contain a broad mix of minerals. This initial query reflected soils developed in recent alluvium from freshly eroded Sierra materials. Some Xerolls are derived from the erosion of old volcanic terraces in the valley's eastern margins, but these soils were removed from the query by excluding the Pentz and the Peters soil series, which occur exclusively on volcanic terrain.

Region 3. Region 3 has moderately developed soils on low terraces derived from granitic alluvium. Region 3 was created from an initial query of all soils formed on low and high terraces that included Durixerepts, Palexeralfs and Durixeralfs at the great group level of soil taxonomy. This query identified all intermediate and well-developed soils in the district. From this query we selected soil map units that were dominated by soils formed on low terraces (San Joaquin or Bruella), and then also included soils found in valley positions of the oldest and highest alluvial terraces (Montpellier and Yellowlark) that are derived from granitic sources but were not in the original query.

Region 4. Region 4 has highly developed soils on old, high terraces derived from older, mixed alluvium (granitic, metamorphosed sedimentary and metamorphosed volcanic rock). These soils were selected from the same original query we used for region 3. From that original query, we excluded map units with dominant soil components of San Joaquin and Bruella.

The main difference between regions 3 and 4 is that region 3 soils are derived from granitic alluvium, which contain micas that weather to vermiculite, whereas region 4 soils are derived from older alluvium of mixed rock sources, which weather to mostly kaolinite and iron oxides.

Region 5. Region 5 has weakly developed soils formed on undulating volcanic terrain. Soils were identified through a query of the dominant soil series that occur exclusively on this parent material, including Pentz, Peters, Pardee and Keys. All map unit names that contained these soil series as the dominant soil were selected.

Characterizing the soil regions

Following preliminary fieldwork to assess soil variations within these five regions, several soil profiles in each region were sampled and analyzed. We then selected one soil profile from each to represent our model. Standard soil-survey techniques characterized the morphologic, chemical and physical properties of soils. Potassium fixa-

TABLE 2. Chemical, physical and morphological properties of representative soils in Lodi Winegrape District

Horizon	Depth	Color*	Sand	Silt	Clay	Clay mineralogy†	pH	CEC	Exchangeable K	K fixation
	inches	*moist soil*	. . . . %					*cmol(+)/kg soil‡*	. . . . . . *mg/kg soil*	
Region 1										
Ap	0–5	10YR 3/1	19	37	44	S, M, K	6.2	29.1	631	0
Btss1	5–15	10YR 2/1	16	37	47	S, V, K	6.3	27.8	207	96
Btss2	15–24	10YR 2/1	15	39	46	S, V, K	6.3	28.4	211	277
2BC	24–43	7.5YR 3/3	32	38	30	S, V, K	6.4	17.6	92	467
Region 2										
Ap	0–5	10YR 3/2	62	29	9	M, K	5.6	7.1	233	0
A	5–17	10YR 3/3	61	29	10	M, K	5.7	4.8	146	0
AB	17–23	10YR 4/3	59	29	12	M, K	6.0	5.8	110	0
Bt1	23–34	10YR 4/3	61	27	12	M, K	6.0	5.4	99	0
Bt2	34–41	10YR 4/3.5	63	26	11	M, V, K	6.0	4.5	72	87
C	41–47	10YR 4/3	60	28	12	M, V, K	6.0	5.9	49	425
Region 3										
Ap	0–6	7.5YR 3/4	49	26	25	M, K	6.1	6.9	110	72
BA	6–12	5YR 3/4	49	24	27	nd	6.4	6.2	186	112
Bt1	12–23	5YR 3/4	51	20	29	nd	6.5	6.2	182	67
Bt2	23–33	5YR 3/4	54	19	27	nd	7.0	6.2	165	160
Bt3	33–37	5YR 4/4	49	19	32	nd	6.9	8.5	33	129
Btqm	37–55	7.5YR 4/4	61	26	13	V, K, M	6.7	8.3	21	230
2BC	55–72	7.5YR 4/4	64	20	16	nd	6.6	6.1	22	268
Region 4										
Ap1	0–6	5YR 4/4	38	33	29	K, M (tr)	6.0	11.5	384	0
A/Bt	6–24	5YR 4/4 & 2.5YR 3/6	36	30	34	K, M (tr)	4.2	6.8	213	0
Bt1	24–38	2.5YR 4/4	59	16	25	K, M, V (tr)	3.9	11.6	110	0
Bt2	38–42	2.5YR 4/6	32	20	48	K, M, V (tr)	3.9	10.6	50	0
Bt3	42–57	5YR 4/4	35	22	43	K, S, M	3.7	20.3	68	0
Btqm	57–61	2.5YR 3/4	77	13	10	K, S, M	3.9	13.4	44	0
BCt	61–71	2.5YR 3/6	54	23	23	K, S	4.1	15.9	49	5
Region 5										
Ap1	0–4	10YR 3/2	74	13	13	S, K (tr)	6.2	13.2	512	0
Ap2	4–11	10YR 3/2	53	32	15	S, K (tr)	5.7	13.9	281	0
Bt1	11–16	10YR 4/2	57	28	15	S, K (tr)	5.6	19.1	318	0
Bt2	16–24	10YR 4/2	33	51	16	S, K (tr)	5.7	17.1	272	0
C/Cr	24–27	10YR 4/2	74	11	15	S, K (tr)	5.8	17.7	216	0
R	27	nd	nd	nd	nd	nd	*nd*	nd	nd	0

* Soil color is measured at moist and air-dry states. See http://soils.usda.gov/technical/fieldbook; Schoeneberger et al. (2002).

† S = smectite, M = mica, V = vermiculite, K = kaolinite, tr = trace, nd = not determined.

‡ cmol(+)/kg soil = centimoles of charge per kilogram of soil.

To assess the potassium status of different soils, the authors took soil samples throughout the Lodi Winegrape District to reveal differences in parent materials and degree of soil development.

Characterization of soil profiles provided the basis to divide the District into five soil regions, by integrating the existing soil databases in a GIS and linking soil properties to potassium status.

tion and exchangeable potassium were measured from soil samples collected from the horizons of each soil profile (Murashkina et al. 2007a). Samples were also analyzed for particle size distribution, pH, cation exchange capacity and clay mineralogy.

Region 1. This region's basin alluvium soils are up to 14,000 years old, making them the youngest geologic formation. Much of this soilscape surrounds the margin of the Calaveras River alluvial fan in the south-central portion of the district in San Joaquin County, and smaller patches are present in depressions throughout Sacramento County (fig. 1). Dominant soil series in the region are Stockton, Jacktone, Galt and Hollenbeck.

A typical soil profile in region 1 has four horizons. The cultivated surface layer (Ap) is underlain by two clay-rich horizons with high shrink-swell capacity (Btss1 and Btss2) (table 2). The deepest horizon (2BC) shows that basin alluvium overlies an older and more weathered parent material, as indicated by its redder color relative to overlying soil. Cation exchange capacity was high and pH was slightly acidic. The clay fraction was dominated by smectite in the first two horizons (Ap and Btss1). A mixture of vermiculite and smectite was found in the two deepest horizons (Btss2 and 2BC).

Exchangeable potassium, a plant-available form, decreased with depth but was high throughout the profile, except in the 2BC horizon. High exchangeable potassium (631 milligrams potassium per kilogram of soil) in the surface horizon (Ap) is likely due to fertilization. Potassium fixation was detected in all horizons except the surface layer. Subsoil layers (Btss2 and 2BC) fixed high amounts of potassium. Fixation was highest in the horizon that contained vermiculite (2BC), suggesting that the thickness of basin alluvium overlying other alluvial deposits must be verified to accurately determine potassium response. In many instances basin alluvium covers older, buried soils (similar to soils of region 3) derived from granitic alluvium that contain high amounts of vermiculite, which fixes potassium.

Exchangeable and fixed potassium were both high in region 1 (table 2). Although high exchangeable potassium was expected, high potassium fixation was surprising because smectite-rich soils generally do not fix this nutrient. However, even though the clay fraction was dominated by smectite, there appears to be enough vermiculite in the subsoil to fix potassium. It is also possible that the silt and fine sand fractions contain vermiculite and therefore fix potassium, as found in soils elsewhere in the San Joaquin Valley (Murashkina et al. 2007b).

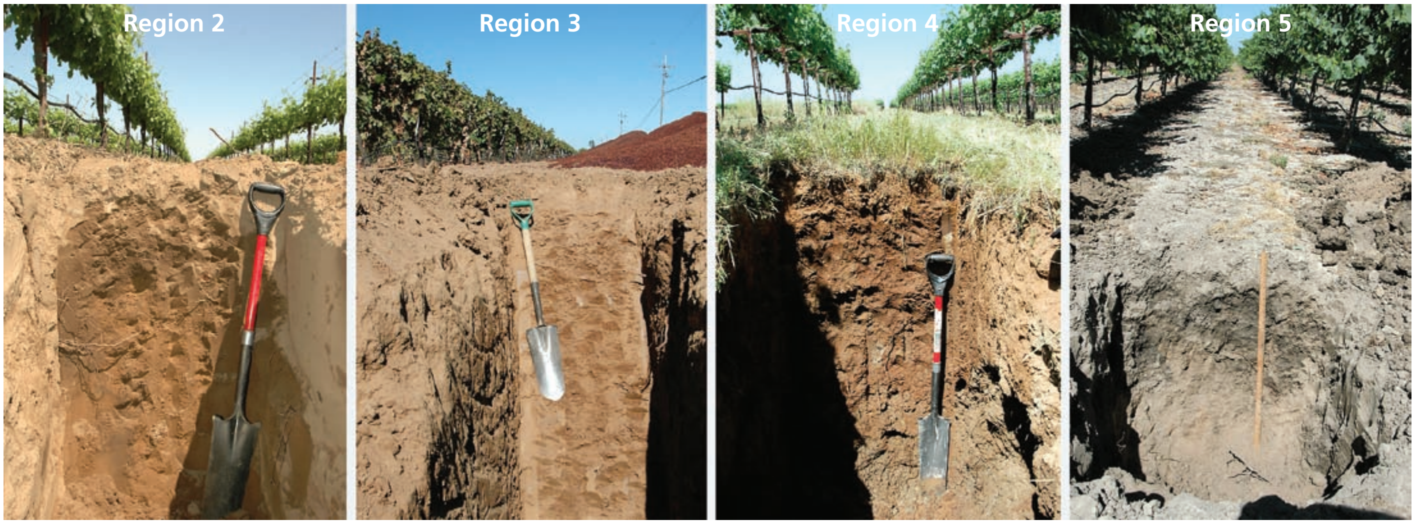
Soil variability within this landscape is low, but variability in the thickness of basin alluvium may be high as a function of distance from the alluvium source.

Region 2. This region consists of post-Modesto-age alluvium, which was deposited from 70,000 years ago to the present along the basin margin. Stringers of this material extend into other parts of the district as flood plains and terraces along streams and rivers. Large expanses of this region exist as fan deposits of the Mokelumne, Cosumnes and Calaveras rivers (fig. 1). The alluvium of the Mokelumne and Cosumnes rivers is predominantly coarse-textured, whereas that of the Calaveras River is loamy or silty. Dominant soils of region 2 are Tokay, Kingdon, Acampo, Columbia and Tujunga.

A typical soil profile in region 2 has six horizons. The surface horizons Ap, A and AB are underlain by Bt horizons with a slight clay accumulation (Bt1 and Bt2), then by a more or less unweathered parent material horizon (C) (table 2). The soil was coarse-textured, and clay content was low throughout the profile. Cation exchange capacity was low due to the low clay content, and pH was moderately acidic (table 2). The clay fraction was dominantly mica with trace amounts of kaolinite. Traces of vermiculite were present in the bottom two horizons (Bt2 and C).

Exchangeable potassium was high in the surface layers and decreased substantially with depth (table 2). The top four horizons did not fix potassium. The bottom two horizons (Bt2 and C) did fix this nutrient, as much as 425 milligrams potassium per kilogram of soil, due to the presence of vermiculite.

We propose that the key characteristics of soils that control potassium supply and retention can be inferred from soil-survey database information.



Region 2 soils formed from coarse, textured alluvium deposited during the last 70,000 years; region 3 soils, with duripans and clay-rich horizons, formed from granitic alluvium deposited 130,000 to 330,000 years ago; region 4 soils formed from alluvium deposited over 600,000 years ago, originating from metamorphosed volcanic and sedimentary rock; and region 5 soils formed from consolidated volcanic mudflows deposited 3 to 10 million years ago. In region 1 (not shown), soils develop from basin alluvium deposited over the last 14,000 years.

Region 3. This region consists of low terraces of Riverbank age, deposited approximately 130,000 to 330,000 years ago. Large expanses of this soilscape are located in the district's central portion (fig. 1). The original landscape consisted of gently undulating microtopography (highs and lows with 5- to 10-foot spacing). Leveling and cultivation have extensively altered this landscape. Soils have formed from granitic alluvium and often contain duripans (silica-cemented hardpan) and clay-rich layers that restrict water and root penetration. Dominant soils of this region are San Joaquin, Bruella, Montpellier and Cometa.

A typical region 3 soil profile has seven horizons. Surface layers (Ap and BA) are underlain by clay-rich horizons (Bt1, Bt2 and Bt3) that overlie a fractured duripan (Btqm) and uncemented, slightly weathered parent material (2BC) (table 2). The duripan was shattered by deep tillage prior to the planting of vines. Clay mineralogy of the top horizon (Ap) consists of kaolinite, mica and vermiculite. Cation exchange capacity was low throughout the profile, likely due to the presence of kaolinite clay. The pH was slightly acidic to neutral.

Potassium fixation was high throughout the profile because soils have weathered to an intermediate degree that favors the formation of vermiculite (table 2). Exchangeable potassium was high in the topsoil, presumably due to fertilization. Low levels of exchangeable potassium in the subsoil were due to a combination of limited leaching, low cation exchange capacity (a limited ability to retain potassium from the bulk soil solution) and potassium fixation by the vermiculite.

Region 4. This region consists of dissected high terraces of Turlock Lake and Laguna age, deposited more than 600,000 years ago. The soilscape is located in the district's eastern portion (fig. 1). Soils have formed from mixed alluvium, mostly from metamorphosed volcanic and sedimentary rock, that once comprised the outer "shell" of the Sierra Nevada and have since eroded away to expose the granitic interior. The soils contain duripans and/or clay pans, but most of these were ripped before planting. The landscape was once a large alluvial fan that has since been dissected by streams and rivers into high terraces (remnant islands) of ancient soils. Some soils in this landscape cap the consolidated volcanic mudflow landscape of region 5. Dominant soils are Redding, Red Bluff and Corning.

A typical region 4 soil profile has seven horizons (table 2). Clay content increased with depth to over 40% in the third and fourth horizons (Bt1 and Bt2). A fractured duripan (Btqm) was present in the subsoil. Cation exchange capacity was relatively low in all horizons except Bt3. The pH was very low and decreased with depth from moderately acidic in the surface horizon (Ap) to extremely acidic in horizons below (table 2). The mineralogy of the clay fraction was dominantly kaolinite. Compared to regions 1, 2 and 3, the soil parent material in region 4 contains less mica. In addition, the soils are intensely weathered, to the point where any initial vermiculite has been altered to kaolinite in the clay fraction.

Exchangeable potassium was high in the surface horizon (Ap) and decreased to levels as low as 44 milligrams per kilogram of soil in the subsoil. Low exchangeable potassium in the subsoil indicates that deep leaching of potassium fertilizer is minimal, or that clays with low cation exchange capacity do not retain much leachable potassium. Furthermore, the low pH values suggest that aluminum may occupy a substantial portion of the cation exchange capacity. No potassium fixation was observed, which was expected, because kaolinite does not fix this nutrient (table 2). Kaolinite has a low net negative charge, so potassium is not strongly adsorbed between its layers. Thus, both cation exchange capacity and potassium fixation potential are low.

Region 5. This region is the oldest geologic formation in the district, consisting of volcanic mudflows mainly of andesitic (intermediate in composition between basalt and granite) lithology deposited about 3 to 10 million years ago. Region 5 is limited to the district's eastern edge (fig. 1). The rock has been uplifted over time with the corresponding uplift of the

Sierra Nevada, and as a result has been dissected by erosive forces. The rolling hills of this landscape are remnants of what was once locally a continuous ancient surface. The complex, undulating terrain makes these landscapes highly erodible, and erosion outpaces soil-forming processes. Thus, although the parent material is quite old, the soils are relatively young and weakly developed. Typical soils occurring in this region are Pentz, Peters, Pardee and Keyes.

A typical region 5 soil profile has six horizons. The surface layers (Ap1 and Ap2) are underlain by horizons with a slight clay accumulation (Bt1 and Bt2), and then by volcanic bedrock (C/Cr and R) (table 2). Soil textures are mostly sandy loams with clay contents between 13% and 16% throughout the profile. Cation exchange capacity was highest in the Bt1 horizon where exchangeable potassium was also highest. The pH ranged from slightly to moderately acidic. Mineralogy of the clay fraction was dominated by smectite with trace amounts of kaolinite.

Exchangeable potassium was very high throughout the profile. These high levels are likely due to the leaching of potassium fertilizer into subsoil horizons as well as the natural supply of potassium from the weathering of volcanic rock. None of the horizons fixed potassium, because vermiculite was not present in the clay fraction (table 2). These andesitic parent materials weather rapidly and supply potassium as the primary minerals decompose. The andesite lacks mica, therefore vermiculite does not form and potassium fixation is low.

Fine-tuning the model

While regions 1 and 5 share similar potassium supply characteristics (table 1), they are in separate management zones because their parent material, topography, soil depth and soil texture differ greatly. The soil profiles characterized for regions 3, 4 and 5 corresponded well with the potassium supply predicted by our model. However, in regions 1 and 2, measured potassium fixation did not fully match the model (tables 1 and 2). The thickness of recent alluvium is a variable that must be addressed. In both of these regions, vermiculite was detected in the subsoils but not in overlying strata. These landscapes represent the most recent and active sediment-deposition zones, and these sediments apparently overlie older or more weathered soils.

The thickness of recent alluvium is likely a function of the proximity to its source (a stream or river). Also, contrasts in the mineralogy of alluvium from the Mokelumne and Cosumnes rivers (dominantly granitic) versus the Calaveras River (metamorphosed sedimentary and volcanic) may have a strong influence on soil potassium behavior in regions 1 and 2.

There are also limitations in the use of soil survey information. The level of detail in mapping (map unit delineation intensity) can differ across a soil survey area based on intended land uses. For example, the detail of soil mapping and intensity of investigation in Sacramento and San Joaquin counties was much higher in traditional agricultural areas, such as region 2, than in regions 4 and 5. At the time of mapping (mid-1970s to mid-1980s), these latter regions were mostly rangeland, a lower intensity of agricultural use. As a result, a great detail of soil variation was disregarded during mapping. These lands are now prime locations for vineyards, but mapping intensity in regions 4 and 5 may not capture important soil variation for wine-grape production. In contrast, soil mapping in region 2 may be more detailed than needed for wine-grape production, but could have large impacts on other potential land uses such as riparian restoration, septic-tank suitability or urban development.

Nonetheless, this research demonstrates the utility of combining soil survey information with limited ground-truthing to develop nutrient management regions for wine-grape production. Our model delineates five potassium-management regions based on the nature of parent material and degree of soil development. These five regions stratify the landscape of the Lodi Winegrape District into distinct soilscapes. Each nutrient management region has a unique combination of native potassium supply, exchangeable potassium and potassium fixation potential. The model will serve as a foundation to address a variety of nutrient management strategies and best management practices. Our current research is aimed at refining this model and documenting the degree of soil variability within each region.

A.T. O'Geen and S. Pettygrove are Cooperative Extension Soils Specialists, R. Southard is Professor, and H. Minoshima is Graduate Student, Department of Land, Air and Water Resources, UC Davis; and P.S. Verdegaal is Cooperative Extension Advisor, UC Cooperative Extension, San Joaquin County. *The authors gratefully acknowledge research funding from the Lodi Winegrape Commission as well as the multiple landowners and vineyard managers who provided field support and access to sites. We also thank Jiayou Deng, Tony Orozco and Chuck Ingels for their support in the field and laboratory.*

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RESEARCH ARTICLE

Vineyard nutrient needs vary with rootstocks and soils

by Jean-Jacques Lambert, Michael M. Anderson *and* James A. Wolpert

Sustainable vineyard fertilization can lead to cost savings while protecting the environment. However, appropriate fertilization conditions depend on the rootstocks, which differ in their uptake of macro- and micronutrients, as well as on the vineyard soils' physical and chemical characteristics, which affect the soil nutrient reservoir. We studied identical sets of 14 rootstocks on three different soils. Rootstocks had a significant impact on petiole levels of nitrogen and potassium throughout the growing season. Pruning weight and fruit yield also varied considerably by rootstock and site. However, rootstock performance was not consistent among sites, nor was the seasonal pattern of change in nitrogen and potassium consistent among sites. The observed differences emphasize the impact of soil texture and nutrient availability on plant growth. Further studies will help guide the development of site-specific sustainable fertilization regimens.

In the Sacramento Delta, a vineyard grows in Egbert and Tinnin soil series on a flat alluvial plain.

An Amador County vineyard is planted on rolling hills with Sierra soil series over granitic bedrock.

The fundamentals of nitrogen and potassium nutrition in grapevines are well known. Excess nitrogen leads to high vigor, increasing fruit yield and affecting juice composition (i.e., pH and concentrations of organic acids and esters), but may also create conditions favorable to disease such as bunch stem necrosis and *Botrytis cinerea* bunch rot (Keller et al. 2001). Potassium deficiency adversely affects ripeness, but excess berry potassium is detrimental to wine quality (Mpelasoka et al. 2003).

While adjusting nutrient input to attain the desired wine quality, viticulturists must also heed the call for sustainable management practices that minimize impacts on soil microorganisms and nutrient balances. The development and application of site-specific fertilization plans can increase sustainability by reducing nutrient runoff into waterways. By developing a better understanding of soil-vine interactions as well as the specific nutrient needs of particular rootstocks and cultivars, we hope to establish site-specific fertilization plans to save money and limit fertilizer input, ultimately promoting sustainability.

California vineyards are planted in diverse geographic settings and climates, on soil types ranging from acid to alkaline, fine textured to coarse, deep to shallow, level to sloping, and fertile to less fertile. Several-dozen rootstocks were developed in response to the inadvertent importation into Europe of the grapevine pest phylloxera, from its native eastern North America (Pongracz 1983). The European grape *Vitis vinifera* is highly susceptible to phylloxera, but many American native species are not. As a solution, the practice of grafting European scions (the grafted fruit-bearing part of the plant) onto phylloxera-resistant rootstocks was developed (Pongracz 1983). This practice is still in use today, and these rootstocks are suited to a variety of conditions reflecting the original environments of the parent plants (Granett et al. 2001). For example, high-vigor rootstocks are used with low-vigor scions on less fertile soils, while low-vigor rootstocks are used with high-vigor scions on fertile soils (Pongracz 1983). Rootstocks also differ significantly in their resistance to drought (Carbonneau 1985).

The range of available rootstocks represents an important resource for the viticulture industry with respect to the long-term sustainability of grape-growing in California. However, much remains to be learned in order to fine-tune the use of these genetic resources in the wide range of California growing conditions. Our current understanding of rootstock nutrient requirements is general yet incomplete, based in most cases on empirical findings.

Nutrient availability, uptake

Soil texture and structure have an important impact on nutrient availability to the plant. Soils rich in organic matter are generally high in available nutrients, including zinc and iron. Clay soils can fix potassium in soil, thereby decreasing the availability of this nutrient to the plant. Rapid leaching can drain nutrients from sandy soils.

Within the root zone, the availability of moisture and its movement in the soil can have significant effects on nutrient availability. Excess leaching may cause nitrogen loss to the water table, and waterlogging may cause denitrification (the conversion of nitrate to nitrogen gas, which occurs where oxygen is in short supply).

Rootstocks also have a pronounced influence on the mineral nutrition of the scion, which should be considered when developing fertilization programs (Koblet et al. 1996). Some rootstocks, such as Malègue 44-53 (44-53), have a higher affinity for potassium than magnesium and therefore may fail to take up sufficient magnesium from the soil. This is compounded by the fact that high levels of potassium in the soil solution can limit the solubilization of magnesium, reducing the availability of magnesium to the plant. (Brancadoro et al. 1994). Other rootstocks, such as Paulsen 1103 (1103P), easily absorb magnesium (Scienza et al. 1986). In high-potassium soils, selecting a "magnesium-absorbing" rootstock may be the easiest way to correct for a deficiency of this nutrient (Brancadoro et al. 1994). Our understanding of rootstock-scion interactions is further complicated by the fact that grape cultivars respond differently to nutrients. For example, Chardonnay and Cabernet Sauvignon have high requirements for magnesium, which can result in deficiencies in this mineral (Loue and Boulay 1984).

Vines grown on different rootstocks may also differ in their tolerance to lime (calcium carbonate) and susceptibility to iron deficiency. High lime content induces chlorosis (a condition in which leaves produce insufficient chlorophyll due to iron deficiency) by slowing iron uptake and translocation (Bavaresco et al. 1992). In calcium-rich soils, total leaf chlorophyll and iron content were higher in Chardonnay grafted onto lime-tolerant rootstocks such as Ruggeri 140 (140R) or Selection Oppenheim 4 (SO4) than on the less lime-tolerant rootstock Millardet et De Grasset 101-14 (101-14) (Bavaresco et al. 1992). Under high salinity conditions, Syrah grafted on Ramsey and 1103P (both salt-tolerant rootstocks) had higher wine potassium, pH and color than on its own roots (Walker et al. 2000, 2002).

Assessing rootstocks and soils

Ideally, vineyard management strategies should consider the site-specific properties of individual soils, the individual requirements of the rootstock and the scion, as well as the relationship between the two. By considering these factors individually and collectively, we will be able to better understand the soil-vine relationship and begin to develop site-specific, sustainable, vineyard management plans.

In this study, we examined the nutrient status and growth characteristics of 14 common rootstocks on three distinct soil types. Two vineyards were located in the Sacramento River Delta near the town of Hood; the scion was Chardonnay on Egbert clay (sandy loam variant) soils at one vineyard, and Cabernet Sauvignon on Tinnin loamy sand soils at the other (Anamosa 1998). A third vineyard was in Amador County's Shenandoah Valley, and the scion was Zinfandel on a Sierra sandy loam soil.

At all three vineyards, we evaluated an identical set of 14 rootstocks: Teleki 5C (5C), Kober 5BB (5BB), Couderc 3309 (3309C), Millardet et De Grasset 101-14 (101-14), Richter 110 (110R), Paulsen 1103 (1103P), Millardet et De Grasset 420A (420A), Couderc 1616 (1616C), Rupestris St. George or Rupestris du Lot (St. George), Malègue 44-53 (44-53), Ramsey, Harmony, Freedom and VR O39-16 (O39-16) (table 1). Twenty-five replicate vines were planted for each rootstock/scion pair. All three sites were drip-irrigated and managed according to routine pest and nutrient management practices. Weeds were controlled by a combination of contact and pre-emergent herbicides, and resident vegetation was present between rows. Vineyards planted with multiple rootstocks were managed uniformly.

Petiole nitrogen and potassium. The sites were not deficient in nitrogen, and

TABLE 1. Rootstock characteristics

Rootstock	Parentage	Vigor*	Drought resistance	Lime tolerance†	Salt resistance	Wet feet‡	Soil preference§
				%			
St. George	*V. rupestris*	H	Var	14	M/H	L/M	Deep, uniform, loam
1616C	*V. solonis* × *V. riparia*	L	L	L/M	M/H	H	Deep/fertile
3309C	*V. riparia* × *V. rupestris*	L/M	L/M	11	L/M	L/M	Deep, well-drained
44-53	*V. riparia* × 144M	M	M/H	10	na	H	Loam/good fertility, high Mg
101-14	*V. riparia* × *V. rupestris*	L/M	L/M	9	L/M	M/H	Heavy, moist clay
420A	*V. berlandieri* × *V. riparia*	L	L/M	20	L	L/M	Fine texture, deep/fertile
5BB	*V. berlandieri* × *V. riparia*	M	L/M	20	L/M	Var	Moist clay
5C	*V. berlandieri* × *V. riparia*	L/M	L	20	M	Var	Moist clay
1103P	*V. berlandieri* × *V. rupestris*	H	H	17	M	H	Adapted to drought, saline soils
110R	*V. berlandieri* × *V. rupestris*	M/H	H	17	M	Var	Hillside soils, acid soils, moderate fertility
Freedom	1613 C × *V. champinii*	H	M/H	M	L/M	L	Sandy to sandy loams
Harmony	1613 C × *V. champinii*	M/H	Var	M	L/M	L	Sandy loams, loamy sands
Ramsey	*V. champinii*	VH	H	M	H	L/M	Light sand, infertile soils
O39-16	*V. vinifera* × *V. rotundifolia*	H	L	L	L	na	Poor on coarse, sandy soils

* L = low; M = medium; H = high; VH = very high; Var = variable; na = not available.

† Tolerance to lime-induced chlorosis (percent by weight of finely divided calcium carbonate in soil that can be tolerated by the rootstock).

‡ Wet feet = tolerance to excessive moisture caused by poor soil drainage.

§ Actual performance characteristics of these rootstocks on specific soils and scions may vary.

Source: Christensen (2003) and Pongracz (1983).

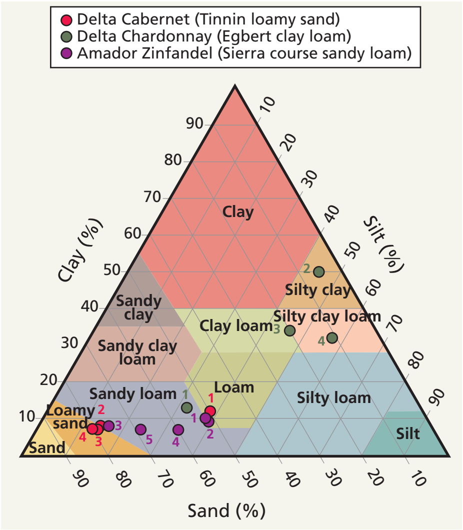

Fig. 1. Soil textural triangle for three vineyards, showing percentages of sand, silt and clay for each soil horizon. Numbers correspond to horizons, increasing with depth.

rootstock was the only treatment. At all sites, petiole (leaf stalk) and blade (leaf body) tissues were collected at bloom, veraison (color change at ripening) and harvest. Bloom samples were leaves opposite the basal-most grape cluster. Samples were collected over three sequential years. At each sampling date, 20 petioles and blades were collected per treatment replicate. The petioles and blades were separated, oven-dried and sent to UC Davis for processing and analysis. All samples were analyzed for nitrate-nitrogen, expressed as parts per million (ppm); total nitrogen, expressed as percent nitrogen; and percent potassium. Due to space considerations, only bloom petiole samples will be discussed in detail here.

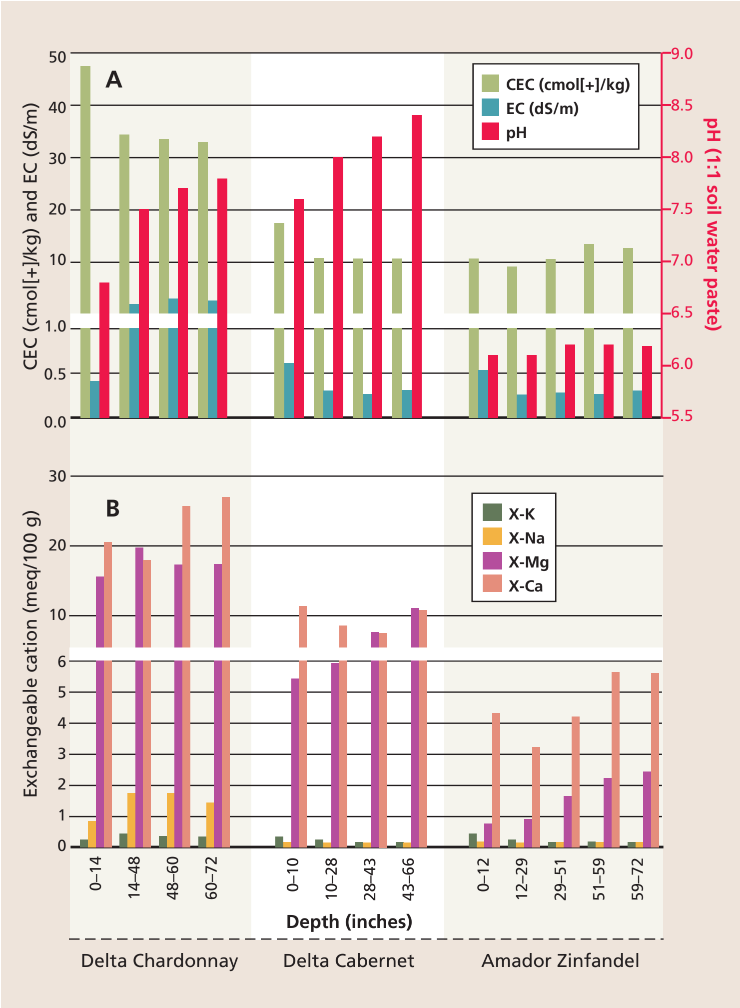

Fig. 2. (A) Cation exchange capacity (CEC, cmol[+]/kg), electrical conductivity (EC, deciSiemens per meter [dS/m]) and pH, and (B) exchangeable cations (Ca, Mg, K and Na; meq, milli-equivalents per 100 grams of soil) for each horizon of three vineyards.

Soil sampling. Soil sampling was performed at each site using a backhoe to dig a sampling pit to a maximum depth of 70 inches. Soil morphology was described as outlined in the U.S. Soil Survey Manual (Soil Survey Division Staff 1993), and samples were collected from all horizons (distinct soil layers).

Geographic location was measured by a Garmin 45XL geographic positioning system. Soil samples were air-dried, ground, sieved to pass through a 2-millimeter grid, and submitted to the ANR Analytical Laboratory for analysis. Gravel content was calculated from the weight of material retained by the sieve. Soil pH was measured in a saturated paste, and electrical conductivity was measured in the saturated paste extract (Sparks 1994). Exchangeable cations (calcium, magnesium, potassium and sodium) were extracted using ammonium acetate, pH 7.0. Sand, silt and clay were measured using the hydrometer suspension method (Klute 1986). Official soil series descriptions were collected from the Web site of the USDA National Soil Series Description Facility in Lincoln, Neb.

Delta Chardonnay vineyard

Soil characteristics. The soils at the Delta Chardonnay site belonged to the Egbert clay loam series, which has subsoil textures of clay loam and silty clay loam. This was the heaviest textured soil of the three studied, ranging from 13% to 50% clay (fig. 1). The cations studied were potassium, sodium, calcium and magnesium. This soil had a fairly high cation exchange capacity (CEC), ranging from 33 to 48 cmol(+)/kg (centimoles of charge per kilogram of soil), and the highest exchangeable cation (EC) content of the three soils studied (figs. 2A, 2B).

Potassium availability was measured by the potassium-to-CEC ratio, which was below the predicted value of 2.5 found in the literature for this soil texture (Champagnol 1984; Etourneaud and Loue 1986) (fig. 3A). The concentration of soluble salts in the soil solution was measured by electrical conductivity, which exceeded 2.5 in the two deepest horizons (fig. 2A). Electrical conductivity values above 2.5 may limit vine vigor (Nicholas 2004). The exchangeable sodium percentage (ESP), defined as the sodium-to-CEC ratio, approached but did not exceed 6, the level above which sodium content can negatively affect vine vigor (Nicholas 2004) (fig. 3B).

Similarly, the calcium-to-magnesium exchangeable cation ratio fell below 1-to-1 in the root zone at soil depths from 14 to 48 inches (excess magnesium is detrimental so the 1-to-1 ratio is a threshold not to be exceeded) (fig. 3C). High soil magnesium can induce potassium deficiency, which negatively affects vine growth and crop load. High magnesium also reduces soil aggregate stability, reducing water infiltration (Dontsova and Norton 2001).

Rootstock performance. In this vineyard, four rootstocks gave above-average fruit yields and pruning weights (the weight of vine canes removed at pruning, a measure of plant vigor): 1103P, 101-14, 1616C and Freedom (fig. 4A). Rootstocks with below-average pruning weights and fruit yield in this soil included 420A, 44-53 and O39-16 (fig. 4A). Rootstock 420A is sensitive to potassium deficiency (Pongracz 1983) and so may have been affected by the lower-than-expected potassium availability for a heavy-textured soil (fig. 3A) (Etourneaud and Loue 1986).

Plant mineral content. Petiole nitrate-nitrogen was on average lower at bloom and veraison, but higher at harvest (386 parts per million [ppm] and 382 ppm versus 947 ppm, respectively). In general, the highest bloom petiole nitrate values were seen in rootstock 1103P, and the lowest in 1616C, 44-53 and Harmony (fig. 4A). Linear regression analysis revealed a significant correlation between yield and petiole nitrate-nitrogen at bloom ($r^2 = 0.438$).

Petiole potassium was higher at bloom and veraison, while much lower at harvest (2.81% and 2.73% versus 1.59%, respectively). The highest bloom petiole potassium values included rootstocks 44-53 and 1616C (fig. 4A). Notably, rootstock 44-53 had the highest petiole potassium levels at bloom in both the Chardonnay and Cabernet vineyards, as well as the third-highest levels in the Zinfandel vineyard (fig. 4).

Delta Cabernet Sauvignon vineyard

Soil characteristics. The alluvial soils at the Delta Cabernet Sauvignon site were mapped as Tinnin loamy sand. The soil at the sampling site was characterized by a loamy surface horizon, and light-textured subsoil horizons that increased in sand content with depth (fig. 1). This soil had the highest pH range of those studied, from neutral at the surface to alkaline in the subsoil (fig. 2A). It also had lower electrical conductivity and exchangeable cation levels than the Delta Chardonnay vineyard, with a relatively low CEC of 10 cmol[+]/kg except at the surface (fig. 2A).

The potassium-to-CEC ratio was in the satisfactory range in the upper horizons, but there was a slight potassium deficiency in the lower root zone (fig. 3A) (Etourneaud and Loue 1986). Sodium content in this soil was low (fig. 3B) (Nicholas 2004). The calcium-to-magnesium ratio was below 1 in the subsoil, indicating a relative excess of magnesium (fig. 3C) (Champagnol 1984).

Rootstock performance. Pruning weights were above average in this vineyard for rootstocks Ramsey, 110R and 1103P, while O39-16 gave the highest fruit yield (fig. 4B). Rootstock 44-53 had the lowest pruning weight, and among the lowest fruit yields.

Plant mineral content. Petiole nitrate-nitrogen declined significantly between bloom and veraison (from 567 to 307 ppm), but by harvest returned to a level similar to that at bloom (data not shown). Rootstocks with the highest petiole nitrate-nitrogen at bloom included Ramsey and O39-16 (fig. 4B).

Petiole potassium levels declined sharply from bloom to veraison and harvest (2.33% versus 1.21% and 0.38%, respectively). The highest levels at bloom were in rootstocks 44-53 and Freedom, while the lowest were in 420A and 110R (fig. 4B).

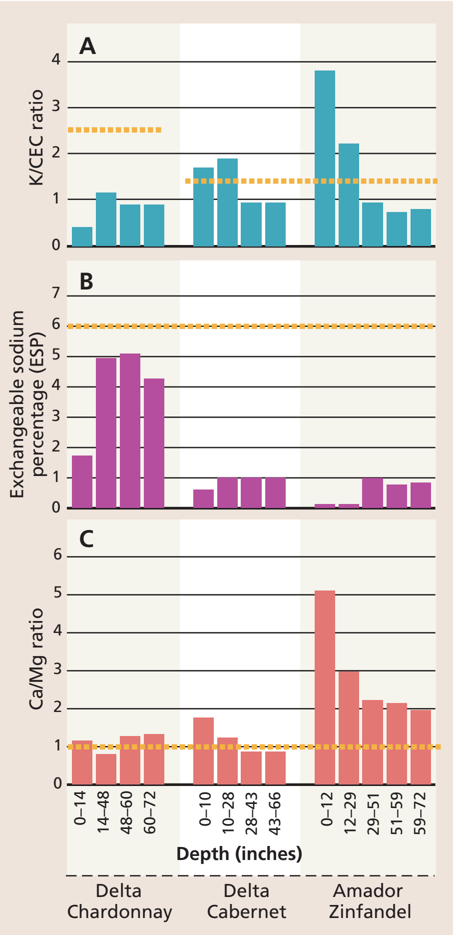

Fig. 3. Soil elemental ratios for (A) K/CEC ratio (orange lines indicate recommended values for a given texture class); (B) exchangeable sodium percentage (ESP) (orange line indicates threshold ESP value of 6%, above which salt concentrations may adversely affect vines); and (C) Ca/Mg ratio (values below 1 indicate excess Mg, which may be detrimental to vines).

Amador Zinfandel vineyard

Soil characteristics. The soil at the Amador Zinfandel site was mapped as Sierra coarse sandy loam, a light-textured soil with a large sand fraction and low clay content (fig. 1). In addition, this soil had a high coarse-fragment content, as the Sierra soil series developed from a fractured granitic substratum. This soil had a paralithic contact (direct contact with fractured bedrock) with soft, decomposing granite rock at a depth of 30 inches (Anamosa 1998). Vine roots penetrated to 60 inches in rock cracks. Due to

California vineyards are planted in diverse geographic settings and climates, on soil types ranging from acid to alkaline, fine textured to coarse, deep to shallow, level to sloping, and fertile to less fertile.

its light texture and high coarse-fragment content, this soil's potential water-holding capacity was very low and would make it sensitive to drought if dry-farmed. It also had a slightly acidic pH with respect to the other two profiles studied (fig. 2A) and a relatively low CEC, and therefore, a small nutrient reservoir (figs. 2A, 2B). However, it also had high manganese content (not shown), likely due to the presence of this element in the parent material and the slightly acidic pH.

For light-textured soils, a satisfactory potassium-to-CEC ratio is in the range of 1.5 (Etourneaud and Loue 1986). In this vineyard, the potassium-to-CEC ratio was highest in the topsoil, likely reflecting an excess of potassium due to fertilization (fig. 3A). The potassium-to-CEC ratio was lower in the subsoil, indicating potassium deficiency in the lower horizons (Etourneaud and Loue 1986). This soil also had a high calcium-to-magnesium ratio, and the lowest exchangeable magnesium of the three sites studied (figs. 2B, 3C).

Rootstock performance. Rootstocks with above-average pruning weights on this soil included 5BB, 1103P, 1616C and Freedom (fig. 4C). Rootstocks with high fruit yields included 5BB, 420A, 110R and 1103P. Rootstocks 44-53, 101-14 and 420A gave the lowest pruning weights, while O39-16 gave the lowest average fruit yield (fig. 4C).

Plant mineral content. Petiole nitrate-nitrogen levels declined sharply for all rootstocks from bloom to veraison and harvest (1,317 ppm versus 80 ppm and 102 ppm, respectively) (data not shown). Large differences in bloom nitrate-nitrogen values among rootstocks were seen, with the highest for O39-16 and 5BB, and the lowest for 420A.

On average, petiole potassium levels were unchanged from bloom to veraison but declined significantly by harvest (2.06% and 2.00% versus 0.87%, respectively) (data not shown). Rootstocks with the highest petiole bloom potassium were Freedom, O39-16 and 44-53, and the lowest were 420A and 110R (fig. 4C).

Fig. 4. Yield and plant mineral content at bloom for 14 rootstocks with (A) Delta Chardonnay, (B) Delta Cabernet and (C) Amador Zinfandel. Dashed lines indicate average values for all 14 rootstocks, calculated separately for each vineyard. Values shown are averages for 3 sequential years.

Three sites compared

Rootstocks had an impact on the foliar levels of nitrogen and potassium in petiole tissues at all three sampling dates throughout the growing season. Some rootstocks consistently showed high petiole potassium values in all three vineyards, notably 44-53, which has been previously noted for this characteristic (Champagnol 1984). In contrast, rootstock 420A consistently showed low petiole potassium in all three vineyards. As reported by Wolpert et al. (2005), petiole potassium content at bloom was lower for rootstocks that had *Vitis berlandieri* genetic backgrounds than for those that did not (fig. 4). In this study, rootstocks with *V. berlandieri* backgrounds were 420A, 5BB, 5C, 1103P and 110R (table 1).

Pruning weights also varied considerably by rootstock and by vineyard. However, rootstocks differed in their rankings among the three trials. For example, rootstock 5BB had high vigor with the Zinfandel scion, but below-average vigor with the Chardonnay scion; in contrast, rootstock 101-14 had high vigor with the Chardonnay scion but below-average vigor with the Zinfandel scion.

The three soils in this study exhibited large differences in texture, and in physical and chemical properties, which contributed to differences in plant vigor. For example, the Chardonnay vineyard's Egbert clay loam was a heavy-textured soil with high exchangeable cation content. The rootstocks that had the highest pruning weights and fruit yield on this soil were well adapted to clay soils (101-14) and/or humid, fertile soils with moderate salt (1616C).

In contrast to the Egbert clay loam, the Cabernet Sauvignon vineyard's Tinnin loamy sand and the Zinfandel vineyard's Sierra sandy loam were light-textured soils with high sand content. Rootstock 101-14, which had high vigor on Egbert clay, had below-average yield and pruning weight in Sierra sandy loam. Rootstocks Ramsey and 110R had high vigor in Tinnin loamy sand. It should be noted, however, that pruning weight and fruit yields are not the only criteria for vine performance, and other considerations such as berry juice chemistry and sensory characteristics must be taken into account when selecting rootstocks for particular scions.

Despite the site-specific differences in soils, some rootstocks showed similar trends in plant mineral content and vigor at all three sites. For example, rootstock 44-53 had below-average vigor, petiole nitrogen and nitrate-nitrogen at bloom in all three vineyards.

Plant nutrient levels can be influenced by scion-specific differences in nutrient metabolism (Christensen 1984), and scion genotype can also affect rootstock performance (Virgona et al. 2003). In the present study, the variability observed in rootstock performance also suggests a potential role for rootstock–scion interactions.

Tailored vineyard fertilization

Additional trials are needed in the diverse environments in which grapevines are grown within California, in order to better match rootstocks and scions to particular soil types and local edaphic conditions (such as soil water content, pH, aeration and nutrient availability). As we learn more about the nutrient input requirements of specific rootstocks and scions, the measurement of plant nutrient levels, and the physical and chemical properties of soil, site-specific fertilization management programs can be tailored to individual vineyards. The ultimate goal of such programs is to decrease fertilization costs and environmental pollution, thus promoting sustainability. Future studies will include rootstock trials on soils with different physical and chemical properties in an effort to increase our understanding of the soil-vine relationship.

J.J. Lambert is Assistant Research Soil Scientist, M.M. Anderson is Staff Research Associate, and J.A. Wolpert is Cooperative Extension Specialist, Department of Viticulture and Enology, UC Davis. The authors greatly appreciate the cooperation of Trinchero Family Estates and Montevina Vineyards, and UC Viticulture Advisors Donna Hirschfelt (Amador) and Chuck Ingels (Sacramento); and funding support from the American Vineyard Foundation and the USDA Viticulture Consortium.

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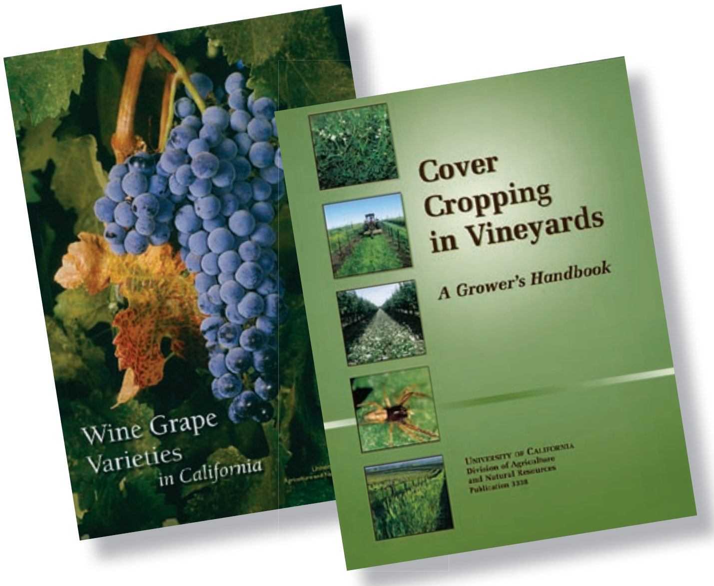

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