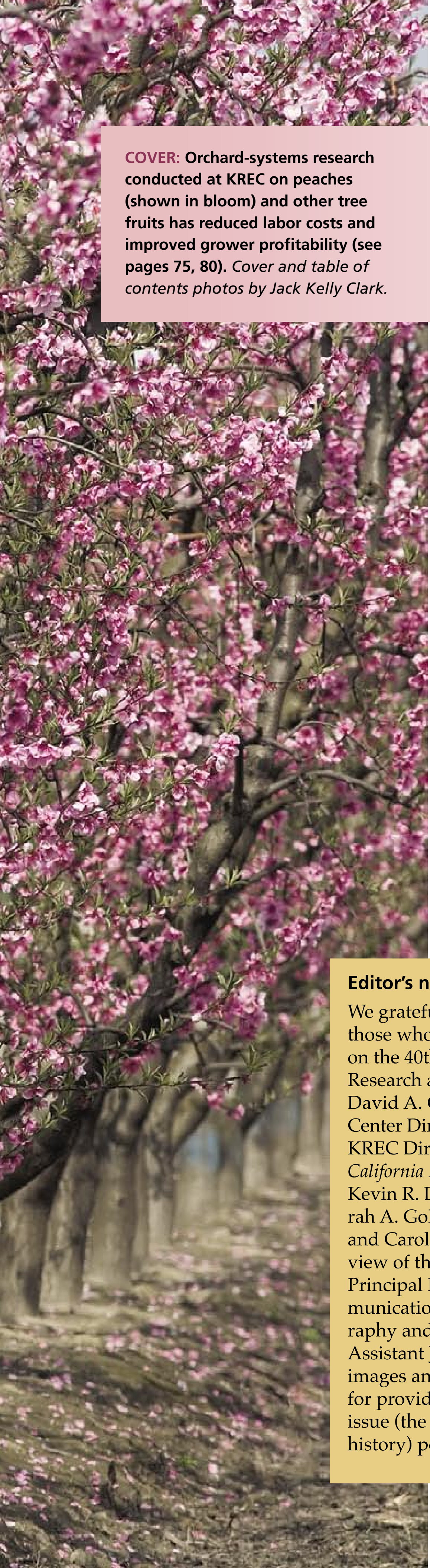
APRIL–JUNE 2005 ∘ VOLUME 59 NUMBER 2

California Agriculture

Kearney at 40:
Research blooms in the Valley



COVER: **Orchard-systems research conducted at KREC on peaches (shown in bloom) and other tree fruits has reduced labor costs and improved grower profitability (see pages 75, 80).** *Cover and table of contents photos by Jack Kelly Clark.*

40 Kearney Research and Extension Center

News departments

Research articles

Editor's note

We gratefully acknowledge the efforts of those who contributed to this special issue on the 40th anniversary of the UC Kearney Research and Extension Center (KREC): David A. Grantz, Kearney Agricultural Center Director, and Frederick H. Swanson, KREC Director, who served as co-chairs; *California Agriculture* Associate Editors Kevin R. Day, Steven A. Fennimore, Deborah A. Golino, Mark E. Grismer, John Letey and Carole Lovatt, who oversaw peer review of the manuscripts; Jack Kelly Clark, Principal Photographer with ANR Communication Services, for original photography and digital color correction; Photo Assistant John Stumbos, for compiling the images and writing captions; and KREC for providing funding to make this double issue (the largest in *California Agriculture* history) possible.

Signs of the times

Since its dedication on May 26, 1965, the place commonly known as "Kearney" has undergone numerous name changes. Today, the "UC Kearney Research and Extension Center" (KREC) refers to the entire 330-acre facility, including field sites, greenhouses, laboratories, administrative offices, meeting rooms, dormitories and an airstrip. The "UC Kearney Agricultural Center" (KAC) is an academic unit, akin to a campus, which includes scientists in residence and their staff. *Far left*, Fred Swanson.

Kearney Research and Extension Center

For more information:

KREC: http://danrrec.ucdavis.edu/kearney/home_page.html

Kearney Agricultural Center: www.uckac.edu/uckac

Vital statistics:

- 330 acres
- Mediterranean climatic zone
- Flat alluvial plain terrain, 337 feet above sea level
- 10.6 inches annual precipitation
- Summer maximum mean temp.: 94.9°F
- Winter minimum mean temp.: 39.4°F
- Soil series: Hanford – fine sandy and sandy loam; Hesperia – fine sandy loam; Exeter – sandy loam shallow
- Geographic location: Latitude – 36° 36' 1.5" N, Longitude – 119° 30' 38.8" W

California Agriculture

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Letters

WHAT DO YOU THINK?

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

La Conchita and mudslide science

In the horrific mudslide in La Conchita, the news media were focused on the tragedy and neglected to address the science. The most valuable footage was taken by a helicopter, which showed the elevation of the slide area and the fact that it was gently sloping, heavily planted land. Apparently it got saturated from the rains by holding the water in the soil. There are untold thousands who want to live in the scenic hills; those homeowners need to know the science of mudslides. Are the hills trapping all the water and does little run off? Why was the root system of trees not able to cope or was that brush and no significant tree cover? Was the original tree cover destroyed in periodic fires, making the hills dangerous? With all these rains, it will be important to monitor how many slides occur and where.

Nicholas Terebey, Jr.
Laveen, AZ

Nicholas Sitar, UC Berkeley professor of civil engineering, responds:

The short answer is that there is a lot of research on the subject and we know a lot. Usually the biggest problem is not a lack of scientific knowledge but the fact that public policy does not have a good way of dealing with geologic uncertainty. In addition, generally there is no money to deal with these problems proactively, unless something terrible happens.

Specifically, regarding the possibility of debris flows (or mudflows), the fact is that they occur in all climatic zones. The principal difference is the threshold amount of precipitation and its intensity. Desert areas of California, Nevada, Utah and Arizona are well known for their destructive flows. Unfortunately, the rapid urbanization of previously untamed land has often not kept pace with the proper mitigation of these hazards, and the occurrences of destructive debris flows are increasing (they were there all along, but there were no houses in their path).

Vegetation does play a role in certain climates. For example, debris flows are rare on heavily forested slopes, but become more frequent with deforestation. Fire has been similarly implicated in increased landslide susceptibility in areas where it eliminated deep-rooted vegetation. In sparsely vegetated desert areas, debris flows are more common and often are the principal mode of erosion and sediment transport. In desert settings, the source areas and the depositional fans are relatively easy to map, and hazard maps have been prepared for many locations. The problem is in translating these maps into concrete public policy.

For more information, go to the USGS Landslide Web page: http://landslides.usgs.gov/. In addition, see the National Research Council report, "Partnerships for Reducing Landslide Risk: Assessment of the National Landslide Hazards Mitigation Strategy" (2004): www.nap.edu/openbook/0309091403/html/51.html.

Robert L. Schuster, USGS

On Jan. 10, 2005, a landslide struck the community of La Conchita in Ventura County, destroying or seriously damaging 36 houses and killing 10 people.

Grandparenting articles still inspire

I happened to access several articles about grandparents raising grandchildren on your Web site (March-April 2001). I found this such interesting reading, since I raised a grandchild in California. She is now 23. I had a lot of hard roads to cover, but did so with a supportive family.

I am a Senior Assembly Member on the California Senior Legislature, and as such we prepare yearly proposals to present to the state legislators in hopes they will be picked up and written into law. I would like to work this year on a proposal to present at our session next October relating to desired legislation regarding grandparenting laws.

Is there a Web site I can access, or literature that will allow me to familiarize myself with California laws covering this issue, as well as possible problems and concerns I could address in potential legislation at state level? I feel a strong desire to assist at both ends — the young and the old — because I see a need. We all have to deal with abuse, fraud, neglect and caregiving concerns.

Sally Wieck, Senior Assembly Member
California Senior Legislature
Baldwin Park

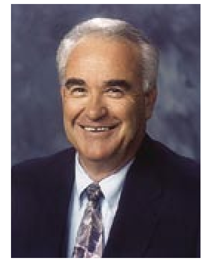
Thank you for your continued interest in this important subject. A good Web site to start with is: www.aarp.org/life/grandparents/helpraising.

Plum trees: Jack Kelly Clark

Editorial overview

David A. Grantz
Director,
Kearney Agricultural
Center

Linda Marie Manton
Regional Director,
Central Valley,
Cooperative
Extension



Frederick H. Swanson
Director,
Kearney Research
and Extension
Center

Collaboration fosters Kearney scientific achievements

UC's Kearney Research and Extension Center (KREC) lies at the heart of one of the most productive and diverse agricultural regions in the world. Also an area of environmental challenges, Kearney's field sites have supported decades of landmark research, addressing issues as diverse as air pollution effects, the development of exotic specialty crops, and the rapid molecular diagnosis of plant disease.

First dedicated as the Kearney Horticultural Field Station in 1965, KREC is one of nine UC Research and Extension Centers (RECs). All are strategically located in key agricultural regions of the state, but Kearney is unique among them in its size and scope. Functioning as a small research campus, KREC encompasses 33 specialized laboratories and hosts the UC Kearney Agricultural Center (KAC), with 24 permanent resident faculty. In addition, 20 to 25 faculty from UC campuses and county UC Cooperative Extension (UCCE) offices conduct research at KREC each year. The center currently supports 90 research and extension projects in 130 different field and laboratory locations. KREC also houses the UCCE Central Valley regional office.

The cutting-edge and practical research conducted at Kearney has helped San Joaquin Valley agriculture become a $16 billion industry, yielding roughly half of California's farm production. This issue of *California Agriculture* commemorates the 40th anniversary of KREC with reviews and reports on recently completed research, much of which has immediate relevance to farmers, packers and shippers.

Kearney has seen steady expansion, modernization and diversification over its 40-year history. Its laboratories and greenhouse facilities rival those found on the UC campuses, and its postharvest facility is state-of-the-art. The center encompasses a variety of alluvial soil types, and more than 50 different crops are cultivated under commercial growing conditions. This combination of land, laboratories and greenhouses enables UC scientists to conduct studies in a carefully managed setting. Professional staff monitor cultivated crops and continually check the operation of sophisticated laboratory facilities.

Collaborative environment. Located in the center of a remarkable agricultural region, Kearney fosters interactions with industry, government agencies, environmental and public policy groups, and university scientists. Whether on small research plots, in laboratories or on-site conference facilities, growers and scientists meet here daily in the collaborative spirit envisioned by the creators of the land-grant university system.

State-of-the art greenhouses opened in 2004.

Since 1983, the resident research and extension faculty have been organized as KAC. About 100 laboratory staff help investigators carry out field and laboratory studies at KREC and off-site in grower fields and packinghouses.

The KAC faculty are multidisciplinary, with scientific expertise in horticultural and agronomic crops, nematology, entomology, plant pathology and physiology, air quality, weed control and mosquito research. The nucleus of resident KAC scientists creates an academic atmosphere that attracts campus and county-based collaborators. The recent completion of the U.S. Department of Agriculture's San Joaquin Valley Agricultural Sciences Center across the road from KREC has widened the circle of collaboration.

The frequent interaction between scientists and industry that is the hallmark of Kearney generates new questions and research approaches, aids in the identification of additional research needs, and extends new information rapidly. Intercampus collaboration also fuels "outside the box" thinking and creates efficiencies in the utilization of research plantings, modern research facilities and specialized equipment.

GIS expertise. KAC operates a complex computer network, a graphic arts department and a Geographic Information Systems (GIS) Facility. GIS allows researchers to explore the spatial distribution of pests, crops and pathogens, and to study the interactions that develop as a result of the patchwork of land use in the San Joaquin Valley. For example, adjacent cotton and alfalfa fields must be managed carefully to control Lygus bugs. GIS techniques now permit KAC-based scientists to post maps that allow growers and pest control advisors to enter data on pest populations, pesticide use and other information directly onto the map-based data archive. Resulting spatial analyses have led to regional approaches to integrated pest management (IPM) of Lygus bug, leafhoppers, peelminers, avocado thrips, olive fly and mosquitoes that vector human diseases.

GIS techniques facilitate the preparation of special-purpose maps and other materials of benefit to agricultural clientele, regulators and the public. Scientists have access to Web-based survey techniques hosted by the Kearney GIS Facility.

Numerous scientific achievements. Living and working in the San Joaquin Valley has led to a number of important discoveries by KAC faculty and collaborators. For example, cultivation techniques are now used routinely to manage summer bunch rot in grapes; a pruning technique known as the "Kearney V" allows for dense planting of orchard crops and earlier harvests (see page 75); and pruning and trellising strategies have been developed to allow raisins to dry on the vine (see page 70). Kearney-based plant pathologists and plant breeders have addressed the problem of root infections that limit yield and plant survival (see page 63).

Plant breeding efforts at KAC led to the UCBI hybrid rootstock of pistachio, combining resistance to Verticillium wilt with tolerance to chilling and salinity. A decade after its introduction, the UC-developed hybrid is the second most-planted pistachio rootstock in California. New varieties of many crops have been developed at Kearney that address local problems, including cherries that can tolerate San Joaquin Valley heat, and the noncaprifying fig 'Sierra', which allows more efficient orchard operations and reduces the risk of fruit diseases.

Pest identification and control. Early studies at Kearney led to the initial identification of "arm and cordon death" on grapevines as "Bot canker" *(Botryosphaeria rhodina),* along with the previously recognized *Eutypa lata*. Current research is exploring whether other *Botryosphaeria* species are responsible for this and other disease complexes on grapes in California.

New crops and varieties often bring new suites of pests and diseases. In addition, new pests of existing crops are introduced continuously into California. Recent research has identified the newest diseases in grapes, dried plums and peaches. When a new citrus peelminer arrived from the south in 1999, threatening a wide range of crops, a technique to raise the pest under laboratory conditions was developed by KAC scientists. This allowed scientists to investigate control techniques. When pistachio nuts became a major crop in the San Joaquin Valley, KAC- and campus-based scientists identified major mite and insect pests.

KAC researchers developed diagnostic techniques to predict Botrytis gray mold in kiwifruit, and conventional and molecular genetic procedures to predict Botryosphaeria blight in pistachio and Monilinia brown rot in tree fruit. Entomologists developed temperature-based phenology models to predict outbreaks of oriental fruit moth, San Jose scale and peach twig borer. These advance-warning techniques allow timely management and marketing decisions, and reduce pesticide applications. A Web-based IPM decision support system (http://tjm.uckac.edu) extends this information to growers. Kearney scientists have developed practical management techniques for endosepsis and smut in figs, Botryosphaeria blight in pistachio, and aflatoxin contamination of pistachios and figs.

Jack Kelly Clark

Aerial view of the center in May 2004.

Research at Kearney has considerably advanced the mating disruption and trapping of pest insects. Pheromones (natural insect communication chemicals) for San Jose scale, vine mealybug and peach twig borer were identified through collaborations between KAC researchers and colleagues from around the country. Mating disruption of oriental fruit moth now controls this pest in stone fruit orchards, the first success of this kind in North America.

As control technologies were implemented, target organisms have developed resistance. Research has determined the mechanism of resistance of Alternaria late blight pathogen of pistachio to a new class of fungicides, the strobilurins. The existence and spatial distribution of resistance of California red scale and San Jose scale to organophosphates and carbamates was discovered at KAC. Using this information, local growers achieved a 70% reduction in use of these materials, and now use insect growth regulators (IGRs) as pest management tools in the San Joaquin Valley.

Changing pesticide usage leads to other changes in agroecosystems. The adoption of IGRs led to disruption of the vedalia beetle, which allowed cottony cushion scale to re-emerge as a serious citrus pest. Again, research at KAC led to the development of management techniques for this pest. Such research is critical to production today, and in adapting solutions for tomorrow's problems.

Cultivation techniques. Cultivation research at Kearney has explored the advantages of no-till planting and cover crops, as well as the use of reflective and straw mulches to repel insects and the viruses they carry, suppress weeds, conserve water and improve profits (see page 90). This work is now being applied to the mitigation of dust emissions from agricultural operations, a potential source of particulate matter in the air. Other research has found that crops in the San Joaquin Valley remove substantial ozone air pollution from the air, with the unfortunate side effect of reducing yields and inhibiting root development and the uptake of water by certain crops (see page 137).

Solarization of perennial crops and more recently of annual crops has been developed at Kearney, using the heating power of sunlight to reduce soil pathogens (see page 84). This work is taking on new importance with the phaseout of methyl bromide. Recently a "double tent" approach to solarization developed at Kearney was registered by the California Department of Food and Agriculture for nursery control of nematodes in containers. KREC has supported the IR-4 field research program, which evaluates reduced-risk pesticides that would otherwise be unavailable to growers of high-value "minor" crops.

Cultivation techniques developed at Kearney have led to border cutting of alfalfa to keep beneficial insects in alfalfa fields rather than causing their dispersion during complete harvests, and to keep pests such as Lygus bugs from migrating to cotton. Use of this technique was reported by 40% of alfalfa growers responding to a recent KAC survey.

Extension to Valley residents. KREC is also home to the Central Valley Regional UCCE office, providing management for county extension efforts throughout the Valley. UCCE provides instruction and demonstration of improved practices in agriculture, natural resources, nutrition, family and consumer science, and 4-H youth development. Kearney has become a focal point of regional activities by UCCE advisors based in neighboring counties as well. At KREC, farm advisors work with their academic partners from the campuses and KAC faculty to conduct agricultural and environmental research. The meeting facilities at KREC host thousands of visitors each year for CE events designed to extend applied, research-based information to industry and other clientele. Field days at KREC provide growers with an opportunity to discover the most recent research developments, and to discuss them directly with the scientists conducting the studies.

As the agricultural economy of California enters a time of increased globalization and competition, and urban development threatens the richest farmland, research by Kearney scientists — and its delivery to many clienteles — will continue to provide solutions to problems of immediate and long-term concern.

Agricultural innovation marks 40 years at Kearney

1962
UC purchases the 195-acre Mosesian Ranch

Brother Norbert blesses the Mosesian Ranch at the 1964 groundbreaking; with bowed head is Guy F. "Doc" MacLeod, entomologist and chair of Board of Trustees for the M. Theodore Kearney Horticultural Field Station.

Early crops at the center included walnuts (shown), plums and grapes.


Kearney Horticultural Station To Hold Dedication Event May 26

Reedley Exponent

RC Scholarships Awarded

40% Savings In Base Tax Rate To Property Holders

May 10, 1965, *Reedley Exponent* announces dedication.

What started 40 years ago as an old ranch at the heart of the San Joaquin Valley is today a world-class research operation, from which flows a steady stream of practical ideas and solutions ready for implementation by the region's farmers.

The UC Kearney Research and Extension Center (KREC) has advanced understanding of every aspect of production and environmental management related to the valley's bounty of fruits, vegetables and field crops. It is no coincidence that Kearney is located in what has become the state's number-one agricultural county, on land that is some of the most productive in the world.

With 24 resident faculty conducting basic as well as field research, the center is like a mini-campus, with 33 specialized research laboratories and 100 laboratory staff members. It also serves more than 100 off-station scientists from three UC campuses and Cooperative Extension offices. Not surprisingly, it is the most utilized off-campus agricultural research facility in the UC system. In addition, more than 6,000 people a year visit the center or participate in its meetings, workshops, field days and seminars.

Kearney's 330 acres of research facilities encompass a new state-of-the-art greenhouse, a postharvest laboratory, a mosquito control laboratory, multiple insectaries, and academic and administrative offices. Its controlled field studies occupy 260 acres of orchards, vineyards and fields.

KREC scientists have developed novel cultivation, pruning and planting methods for the major valley crops, while at the same time introducing newer specialty crops like blueberries and Asian eggplant. Kearney has also been one of the key testing grounds for sustainable farming methods, such as integrated pest management (IPM), biological control, water conservation and nitrogen management.

"As growers, we are dealing with new invasive pests, clean air and water regulations, the need to reduce labor costs, and the search for alternatives to methyl bromide," says Bill Chandler, who farms in the Selma area and is active in KREC committees. "We look to Kearney for sound science to help agriculture grow and thrive."

Turn-of-the-century origins

UC has supported off-campus research sites for more than a century. In the 1880s, UC Berkeley professor Eugene Hilgard established a 20-acre field station southeast of Tulare for variety tests and work on the reclamation of alkali soils. Kearney's origins go back to the turn of the 20th century, when prominent developer M. Theodore Kearney willed his 5,400-acre estate west of Fresno to the University for educational purposes. UC sold the land, generating revenue to establish the Kearney Foundation, which later would supply matching funds for a research center named in Kearney's honor.

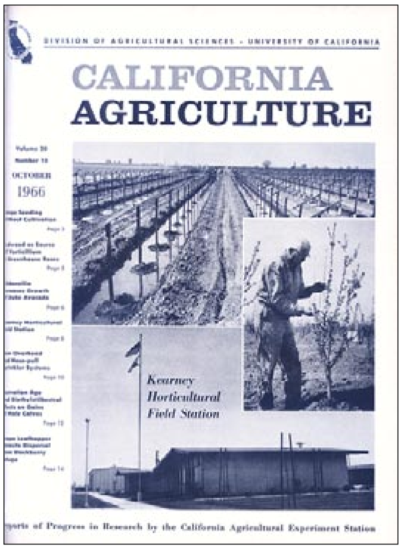
In the early 1960s, the San Joaquin Valley was fertile ground for the expansion of agricultural science and technology. However, prominent San Joaquin Valley agriculturists knew that problems peculiar to the valley could "tarnish the bright

1964
Groundbreaking for two houses, an office, a laboratory and machine-storage and equipment-repair building

1965
Formal dedication of the Kearney Horticultural Field Station, May 26

1966
Additional 30 acres purchased

1969
$165,000 contract awarded to build a 97-by-100-foot building with 14 offices, laboratories and conference room



October 1966 *California Agriculture* features Kearney.

The research center has brought together the laboratories, fields and collective brainpower needed to solve the most pressing problems of soil, water, fruit growing and pest management.


Tea plantings in 1965 were sponsored by Lipton.


Sampling sudangrass plots in 1963.

potential of this unique farming area," according to noted banker and agricultural economist Jesse Tapp (*Reedley Exponent*, June 2, 1965). Challenges included irrigation management, alkali soils, pests and diseases, evaluating new tree and vine varieties, and developing rootstocks with resistance to nematodes and disease.

KREC director Fred Swanson credits Tapp and other midcentury valley agriculturalists for their prophetic understanding that investing in regional agricultural infrastructure would reap great rewards. "These visionaries knew that the valley was a unique production area and that agricultural research needed to be local, relevant and accessible," Swanson says.

In 1959 the Fresno County Farm Bureau took the lead in forming the San Joaquin Valley Fruit and Grape Station Trust, which collected contributions from farmers, fruit packers, agricultural suppliers and others. Gifts ranging from $2 to $10,000 amounted to $128,500 to match Kearney Foundation funds. After serious consideration of several sites, a committee suggested the Mosesian Ranch, a uniform alluvial plain with favorable sandy loam soil. UC consented and the 195-acre Mosesian Ranch, at the intersection of Manning and Riverbend avenues between the cities of Reedley and Parlier, was purchased on Aug. 12, 1962.

Officials broke ground nearly 2 years later on two houses, a laboratory and a building for machinery storage and equipment repair. A year later, on May 26, 1965, the Kearney Horticultural Field Station was formally dedicated with several hundred spectators on hand, according to newspaper accounts. Visitors took tours to see research plantings of tea, grapes, peaches, plums, olives, nectarines, almonds, walnuts and other crops that were already under way.

In the following four decades, the center steadily grew to accommodate new research needs, reflecting the region's rapidly expanding and changing agricultural economy. In 1985, the last 65 acres of land was purchased, bringing the total acreage to the present 330.

Meanwhile, the Kearney center expanded its outreach. Educational programs have attracted hundreds of elementary through college-level students in recent years, including those attending science and career fairs, and agricultural tours.

Kearney scientists advance IPM

Kearney research over the decades has linked UC faculty to "on the ground" problems. Interacting closely with growers, UC scientists developed innovations, including new pest management technologies.

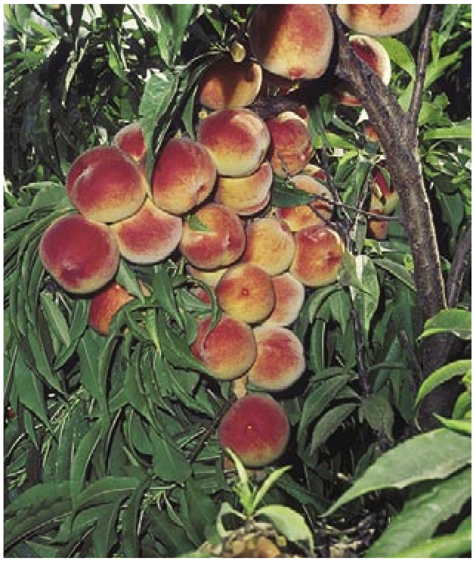
The low price and effectiveness of pesticides available to farmers after World War II led to their acceptance as normal and automatic, setting off a ripple of developments. Farmers, farm advisors and specialists began observing pest resistance and long-term pesticide residuals on farms and in the

1970
New building is completed

1972
Added another 40 acres

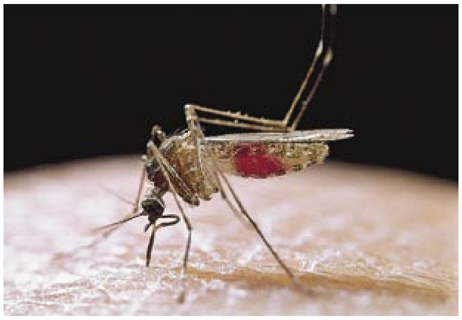
1973
Added biological control unit with quarantine laboratory, one of five in the United States

1977
Capital improvements included five office-laboratory trailers, fruit and vegetable handling lab, volatile storage building, two greenhouses, one potting shed and one storage building


Orchard-systems research got under way in the early 1970s.

"Pioneering work in integrated pest management for California tree crops was conducted at Kearney."
— Frank Zalom, Cooperative Extension entomologist


"Grape Day" brings growers to the center in 1974.


UC mosquito research was conducted in Fresno throughout the 1970s; the lab moved to Kearney in early 1984.

environment. In other areas, they witnessed the phenomena of biological control when, without any pesticide treatment, a pest population would spontaneously disappear. Scientific evaluation revealed natural pest predators at work. In the 1950s, the campus-based scientists, researchers in the valley, farm advisors and specialists began making connections. They studied the concepts of "integrated control" and "economic thresholds" and soon, just as research at Kearney was hitting its stride, "integrated pest management" was born.

"Pioneering work in integrated pest management for California tree crops was conducted at Kearney," says Frank Zalom, a Cooperative Extension entomologist and former director of the UC Statewide IPM Program. In particular, Zalom credits retired Kearney-based entomologist Richard Rice and colleagues with the successful development of pheromone trapping, "degree day" models that predict the growth of common stone fruit pests such as San Jose scale and peach twig borer, and egg traps for the navel orangeworm, the most important insect pest of almonds.

Kearney entomologists, plant pathologists and nematologists have worked to minimize pesticide use and utilize reduced-risk products for pest control. For instance, they advanced the use of plastic reflective mulch to repel aphids that spread viruses, reducing virus disease incidence up to 80% (see page 90). "This level of disease reduction assures an acceptable product for the grower who might otherwise be unable to make a profit," says Charles Summers, a UC Davis entomologist based at Kearney.

Other advances include the development of rapid molecular assays to detect microscopic fungal spores, as well as their resistance to fungicides. This could save growers millions of dollars in unneeded fungicide applications, while reducing environmental damage from pesticide runoff (see page 115). Also, spurred by the ban of the nematicide DBCP in 1979, Kearney research advanced the understanding of how root growth timing and patterns could help identify best nematode treatments (see page 63).

Focus on fruits, nuts and grapes

While working to combat crop pests in environmentally sensitive ways, UC scientists have also used Kearney as a laboratory to dramatically improve the economics of growing perennial crops by focusing on varietal improvements and cultivation techniques. From the beginning, deciduous fruits, nuts and grapes were the agricultural focus at the Kearney Horticultural Field Station.

Over the years, numerous vineyards were planted at Kearney to conduct experiments on table, raisin and wine grapes. Scientists have found, for example, that excellent varietal wines can be produced in the valley's hot, dry conditions. Numerous table grape varieties were studied for optimum farming practices. Scientists here identified the

1985

Added parcel across Riverbend Avenue, bringing total acreage to 330

1986

Weighing lysimeters installed

1989

Dedicated new office and laboratory building

May 29, 1987, groundbreaking for the new building at Kearney. *Left to right*: State Senator Rose Ann Vuich, Lowell Lewis (Associate Director of Agricultural Experiment Station), Dick Markarian (California Raisin Bargaining Association), Fresno County Supervisor Vernon Conrad, State Assemblyman Bill Jones, Ken Farrell (Vice President, UC Division of Agriculture and Natural Resources), Leo S. Kolligian (UC regent) and mule skinner Bob Simmons on a Fresno scraper, with two show mules.

Two huge lysimeters have continuously logged water-use data since 1986.

The current main office and laboratory building was dedicated in 1989.

Jack Kelly Clark

Left, the dormant tree can be seen through open framework. *Right*, a frame covered with plastic protects the tree from outside pollen during bloom period.

raisin varieties and trellis systems that are most conducive to dried-on-vine (DOV) raisin production, which could result in substantial savings to growers as well as significant improvements in air quality (see page 70).

Today, California produces nearly 60% of the nation's peaches, and the region is a significant producer of plums, dried plums, apricots, almonds, pistachios and other commodities. UC scientists have increased understanding of stone fruit nutrition, water needs, pest and disease management, pruning and postharvest handling. For instance, they developed high-density pruning systems that have become the industry standard (see page 75).

"The advantage of high-density systems is that you get early production. In the third, fourth and fifth year, you can get much more fruit per acre than an open-vase orchard of the same age," says Kearney-based pomologist R. Scott Johnson. A successful high-density pruning system has taken the name "Kearney" worldwide. In addition to California, the system is popular in Australia, Chile, Europe and Canada.

Grower groups such as the California Tree Fruit Agreement (CTFA) provide active support and collaboration. Representing about 1,500 stone fruit growers, three-quarters of whom live within 60 miles of KREC, CTFA provides substantial funding support for Kearney research into rootstock development, orchard design,

Legendary "mother" pistachio tree to be retired

Always a curiosity to Kearney visitors is an extra large pistachio tree growing within a huge wooden frame. In the spring, the scaffolding in this frame supports a plastic cover that allows this "mother tree" to be hand-pollinated.

It was planted as part of a variety block of pistachios at KREC by now-retired UC Cooperative Extension pomologist Carl Optiz. The female parent tree, *Pistacia atlantica*, was crossed in 1980 with a male *Pistacia integerrima* in the same block by Lee Ashworth in the UC Berkeley Department of Plant Pathology.

The resulting rootstock produces the highest yields of any pistachio rootstock in California and has an optimal combination of tolerance to cold, salinity and Verticillium wilt. "This means the California pistachio industry can be extended into areas previously thought too cold for other rootstocks," says Cooperative Extension pomologist Louise Ferguson. "More importantly, trees can be planted in soils not suitable for any other fruit or nut tree in California, except dates, and irrigated with sub-par water quality.

This rootstock is now in extensive use in the lower west side of the Central Valley. Because the Foundation Plant Materials Service produces seed of this cross and budwood has been propagated by private source, Kearney's will be retired later this year and the scaffolding removed.

"But, like a good mother," Ferguson says, "she'll always be there." — *John Stumbos*

1992

Dedicated F. Gordon Mitchell Post Harvest Center

1999

Renamed the UC Kearney Research and Extension Center

Jack Kelly Clark

Postharvest research, 1995.

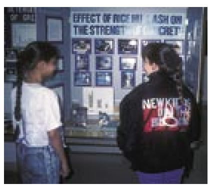
F. Gordon Mitchell and LeRoy Giannini, 1992.

Jack Kelly Clark

Kent Daane at 1995 field day.

Jack Kelly Clark

Mating disruption research leads to control of oriental fruit moth in stone fruit, in the 1990s.



Parlier students attend center's first science fair, 1990.

Today, nearly 70% of the California wine and grape concentrate crush, 95% of California raisins and 90% of the state's table grapes are grown in the San Joaquin Valley.

Winter pruning of orchard trees, February 1997.

water management, IPM and postharvest physiology. "It's really important to have this facility close by," says Gary Van Sickle, CTFA's director of research. "Our growers don't have time for trial and error, and the center is just a few miles away. We hold a lot of field days so growers can see how to best apply the research results."

Unique setting fosters innovation

Swanson says that what makes Kearney unique is its mixture of scientists, extension specialists and research technicians linked to three UC campuses and their many different departments. "There's a critical mass here of knowledge and experience that is a catalyst for creative thought and imagination," he says. "At any one time up to 90 different research studies are under way on about 50 crops in the fields, labs and greenhouses."

One of the station's newest additions is a 20,000-square-foot, $2.9 million greenhouse, completed in 2004, which offers 24 individual plant-growing modules, computer-controlled for temperature and humidity for year-round research. There are now 18 greenhouse projects exploring the biology and control of insect and fungal diseases, pest-resistant plant selection, the impact of ozone on crop production, and specialty crop evaluation.

Always a curiosity to Kearney visitors is an extra-large pistachio tree growing within a huge wooden frame. During the bloom period, the frame supports a plastic cover that protects the tree from collecting airborne pollen. Instead, the tree is painstakingly hand-pollinated and the nuts carefully harvested (see sidebar, page 59). The frame also supports netting in the fall to protect the nuts from scavenging birds.

In another unusual undertaking, Johnson installed sixty 6-by-12-foot tanks 4-feet deep on a research plot and filled each one with 19,000 pounds of sand. He planted a plum tree, yellow-flesh peach tree and white-flesh nectarine tree in each tank. The sand supports the trees but supplies no nutrients, permitting scientists to carefully measure and apply all the nutrients for tree development. This is the definitive global study on peach, plum and nectarine nutrition, Johnson says, and is also the first nutritional study ever done on white-fleshed fruit, which now makes up 20% to 25% of the California industry.

As early as 1986, the University constructed two huge underground scales on the west side of Riverbend Avenue. Called weighing lysimeters, the apparatuses — one planted with grapevines, the other with peach trees — have allowed scientists to calculate precisely how much water evaporates from the soil and transpires from the tree at any given time (see page 133). "There are very few of these in the world large enough for trees and vines," Johnson says. With knowledge about plant water use gleaned from lysimeter studies, scientists are better prepared to provide science-based information to farmers facing any water problem.

2004
New greenhouse facility dedicated

2005
Kearney marks 40 years

Photos: Richard H. Molinar

New specialty crops (clockwise from top left): dragonfruit (exterior and interior), lemongrass, jujube, capers, mini watermelons.

In a 2005 report, the Public Policy Institute of California predicts that the Valley population will double to more than 7 million by 2045.

UC president (left) Robert Dynes tours Kearney blueberry plots with Manuel Jimenez, April 2004.

Jack Kelly Clark

New greenhouses at night.

"Niche" crops keep small farms afloat

Kearney has also taken a leading role in developing new specialty and "niche" crops that are well suited for the valley's small-scale growers. Grape tomatoes, a popular item replacing cherry tomatoes, mini "personal" watermelons, and pitahaya or dragon fruit are being studied at Kearney in trials by UCCE farm advisor Richard H. Molinar and colleagues. His plots also feature capers, jujube tree, lemon grass, water chestnuts and other plants.

Near the eastern boundary of the research station, UCCE farm advisor Manuel Jimenez maintains 21 varieties of blueberry plants entering their eighth year of production (see page 65). Long considered unsuitable to San Joaquin soils and climate, blueberries are now plentiful in Tulare and Fresno counties due to studies by Jimenez and colleagues on southern highbush varieties and methods of keeping the plant in its preferred low-pH environment. "We have one variety that's just exceptional," Jimenez says. "The taste is far superior to any I have ever tried and the texture is perfect."

Farming at the urban edge

The San Joaquin Valley is undergoing tremendous population growth, which is altering how farmers ply their trade and interact with their urban neighbors. In addition, the resulting air pollution is affecting crop yields and weed interactions. On a research plot west of Riverbend, open-top field chambers allow UC Riverside plant physiologist David Grantz and colleagues to study the effects of different levels of ozone on plant development (see page 137). As early as 1971, William B. Hewitt, who served as director of the San Joaquin Valley Agricultural Research and Extension Center at Kearney from 1969 to 1974, cautioned that urban growth in the valley must consider the importance of the area's agricultural potential.

"Geographically this valley is a basin over which air inversion phenomena is common and thus traps air pollutants," he was quoted in a 1971 *Reedley Exponent* article. "We can not have developments that add to air pollution problems."

Urban growth continues to be an agricultural concern. The valley has changed dramatically during the past 40 years. In a 2005 report, the Public Policy Institute of California predicted that the valley population will double to more than 7 million by 2045. The institute's experts say that doesn't portend the demise of valley farming, but it does apply pressure to sell farmland for development prices, grow crops on less space and farm closer to urban populations.

"If we, as growers and packers, are to survive and compete in a global agricultural economy, we need Kearney's continued assistance," Chandler says. "With their help, we can become more efficient and productive, and continue to produce the safest and most affordable food in the world."

— Jeannette Warnert and Editors

Jack Kelly Clark

Taste tests help Kearney researchers to evaluate consumer preferences.

"Farm to palate" postharvest research ensures high-quality produce

Scientific support for fruit production at the UC Kearney Research and Extension Center (KREC) doesn't stop when the plants are harvested. Consumer demand for quality fruit at grocery stores has increased interest in the highly technical scientific field of postharvest research, which focuses on fruit packaging, handling and transportation.

"After biting into a mealy or off-flavor peach, consumers won't likely buy any more," says Kearney postharvest scientist Carlos Crisosto. "We can improve the eating experience by carefully managing the peach's journey from the farm to the consumer's palate. That expands and strengthens the market for fresh fruit."

At Kearney, the postharvest program accelerated in 1992 when a donation from local stone-fruit grower LeRoy Giannini allowed for the construction of a 9,566-square-foot research facility. The building was named the F. Gordon Mitchell Post Harvest Center in honor of the namesake's extensive contributions to postharvest science. Mitchell, a UC Davis pomologist, retired in 1992.

Two postharvest research scientists are headquartered at the Kearney center, UC Davis pomologist Crisosto and UC Riverside subtropical horticulturist Mary Lu Arpaia. In addition, a wide variety of off-site UC scientists make use of the state-of-the-art facilities, which include 21 walk-in and four reach-in fruit storage chambers, and small-scale processing equipment that duplicates the standard industry machinery.

For more information

KAC Fresh Fruit Postharvest Information: www.uckac.edu/uckac/research

Protecting fruit flavor. Crisosto focuses on stone fruit, kiwifruit and table grapes (see page 103). With the peach industry, he is addressing the fact that peach consumption in the United States has remained unchanged over the last decade. In surveys, consumers misunderstood the difference between "mature" and "ripe" peaches, and were turned off by lack of flavor, flesh browning and mealiness.

In collaboration with UC Cooperative Extension farm advisors Kevin Day and Harry Andris and pomologist R. Scott Johnson, Crisosto has looked at fertilization, irrigation, bruising thresholds, storage temperature, handling, packing materials, contamination and other factors that can make fruit less attractive or palatable.

Their research has resulted in the development of a preconditioning protocol for shippers and a ripening protocol for receivers. The researchers went still further, educating supermarket fruit handlers on how to protect fruit flavor. "The establishment of this new delivery system is giving excellent results. Fruit are moving faster and a premium has been paid for preconditioned fruit," Crisosto says.

In kiwifruit, Crisosto has developed ripening protocols and bin storage techniques. He determined optimum maturity time and which packing materials deliver the fruit to the store with less shrivel and pitting. Crisosto and Kearney-based plant pathologist Themis Michailides developed a curing treatment for kiwifruit to reduce the incidence of the fungal disease botrytis.

Farming practices and postharvest quality. Arpaia's focus is on citrus and avocado. She and her staff continue to collaborate with other citrus researchers to gauge how farming practices influence postharvest quality. For example, they are just completing a multiyear project with two UC Riverside entomologists and one plant physiologist examining the impact of glassy-winged sharpshooter on the postharvest quality of navel and Valencia oranges. Arpaia's group has also collaborated on projects evaluating the impact of fertilization and irrigation practices. Recently, she and her colleagues conducted taste testing to determine the minimum maturity level for navel orange harvest.

That work comes on the heels of a successful multiyear project that determined the ideal time for avocado growers to harvest their crop. "We came up with a way to measure dry weight before ripening and then linked that back to how well people enjoyed eating the fruit," Arpaia says.

With information from the project, Arpaia has established minimum maturity standards for the new varieties of avocados that have been released by UC.

Consumer acceptance. An extensive fresh-fruit sensory program was developed over the last 9 years by Gayle Crisosto, postharvest staff research associate. She has conducted taste and appearance tests on crops such as peaches, plums, nectarines, table grapes, cherries and kiwifruit. Crisosto has worked with American consumers and native Japanese tourists to test their acceptance of early-harvested Bing cherries at different levels of maturity. The Japanese consumers were satisfied with lower maturity than the American consumers. "This shows that fruit preferences in Asia are different than those in the United States," Crisosto says.

Similar work was carried out with 400 American and 250 native Chinese consumers to determine the two ethnic groups' acceptance of 'Redglobe' table grapes at different maturity levels.

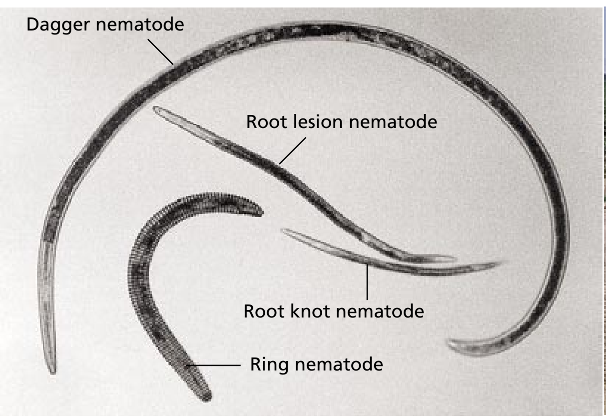
At Kearney, Crisosto conducts fruit tasting tests with panels drawn from staff who have been screened for their taste acuity and trained for a specific test. "Most of the panelists enjoy it," she says. "They get a break from their work and they know they are making a positive contribution to the furtherance of our scientific knowledge of fruit quality."

Managing fungal diseases. UC Riverside plant pathologist Jim Adaskaveg is leading postharvest pathology research on stone fruit, pome fruit, kiwifruit, pomegranates and citrus. Recently, he initiated a citrus incubation program at the postharvest center that protects the Korean market for the California citrus industry. In 2003, Korea closed its market to California oranges after detecting the fungal disease Septoria spot. After negotiation and study, Adaskaveg and his team, working with the citrus industry and the U.S. Department of Agriculture, arrived at a plan. The team collects and incubates fruit samples at the center, then assesses them 20 days later for Septoria spot. Fruit positive for the disease are identified and photographed, and the results are provided to the packinghouses. This program was in part responsible for maintaining the $100 million citrus trade between the two countries.

For other crops, Adaskaveg and his team have developed several new reduced-risk postharvest fungicides. They are evaluating new application strategies to improve disease control (see page 109) and have identified diseases like sour rot that have recently become more of a problem for the stone fruit industry.

Ultimately, all the scientists working on postharvest studies at KREC share the same goal, Gayle Crisosto says. "We want to consistently provide good-tasting fruit to the consumer so they'll come back for more." — *Jeannette Warnert*

Stephanie Kaku



A variety of plant parasitic nematodes can sap nutrients from the roots of trees, vines and field crops.

Michael V. McKenry

Vines stunted by root knot nematodes.

After years of hosting an orchard or vineyard, nematodes will have colonized and reproduced to levels that would put a new planting in grave danger.

UC nematologists battle tiny underground pests

Nematodes are the most numerous multicell animals on earth. One cup of soil can contain thousands of the tiny worms. Some are beneficial, but many cause significant damage to agricultural crops.

"You can see insects, and diseases often cause visible symptoms," says Philip Roberts, a UC Riverside nematologist. "The underground feeding of nematodes can be just as harmful, but it is much more difficult to detect."

Roberts and UC Riverside nematologist Mike McKenry, who is based at the UC Kearney Research and Extension Center, preside over a specialized program that offers pest management professionals and growers the latest information on nematode problems and solutions. Their work is particularly important due to past and upcoming bans on chemicals that have traditionally been used to rid soils of nematodes before planting, such as DBCP and methyl bromide.

Perennial crops. As part of his focus on perennial crops, McKenry has pursued "chemigation" as an alternative to preplant methyl bromide soil fumigations. McKenry has developed methods and equipment that use water to carry low-fuming biocides (with short half-lives), 5 feet deep. Large volumes of water can also prevent biocides from escaping at the field surface. By 1991, he demonstrated that in highly porous soils, chemigation with biocides such as metam sodium could provide nematode control equivalent to that of methyl bromide. "Today, new products and equipment for preplant chemigation are plentiful," McKenry says.

A promising new natural treatment for nematodes

Root knot nematodes can cause galling and forking of carrot roots.

was discovered in 1979 by McKenry and his UC Riverside colleagues. The scientists identified microorganisms that were protecting five Fresno County peach orchards from root knot nematodes. The fungus, *Dactylella oviparasitica,* was found to be attacking the pest's eggs.

"This fungus has now been noted in other field settings and in other regions involving other nematode species," McKenry says. "Research is slow and we still do not know how to correctly inoculate fields, but this fungus ranks as a top nematode control agent within nematode-infested soils and is naturally at work in the San Joaquin Valley."

Another method of nematode control is the development of resistant rootstocks. In 2003, McKenry's lab released two new grapevine rootstocks that possess broad nematode resistance.

These and other advancements are of particular interest to growers who plan to replant orchards or vineyards. When land that has not previously been used to cultivate crops is converted to agricultural use, nematodes that damage trees and vines are at a minimum. After years of hosting an orchard or vineyard, however, nematodes will have colonized and reproduced to levels that would put a new planting in grave danger. This is called the "replant problem." To address the complex issues associated with replanting, McKenry has made a 70-page report available for free on his nematode Web site.

Annual crops. Based at Kearney in the 1980s, Roberts established two experimental sites to study nematodes in annuals. The research sites were each inoculated with a distinct species of root knot nematode, the most problematic nematode on San Joaquin Valley commercial farms.

Over the last 20 years, Roberts and other scientists have identified genes that give plants natural nematode resistance, including in tomato, carrot, cotton, sugar beet and various dry grain beans. From the work at Kearney, there have been releases of several nematode-resistant black-eyed varieties, and breeder release lines of resistant carrots that are now being used by seed companies to develop commercial varieties.

Roberts has also been looking at a range of control options to avoid subjecting nematodes to selection pressure by repeatedly growing the resistant crops. He has found, for example, that crops susceptible to nematodes can be planted following some resistant crops without dramatically reducing yields. Cultural practices can also play a role, he says. "If you plant carrots at a cooler time of year, when nematodes are less active, you avoid some plant damage."

— Jeannette Warnert

For more information

Michael McKenry's nematode site:
www.uckac.edu/nematode

Science brief

Lygus study validates treatment thresholds

Lygus bugs *(Lygus hesperus)* are a common insect pest in the San Joaquin Valley, affecting everything from cotton to pistachios and many other commodities. Kearney-based IPM advisor Pete Goodell conducted a study in 1996 of how this pest affects blackeye beans and discovered that the timing of the infestation has more to do with subsequent damage than the sheer number of pests.

In brown exclusion cages, varying densities of Lygus bugs (0, 20, 60 and 120) were released before and after flowering. The bugs were allowed to feed for 2 weeks. Yield data was collected and evaluated to determine impacts on quantity and quality. Field assistants collected Lygus bugs from the bean field with a vacuum sampler.

Field assistants Tommy Koga and Jake Gregory sample for Lygus bugs in a blackeye bean plot with exclusion cages.

"We found that the timing of the infestation has more impact on yield than numbers," Goodell says. "Beans are more sensitive to pressure from equivalent Lygus populations after flowering. Presumably, bean plants damaged early were able to compensate for any damage caused before bloom."

This study, supported by the UC Statewide IPM Program and Dry Bean Council, showed that treatment thresholds developed for older varieties were still valid for newer varieties.

— John Stumbos

Blueberry research launches exciting new California specialty crop

Manuel Jimenez
Francis Carpenter
Richard H. Molinar
Kathryn Wright
Kevin R. Day

Blueberries historically have been grown mostly in the cooler regions of the United States. The recent development of new low-chill cultivars such as 'Legacy', *above*, in concert with innovative growing techniques and strong consumer demand have created an important specialty crop for the San Joaquin Valley.

Observational trials at the UC Kearney Research and Extension Center indicate that new southern highbush blueberry cultivars, which require fewer "chill hours" to produce fruit, are well adapted to the San Joaquin Valley climate. In a replicated cultivar evaluation, we quantified yields and identified several productive and flavorful varieties. These initial trials and ongoing studies on irrigation, plant spacing, mulches and pruning will improve the likelihood of establishing this promising new crop in the semiarid valley. Because blueberries are acid-loving, the soil must be extensively treated before planting, at considerable expense. Growers considering planting or expanding blueberry acreage should develop sound business plans, accounting for lower future prices and improved growing, harvesting and packing efficiencies.

Due to overproduction, market prices for many crops have been depressed for several years, resulting in the removal of thousands of acres of citrus, stone fruits, grapes and olives in the San Joaquin Valley. More than ever, growers are seeking new crops to plant, and many are focusing their attention on specialty or alternative crops. Observational trials indicate that new southern highbush blueberry cultivars are well adapted to San Joaquin Valley conditions. These initial trials and other ongoing studies will improve the likelihood of establishing this crop in the semiarid valley, a region not traditionally known for blueberries. However, prudence is appropriate, since blueberries are one of the most costly crops to establish. Blueberry establishment and production costs can exceed $10,000 per acre, and blueberries require significantly more management than most other specialty crops (Bervejillo et al. 2002). The objective of current UC blueberry research is to develop sound information for selecting cultivars and to verify production practices that will assist growers in establishing blueberries.

Blueberry is a member of the family Ericaceae, which includes woody shrubs such as azaleas and rhododendrons that grow well in acidic soils. Highbush blueberries are woody, shallow-rooted perennial shrubs. Although some species grow taller than 20 feet, most cultivars are 4 to 10 feet tall at maturity. In established growing regions, plants reach full production within 6 to 8 years and can remain productive for 20 years or more. Proper pruning, mulching and pest monitoring are essential to maintain plant vigor and productivity. The San Joaquin Valley's warm winters and hot summers appear to hasten plant development, but could also impact long-term blueberry productivity.

Highbush blueberries *(Vaccinium corymbosum)* and low-bush blueberries *(Vaccinium angustifolium)* are important commercial types and are native to the northeastern United States. Rabbiteye blueberries *(Vaccinium ashei)* are also produced commercially and are native to the southeastern United States.

The terms "northern highbush" and "southern highbush" refer to the chilling requirement of blueberry cultivars. Chilling is the accumulated number of hours between 32°F and 45°F that are necessary for a dormant plant to break vegetative and flower buds. Most northern highbush cultivars require more than 1,000 chill hours for bud-break (Gough 1991). Chill hours in the San Joaquin Valley range from 600 to 1,200 annually. Previous failures at establishing blueberries in California's warm climate were mostly due to the utilization of northern highbush cultivars, which were poorly

Blueberries are acid-loving plants; therefore, most California soils must be acidified for successful plant establishment.

TABLE 1. Estimated North American blueberry acreage, 2003

Region	Acres
Midwest	
Michigan	17,500
Illinois	2,950
Indiana	700
Others	150
Subtotal	*21,300*
West	
British Columbia	11,000
Oregon	3,700
Washington	2,000
California	1,300
Subtotal	*18,000*
South	
Georgia	6,000
North Carolina	5,000
Mississippi/Louisiana	2,000
Florida	1,200
Texas	1,200
Arkansas	350
Others	250
Subtotal	*16,000*
Northeast	
New Jersey	7,500
Eastern Canada	1,200
New York	1,000
Others	700
Subtotal	*10,400*
Total North America	***65,700***

Source: North American Blueberry Council 2004.

TABLE 2. Estimated highbush blueberry crop, 2004

State	Fresh	Processed	Total
	······· *lb. millions* ······		
Alabama	0.5	0.0	0.5
Arkansas	1.6	0.0	1.6
California	3.0	0.0	3.0
Florida	2.5	0.0	2.5
Georgia	7.2	7.8	15.0
Louisiana	0.5	0.0	0.5
Mississippi	1.2	1.4	2.6
North Carolina	16.1	6.4	22.5
Texas	1.0	0.0	1.0
Others	0.1	0.0	0.1
Total	***33.7***	***15.6***	***49.3***

Source: North American Blueberry Council 2004.

Jack Kelly Clark

Growers who are considering planting blueberries or expanding current acreage must develop sound business plans to anticipate market changes and production improvements. Morten Johnson, a Kingsburg dentist and former KREC committee member, attended an open house held for UC president Robert C. Dynes, and learned about new blueberry varieties at the center's research plot.

adapted to the mild winters of the San Joaquin Valley. Breeders in the southeastern United States have developed "low-chill" southern highbush cultivars by crossing northern highbush species with native Florida species. These low-chill cultivars require only 150 to 600 chill hours for bud-break (Gough 1991).

North American production areas

Until recently, blueberries were grown almost entirely in the cooler regions of the United States including Michigan, New Jersey, Oregon and Washington, where winter climates and the natural acidic soils were uniquely suited for blueberry production. However, with the development of improved low-chill cultivars from the 1970s through the 1990s, blueberry production has expanded to the southern United States and now, California.

Increased consumer demand is driving the market for fresh blueberries, making them a potentially lucrative specialty crop. Furthermore, reports on the health benefits of blueberries have contributed to worldwide consumer interest (US Highbush Blueberry Council 2003). Blueberry acreage in North America has increased over the last decade and considerably more so during the last 5 years. In 2003, blueberry acreage in North America exceeded 65,000 acres (North American Blueberry Council 2004)(table 1). Production and disposition figures for 2003 show that 69% of the blueberry crop was for fresh utilization rather than processing, further illustrating the consumer demand–driven market that blueberries currently enjoy (table 2).

The North American harvest usually begins in Florida in early April and concludes in Michigan and British Columbia in early October (Agricultural Marketing Service 2003). The California harvest typically begins in early May and lasts almost 8 weeks (fig. 1). Furthermore, the arrival of low-chill cultivars has expanded global plantings to Chile, Argentina and tropical Colombia, thereby ensuring fruit availability even during the winter in North America.

Planting considerations

Blueberries are acid-loving plants; therefore, most California soils must be acidified for successful plant establishment. The optimum soil pH for blueberry culture is 4.0 to 5.2 (Strik et al. 1993). Soil acidification is most often achieved using sulfuric acid, which is broadcast over the surface of the soil and

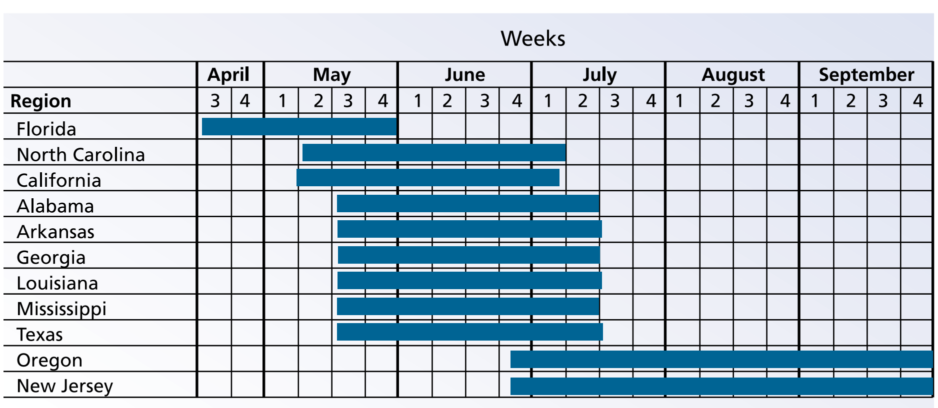


Fig. 1. State blueberry harvest periods that overlap with California's. Source: Agricultural Marketing Service 2003.

TABLE 3. Southern highbush blueberry cultivar characteristics

Cultivar	Plant stature	Productivity*	Harvest period†	Fruit size‡	Hand-harvest ease
Biloxi	Erect	High	Midseason	70–110	Difficult
Bluecrisp	Erect	Moderate	Midseason	65–70	Easy
Emerald	Erect	High	Early/midseason	50–80	Moderately easy
Jewel	Erect	High	Early	60–100	Moderately easy
Jubilee	Erect	Moderate	Early/midseason	80–150	Moderate
Legacy	Erect	High	Midseason	55–100	Very easy
Millennia	Erect	Moderate	Early/midseason	No data	Moderately easy
Misty	Spreading	High	Early/midseason	80–130	Difficult
O'Neal	Erect	Low	Early	100–130	Easy
Ozarkblue	Erect	Moderate	Late	50–70	Easy
Santa Fe	Erect	Low	Early/midseason	60–70	Easy
Sharpblue	Spreading	Moderate	Early/midseason	110–200	Moderate
Southern Belle	Erect	Moderate	Early/midseason	No data	Easy
Southmoon	Erect	Moderate	Midseason	60–120	Easy
Star	Erect	Moderate	Early	60–70	Very easy
Reveille	Very erect	Low	Early	100–130	Moderate

* Productivity represents third-year harvest: low < 5 lb., moderate 5-10 lb., high > 10 lb.

† Harvest period indicates initiation of harvest: early = initial harvest; early/midseason = 7 days later; midseason = 14 days later; late = 21 days later.

‡ Fruit size represents the number of berries per 6 oz. cup. Although fruit size is genetically predetermined, pruning and other cultural practices can affect fruit size significantly.

then flood irrigated with sufficient water to incorporate it to a depth of 12 inches. Soil sulfur can be applied but may require several months to convert to sulfate and change the soil pH. Sulfur is not as predictable as sulfuric acid for changing soil pH. Therefore, when applying sulfur, additional attention must be given to monitoring soil pH and making appropriate adjustments. Citric acid and other acidic compounds may be used to lower soil pH, but they are more costly.

Poor water quality also affects blueberry plant growth. Many agricultural water sources contain high levels of bicarbonates (Gregory 2001; Gaskell 2002). Bicarbonates raise pH and affect the uptake of nutrients by blueberry plants. Additionally, bicarbonate content greater than 1.5 to 2.0 milligrams per liter can cause the precipitation of calcium or magnesium carbonate, resulting in a chalky deposit that plugs drip and microjet irrigation systems (Gregory 2001). The installation of acid injection equipment may be required to maintain acidic conditions in the irrigation water. Water samples should be tested to determine if treatment is needed. Sulfuric acid (93% to 98% acid) and urea sulfuric acid (27% to 55% acid) are the most common acidifying agents for irrigation water; however, phosphoric acid (52% to 54% acid) and citric acid can also be used (Gregory 2001). Soil sulfur, acetic acid (vinegar) and citric acid are the only acidifiers that are acceptable for organic blueberry production. The approximate cost of acid materials ranges from approximately $1.00 to $4.00 per gallon, with sulfuric acid being the least expensive and highest in percentage active ingredient. All acids are potentially hazardous materials and considerable care must be taken to minimize worker exposure and maintain safe working conditions.

The broadcasting of acids to the soil, especially sulfuric acid, is performed by companies specializing in the transportation of hazardous materials and custom application of acids, using specialized application equipment. Once the acid is applied to the soil, followed by an irrigation, the acid reacts with calcium carbonate in the soil and does not present a hazard. The application of sulfur and other sulfur-based soil amendments is a common practice in high calcareous western soils. Depending on the buffering capacity of the soil, the acid is converted, neutralized and used within several inches from where it is applied on the soil. The soil reaction is summarized as: sulfuric acid plus lime gypsum plus carbon dioxide plus water. What is unique about blueberries is that a lower pH is desirable for optimum plant vigor than for any other commercial crop.

Blueberry cultivar studies

Trial I. We initiated blueberry observation trials at the UC Kearney Agricultural Research and Extension Center (KREC) in Parlier in 1997, which have provided insight to key characteristics of numerous blueberry cultivars. The results of these trials indicated that southern highbush blueberry cultivars

Jack Kelly Clark

Field trials showed that Southern highbush blueberry cultivars are well adapted to the San Joaquin Valley. These new cultivars, such as 'Reveille', *above*, begin flowering in late winter and open a harvest window from early May through the Fourth of July.

Blueberries are acid-loving plants; as a result, most California soils must be treated to lower pH to 4.0 to 5.2, and irrigation water is acidified to a pH of 5.0. *Left*, in a Kearney field trial, overhead misters are close to the plant canopy. *Right*, overhead sprinklers are being tested to observe plant growth under a cooler temperature regime. *Below*, in Kearney field trials, planting beds were formed using border disking. Blueberry plants were then placed in furrows and covered with pine mulch.

are well adapted to the San Joaquin Valley. We identified several key, early-season cultivars that will likely form the basis for the young industry that is developing in the state (table 3).

Nearly all the cultivars established at KREC were started from tissue culture and then grown for two seasons by Fall Creek Farm and Nursery in Lowell, Ore. Currently, more than 50 cultivars are under observation at KREC. Although the data does not provide information on fruit quality attributes, it is important to call attention to 'Southmoon' and 'Reveille', a couple of cultivars that produce outstanding fruit quality and are well suited for direct sale to consumers. Although 'Reveille' does not produce large fruit and both cultivars are less productive than others, their sweetness and firmness are distinct and may result in consumer preference and consistent return purchases.

Trial II. In 2001, a multipurpose replicated trial was established at KREC. Prior to establishing the blueberry trials, the 2-acre field was fumigated to kill the nut grass *(Cyperus rotundus)* that covered the entire area. In July, a fumigant mixture was applied, 300 pounds of methyl bromide and 100 pounds of chloropicrin per acre. A soil test indicated that the field pH was approximately 7.0. In September, 5 tons of sulfuric acid was broadcast on the surface of the soil using specialized application equipment. The acid was incorporated to a depth of 10 to 12 inches with flood irrigation, resulting in a pH ranging from 5.0 to 5.5. A complete fertilizer (15-15-15) was broadcast applied at a rate of 400 pounds per acre. Rows were set 11 feet apart. Planting beds were formed using border discs, then rolled to pack the soil. A furrow 12 inches wide and 6 inches deep was cut on top of the raised beds.

Blueberry plants were planted in the bottom of the furrow, which was then filled with pine mulch. Two drip lines were placed on the surface of the mulch, one on each side of the plant row. The emitter spacing was 18 inches apart with each delivering 2 liters of water per hour. Irrigation water was acidified to a pH of 5.0 using urea sulfuric acid fertilizer. The trial received 20 pounds of nitrogen (N) per acre from a 32% urea ammonium nitrate solution (UN32) during the first growing season, followed by 60 and 90 pounds of nitrogen per acre utilizing urea sulfuric acid (US15: 15% nitrogen, 16% sulfur, 49% sulfuric acid)(Gregory 2001) in the second and third growing seasons, respectively.

The replicated cultivar evaluation included eight southern highbush cultivars with the exception of 'Legacy', which is a northern-southern cross. Early-season cultivars were 'O'Neal', 'Sharpblue', 'Misty' and 'Star'; midseason cultivars were 'Legacy', 'Jubilee' and 'Southmoon'; and the lone late-season selection was 'Ozarkblue'. Each

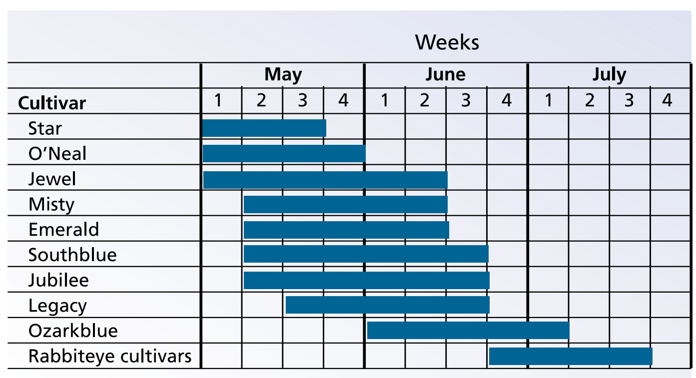


Fig. 2. Harvest periods for key commercial blueberry cultivars in the San Joaquin Valley. The initiation and termination of harvest will vary as much as 10 days, depending on local weather conditions.

Jack Kelly Clark

UC small farms advisor Manuel Jimenez is leading the effort to develop sound information for selecting blueberry cultivars and fine-tuning production techniques.

treatment included seven plants spaced 36 inches apart. The experimental design was a randomized complete block with four replications.

The trial produced a commercial crop in the second growing season. 'Misty' and 'Star' produced the highest yields among the early cultivars, whereas 'Legacy' was the most productive of the midseason-maturing cultivars (table 4). The harvest period for 'Star' in 2003 and 2004 began the first week of May and ended after the third harvest 15 days later (fig. 2). 'Misty' had the longest harvest interval (5 weeks), beginning the second week of May and terminating the second week of June. The harvest period for 'Legacy' lasted 4 weeks, beginning the third week of May and ending during the second week of June. Most other cultivars required five or more harvests, 1 week apart. Yields generally appear to be following the trend of data collected from the observational plots, which are now in their sixth and seventh year of production.

Looking forward

Concomitant with the initiation of the cultivar trial in 2001, several other trials were also established, including an irrigation study, a plant spacing comparison, a mulch evaluation and a pruning study. Although these trials are too young to report upon at this time, forthcoming results will provide critical data that will assist in the establishment of common cultural practices for California blueberries. Several new cultivars have been introduced into the observational collection, and because of their outstanding characteristics, some may actually become more important than those in current use. We are also studying hoop-houses (mobile greenhouses) at KREC, which could potentially hasten or delay fruit maturity so that specific market periods can be targeted. Moreover, other researchers and growers statewide are conducting blueberry research. UC farm advisors Mark Gaskell, Ben Faber and Ramiro Lobo have established trials along the central and southern coast of California, while Abdelaziz Baameur, Calvin Fouche and Mario Moratorio are conducting blueberry research in Northern California. Data is not yet available from these trials.

Since blueberry acreage has increased dramatically to reflect consumer demand, we assume that prices will decline sooner rather than later. Growers who are considering planting or expanding current acreage must develop sound business plans, which account for lower future prices and improved growing, harvesting and packing efficiencies. Staying abreast of technical advances, and establishing and maintaining good marketing relationships are essential to minimize risks. Additionally, California producers should consider taking leadership roles in blueberry marketing and promotion activities and organizations, to sustain blueberry profitability.

TABLE 4. Cultivar evaluation yields, 2003

Cultivar	2003	2004
	lb./acre	
Jubilee	6,543ab	7,845ab
Legacy	7,279a	9,825a
Misty	4,450c	9,655a
O'Neal	1,678d	3,564c
Ozarkblue	2,338d	3,281c
Sharpblue	4,318c	5,921bc
Southmoon	4,695c	5,619bc
Star	6,034b	9,334a

* Treatment means followed by different letters are significantly different ($P < 0.05$).

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RESEARCH ARTICLE

The future of California raisins is drying on the vine

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Scientists at the UC Kearney Research and Extension Center have developed a new method to produce dried-on-vine (DOV) raisins. Prior DOV systems required costly trellising and harvesting equipment, putting DOV out of reach for most growers. Our new, within-row-alternate-bearing DOV (WRAB DOV) method can be used with the existing trellis and no retro-fitting. DOV raisins are machine harvested, reducing human contact and production costs, and improving profitability. Drying raisins on the vine eliminates the need for intensive cultivation to prepare terraces down row middles. This method also removes the problem of using and disposing of paper trays, solving an important air-quality issue for raisin growers.

Jack Kelly Clark

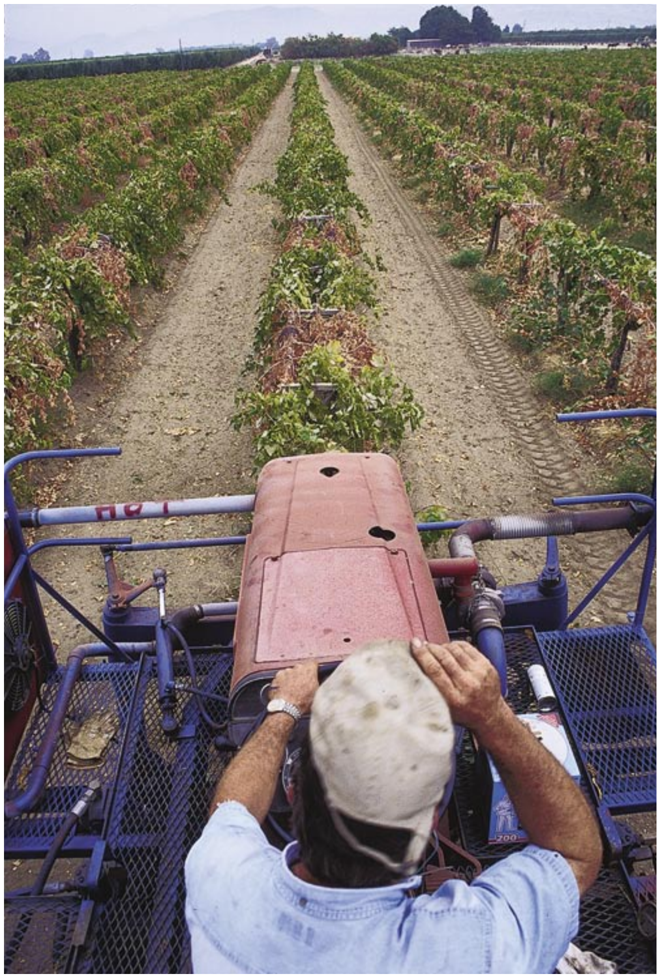
After more than a century of hand-harvesting and drying grapes on trays to produce raisins, California growers now have an economically viable alternative. The alternate bearing, dried-on-vine method (WRAB DOV) developed by Kearney scientists reduces production costs and can be used with existing trellises.

The California raisin industry consists of about 4,500 growers in the southern San Joaquin Valley, growing raisin grape varieties on 250,000 acres. Over 90% of the raisin crop is produced from the 'Thompson Seedless' variety. The 300,000 to 400,000 tons of raisins produced each year constitute about 40% of global production; in 2004, the raisin crop had a farm-gate value of one-third billion dollars.

The traditional method of hand-harvesting and drying grapes on trays for natural raisins has changed little over the past hundred years. Most hand-harvested raisin grapes are dried on individual paper trays placed on a smooth terrace prepared between vine rows. When drying is complete, the raisins are rolled up in the paper trays, then the rolls are picked up by hand or mechanically and the raisins are dumped into bulk containers for removal from the field. Paper trays are usually disposed of by burning in the field. This process is labor intensive, requires close supervision and experienced management, and involves weather risks. In contrast, dried-on-vine (DOV) raisins are mechanically harvested, reducing the labor requirement. The cultivation required to prepare the terrace is eliminated, along with the problem of disposing of paper trays (Christensen and Peacock 2000).

DOV raisins have a milder flavor and no caramelization compared to tray-dried raisins. They are also rounder and have smaller wrinkles. This difference is the result of the drying environment. With tray-drying, the temperature on the tray surface can exceed ambient temperatures by 30°F to 40°F, and raisins dry in 10 to 20 days depending on the weather. In contrast, DOV raisins are dried on the vine at temperatures closer to ambient and it takes 30 to 40 days to complete the drying process.

The potential for drying raisins on the vine was first noted by scientists



Above, **dried-on-vine raisins can be mechanically harvested with a wine grape harvester.** ***Below***, **hand-harvesting requires much higher costs for labor, paper tray disposal and preparation of clean middle rows.**

working at the UC Kearney Research and Extension Center (KREC) in 1965. Since then, a number of DOV systems have been developed by UC researchers and growers. These systems, however, require expensive trellising and harvesting equipment that excludes many growers from producing DOV raisins (Christensen 2000).

We developed a DOV raisin method at KREC that has opened the door for growers to produce DOV raisins. The method is based on the separation of fruiting canes and renewal shoots alternating between vine sections down the vineyard row. We call the method "within-row-alternate-bearing dried-on-vine" (WRAB DOV).

WRAB DOV is applicable to all raisin trellises, and raisins are harvested from the vine using a canopy shaker wine-grape harvester. Prior DOV systems, such as south side, overhead and open gable, required expensive trellising and harvesting equipment. Start-up costs were prohibitive for most growers, especially during the recent economic down cycle. However, the WRAB DOV method can be used with the existing trellis and no retrofitting.

Research began on the WRAB DOV method in 1999 at KREC. We compared WRAB DOV and traditional tray-drying, measuring yield, raisin quality and harvest costs over 4 consecutive years. Canopy management, summer pruning and harvesting techniques were developed for WRAB DOV. Various trellis widths were evaluated to determine the impact of trellis expansion on yield and vine capacity.

Production and canopy management

We established a trial plot at KREC for the dual purposes of comparing WRAB DOV production with traditional tray-drying and evaluating various canopy-management techniques. It was located in a mature raisin block trellised with a cross-arm (18 inches and two wires) and 7-foot stakes. The experimental design was a completely randomized block with six blocks (replications) and four treatments, and using five vine plots. The three middle vines within the five vine plots were used for data collection. Treatments were WRAB DOV with: (1) no canopy management; (2) shoot thinning; (3) shoot thinning plus shoot positioning; and (4) control, traditional tray-drying. Statistical analysis was by ANOVA using least significant difference for treatment mean separation.

All DOV and tray-drying treatments were pruned to five fruiting canes and six renewal spurs. Fruiting canes were 12 to 15 nodes in length. Canes on the tray-drying treatments were tied in the traditional fashion, and canes on DOV were tied using the within-row alternate-bearing system.

Shoot thinning DOV treatments occurred in mid-April and consisted of retaining eight shoots on the renewal side of the vine to become the next year's fruiting canes. Shoots were selected based on their location. The goal was to establish a clear division between the renewal side and fruiting side of the head (trunk). Shoot positioning occurred in late May, around berry set, and consisted of wrapping or twirling five of the shoots that had been retained on the renewal side during the shoot-thinning operations (the next year's fruiting canes) down support wires.

Jack Kelly Clark

Yields similar, grades higher

We found no significant differences between the yields of WRAB DOV and tray-drying for each of 4 consecutive years. The average yield during that 4-year period was 2.7 tons per acre for the WRAB DOV treatment compared with 2.8 tons per acre for the tray-dried treatment.

***Left*, with the traditional method, fruiting canes of 'Thompson Seedless' vines are tied in both directions. *Right*, with WRAB DOV, fruiting canes and renewal sections alternate down the vine row.**

DOV raisins graded higher than tray-dried raisins when at the same fruit maturity. To compare grades, we picked tray-dried fruit on Aug. 21, 2003, and spread it on paper trays. That same day WRAB DOV vines were summer-pruned to initiate drying on the vine. Fruit maturity was measured prior to harvest by collecting 150 berries from each treatment, juicing and then measuring soluble solids in degrees Brix (°Brix) with a refractometer. Raisin quality was determined as percentages at "B or better" (BorB) grade, "substandard" grade (sstd.) and mold (mold). Raisin samples were submitted to the U.S. Department of Agriculture's Agricultural Marketing Service in Fresno for testing. The raisin grades were 63% B or better for WRAB DOV raisins and 36% B or better for tray-dried, a 43% improvement in grade (table 1).

Shoot thinning of WRAB DOV vines separated the fruiting and renewal areas, reduced shoot congestion and facilitated summer pruning. Shoot thinning also enhanced the development of the flower cluster primordia of retained shoots as reflected in the increase in cane fruitfulness the following year (table 2).

The cluster begins as a flower cluster primordia that forms in the bud during the preceding season. This process begins in April and continues through the summer. The early season, beginning about bloom, is a crucial period that determines whether tissue differentiates into flower clusters or into tendrils. Climate, along with the carbohydrate nutrition of the bud, plays an important role. Seasonal variation in vine fruitfulness can usually be attributed to climate conditions in May of the previous year. It can also be attributed to cultural practices during the previous year that affected light and temperature within the canopy and carbohydrate flux in the vine (Williams 2000).

In our research, shoot thinning increased fruitfulness in years when climatic conditions were less than ideal for flower cluster differentiation. We believe that the increased cane fruitfulness that resulted from shoot thinning was the effect of improved carbohydrate nutrition in the retained shoots.

TABLE 1. Quality of WRAB DOV raisins compared with other methods at same fruit maturity, summer pruning and tray harvest (8/21/2003)

Treatment	Fruit maturity	Raisin quality		
		Mold	BorB*	Sstd.†
	°Brix	.... %		
Control: standard tray-dried	18	0.10	36	11
DOV:				
Shoots thinned & positioned	18	0.30	63	5
Shoots thinned only	17	0.20	48	4
No canopy management	17	0.30	57	4
Mean separation — $LSD_{.05}$‡	ns	ns	17	ns

* BorB = B or better. USDA maturity standard for (must grade 35% or above to pass).
† Sstd = substandard. USDA standard for maturity (grades below 17.1%).
‡ $LSD_{.05}$ = least significant difference with a confidence of 95%.

Shoot positioning did not affect cane fruitfulness. However, the shoot positioning placed fruiting canes out of harm's way so that the skirt of the canopy could be hedged higher prior to summer pruning. This positioning facilitated winter pruning and tying.

Trellis expansion

Raisins will not dry on trays unless they are fully exposed to sunlight, and this puts serious constraints on the trellis design and vineyard layout. A wide trellis or narrow row-spacing results in shading of the terrace on which fruit is placed on trays to dry. To increase yields, raisin trellises have gotten a little larger over the years, but not much. Research at KREC has demonstrated that raisin yields will improve 15% to 20% with a 7-foot vertical trellis compared with a 6-foot vertical trellis (Kasimatis 1976). In addition, a small cross-arm (18 to 24 inches) can also improve yields and fruit maturity. But, if the trellis size is increased much more than that and row middles become shaded, the raisins will not dry. Because of trellis limitations imposed by tray-drying, raisin growers have not been able to capitalize on new trellis and canopy management systems. With DOV production, they now can.

In 2002, we began evaluating the effect of different trellises (vertical and "T" trellises) on 'Thompson Seedless' WRAB DOV raisin production. The trial was located at KREC in a 2.5-acre block of mature 'Thompson Seedless'. The vineyard block was originally trellised with 7-foot stakes and 1.5-foot cross-arms with two support wires, but was retrellised to accommodate this experiment. The experiment was designed as

TABLE 2. Shoot thinning WRAB DOV increases cane fruitfulness

	Total flower clusters per vine		
Treatments	2001	2002	2003
Control: standard tray-dried	39	75	42
DOV:			
Shoots thinned only	48	73	54
No canopy management	36	73	37
Mean separation — $LSD_{.05}$*	9	ns	10

* $LSD_{.05}$ = least significant difference with a confidence of 95%.

TABLE 3. WRAB DOV yields increased by expanding width of trellis (summer pruned, 8/13/03; harvested, 9/26/03)

Trellis treatment	Berry weight (8/13/03)	Soluble solids (8/13/03)	Raisin moisture (9/26/03)	Raisin quality	Raisin yield*
	g	*°Brix*	*%*	*% BorB*	*tons/acre*
Vertical & 1 wire	1.9	17.2	14.8	46	1.96
Vertical & 2 wires	1.8	17.6	14.4	40	2.06
18" cross arm & 2 wires	1.9	17.7	15.0	57	2.54
36" cross arm & 3 wires	2.0	17.5	14.3	49	2.76
48" cross arm & 4 wires	1.9	17.7	14.1	55	3.46
Mean separation — $LSD_{.05}$†	ns	ns	ns	ns	0.44

* Raisin yield adjusted to 14% moisture for comparison.
† $LSD_{.05}$ = least significant difference with a confidence of 95%.

a completely randomized block with six blocks (replications) and five treatments and using 40 vine plots. Five vines per plot were used for data collection.

All trellises utilized 7-foot stakes. Trellis treatments were: (1) vertical, one wire on top; (2) vertical, two wires (top and 14 inches below); (3) 1.5-foot cross-arm and two wires; (4) 3-foot cross-arm and three wires; and (5) 4-foot cross-arm and four wires.

Vines for all treatments were pruned to five fruiting canes per vine. Canes were tied using the WRAB DOV system. Shoots were thinned and positioned in the spring. Summer pruning occurred in mid-August. Head fruit was harvested and hung on foliage wires 7 days after summer pruning. Raisins were hand-harvested and weighed, and a subsample was collected for moisture and raisin quality measurements. Raisin yield was adjusted to 14% moisture based on the moisture content of raisin samples.

Raisin yield dramatically increased with the width of the cross-arm, and the results for 2002 and 2003 were similar. In 2003, the 1.5-foot, 3-foot and 4-foot cross-arms increased yield by 27%, 38% and 73%, respectively, compared with the vertical trellis. The vertical trellis (no cross-arm) was the least productive. The width of the cross-arm had no significant effect on berry weight, soluble solids or raisin quality. Raisin moisture was similar for all cross-arm widths (table 3). A yield increase with no lowering of fruit maturity indicates that the wider trellises increased the vine's capacity for production.

Harvesting costs and methods

WRAB DOV harvest costs were calculated for 2- and 3-ton-per-acre vineyards. This typifies the range in raisin yield across the growing region (table 4). Harvest costs for WRAB DOV are fixed on a per-acre basis; therefore, increasing yield proportionately decreases the harvest cost per ton. Tray-drying costs are fixed on a per-ton basis. For cost comparison, the harvest cost for tray-drying raisins is about $300 per ton; whereas, the WRAB DOV harvest cost per ton is $187.50 for a 2-ton-per-acre vineyard and $125 for a 3-ton-per-acre vineyard.

WRAB DOV production costs include shoot thinning and positioning to separate the fruiting and renewal sections, summer pruning, head fruit removal, machine harvest and trellis repair. The cost of summer pruning and head fruit removal varies considerably between vineyards. Summer pruning costs vary with vineyard age, vigor and vine architecture, and with how well the fruiting and renewal vine sections were separated by shoot thinning. WRAB DOV growers do not have the option of delaying summer pruning beyond late August if they are to successfully dry the raisins on the vine. Vines must be summer pruned no later than Aug. 20 in order to successfully dry raisins to 16% moisture or below (USDA moisture requirement). It takes about 6 weeks for raisins to dry to 16% moisture when vines are summer pruned in mid-August. The drying season is essentially over by mid-October.

It is important that green fruit (head fruit) be removed prior to mechanical harvest, which is a major expense. Head fruit is found behind summer-pruned canes, on spurs or on canes that were missed during the summer pruning operation. Head fruit should be harvested within 1 to 10 days of summer pruning and placed on trellis wires to dry. If head fruit is to dry on the vine successfully, it must be placed on the wire no later than Aug. 20.

TABLE 4. WRAB DOV vine preparation and harvesting costs

Vine preparation and harvest cost		Vineyard production 2 tons/acre	3 tons/acre
	$/acre	*$/ton*	*$/ton*
Shoot selection and positioning (spring)	75.00	37.50	25.00
Summer pruning	100.00	50.00	33.33
Harvest green clusters (hang on wire)	75.00	37.50	25.00
Mechanical harvest*	125.00	62.50	41.67
Trellis repair after machine harvest†	50.00	25.00	16.67
(Winter pruning credit)‡	(50.00)	(25.00)	(16.67)
Total cost§	375.00	187.50	125.00

* DOV raisins can be hand-harvested for about $75.00 per ton.
† Trellis damage resulting from mechanical harvesting varies from little to significant depending on the age and condition of trellis. We estimated repair cost at $50/acre.
‡ Winter pruning was $50 per acre less than the cost of pruning tray-dried vines.
§ Tray-drying harvest cost averages about $300 per ton.

Dried-on-the-vine raisins grade higher than paper tray-dried raisins. They also have a milder flavor, no caramelization, are rounder and have smaller wrinkles — the result of a slower drying process that is 30°F to 40°F cooler than paper trays on the ground.

We found no significant differences between yields of dried-on-vine and tray-dried raisins for each of 4 consecutive years.

Alternatively, growers can harvest head fruit and place it on trays to dry or haul it to a winery. The amount of head fruit will depend on the cultivar, the year and vineyard management practices. For 'Thompson Seedless', five to 10 clusters of head fruit per vine is typical. Growers may opt to remove head fruit as flower clusters in April, which is less expensive but also reduces yield.

Head fruit that was missed is harvested as green fruit by the mechanical harvester along with the raisins, and this increases the average raisin moisture in the bin. Equilibration is complete after a few weeks. An average of one green cluster per vine will raise the average raisin moisture in the bin by two to three percentage points. Growers can opt to hand-harvest WRAB DOV raisins rather than use a wine grape harvester. With hand-harvesting, the worker leaves the head fruit on the vine so it is much less of an issue. At KREC, we have successfully harvested WRAB DOV raisins with a variety of canopy shaker wine-grape harvesters. Our harvest cost is based on the use of a contract wine-grape harvester. Contract harvesting varies depending on location and acreage. Harvester costs would be much lower for growers who own machines.

Raisins are machine harvested much more easily and faster than wine grapes. The dry capstems of the raisins are easily detached from the rachis. DOV raisins harvest predominantly as individual raisins rather than as clusters. After rainfall, however, the capstems rehydrate and mechanical harvest is more difficult. Typically, the harvesting ground speed is about 3 miles per hour (mph) in the morning and 4 mph later in the day. Picking head and fan rotations per minute (rpm) are increased as the day goes on, and both should be evaluated every few hours and adjusted accordingly. The fans are adjusted to remove leaves and some substandard raisins. The picking head, ground speed and fan are adjusted so that harvest efficiency is maximized while damage to the trellis is kept at a minimum. Mechanically harvested raisins can be delivered directly to the packinghouse without shaking across a screen to remove sand and other debris, as is often required with tray-dried raisins.

Trellis damage caused by the machine will vary depending on age and construction material. Damage is greatest the first year of machine harvesting and then diminishes in subsequent years. We budgeted $50 per acre for trellis repair, but we also credited a $50 per acre savings in winter pruning cost.

DOV research, outreach continues

Most of the ongoing DOV research focuses on varietal development. 'Selma Pete' is a high-producing cultivar that matures 2 weeks earlier than 'Thompson Seedless'; consequently, 'Selma Pete' can be summer pruned earlier. 'Selma Pete' also dries on the vine more quickly than other DOV cultivars. These characteristics greatly enhance the probability of successful vine drying.

A 'Selma Pete' vineyard on 'Freedom' rootstock is currently being established at KREC. Row spacing and trellis designs that maximize raisin quality and production will be tested. Mechanizing summer pruning is an additional objective. Vines are bilateral, cordon-trained and cane-pruned in order to facilitate summer pruning by machine. In addition to this project, a trial has been initiated to evaluate the performance of 'Selma Pete' grafted to 'Thompson Seedless' and using WRAB DOV.

We have completed our fourth year of research and development of the system, and have extended new information to the industry through newsletters, news releases, seminars and industry meetings. Numerous field days at KREC and in growers' vineyards have introduced raisin growers to WRAB DOV. Growers are accepting the system as a way of cutting production costs, and they recognize the potential for increasing yield by expanding the trellis. In 2003, about 30,000 tons of DOV raisins were produced using this method.

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Orchard-system configurations increase efficiency, improve profits in peaches and nectarines

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Theodore M. DeJong
R. Scott Johnson

Simply put, a fruit tree can be viewed as a solar collector that converts sunlight into fruit. The more efficiently this is done, the greater the potential yield and profit. Consequently, growers face an important question when planting an orchard — what planting system to use? While varieties can be changed rather easily through grafting, the spacing, rootstock and conformation aspects of an orchard are typically permanent until that orchard is removed entirely, usually only after 15 to 20 years. These aspects can have profound effects on orchard productivity. Research conducted at the UC Kearney Research and Extension Center on orchard systems — including higher-density plantings and pruning techniques that enhance light interception — has allowed growers to make better-informed decisions when planting new orchards.

Photos: Jack Kelly Clark

Tree form and height are two key factors in determining how efficiently stone fruit orchards produce fruit and grower profitability. Kevin Day, UC Cooperative Extension tree fruit farm advisor in Tulare County, *above*, is one of the principal UC scientists involved in studying different tree systems. The Quad-V orchard shown is a popular high-density system. *Right*, the traditional "open vase" peach tree is less uniform and thus more costly to maintain.

The productivity of an orchard depends in part on how well it collects sunlight. As such, "light interception" is a function of the density, height and shape of the trees, which in turn incorporates the number, angle and orientation of their branches. These characteristics are the primary components of what is called a "planting system." The ideal orchard planting system can vary based on numerous factors, including geographic location, variety and species, soil type, rootstock, and local cultural and economic concerns. However, each system has inherent qualities that, if understood, can be used to help growers meet their goals for the orchard. UC pomologists have been studying and elucidating these planting-system characteristics at the UC Kearney Research and Extension Center (KREC) for more than 30 years, in order to help growers develop profitable and sustainable orchards.

Production in orchard systems

Since the inception of the fresh-shipping tree fruit industry shortly after the California Gold Rush (during the 1860s and 1870s) the state's dominant orchard system has been the open vase, with trees trained into a wide "cone" tree shape at relatively ample spacings within the orchard. Originally, trees were planted on wide, 22-to-25-foot spacings (70 to 90 trees per acre) in both directions to allow for easy access by horses, mules and the primitive mechanized equipment that was then available. However, such wide-spaced systems came into production slowly because the trees must grow for many years before they reach full size. One of the basic axioms of planting-system design is that a tree should fill its allotted space as quickly as possible, and having done so, be maintained easily within that space.

Growers were able to reduce spacings somewhat in the 1950s due to the introduction of chemical herbicides, which reduced and sometimes even eliminated the need for cross-cultivation. Cross-cultivation is cultivating across the rows of the orchards instead of just down the row; it was

Photos: Jack Kelly Clark

The first high-density or "hedgerow" orchard systems were introduced into the United States from Europe in the 1960s. *Top*, densities as high as 600 trees per acre were obtained with trees trained to take up less space — a single upright leader (right) or a parallel-V. Increased yield in the early life of these high-density orchards was confirmed by the first UC orchard-systems trial planted at Kearney in 1972.

Just because a tree is tall does not ensure that it is inherently more productive or intercepts light more efficiently than a shorter tree.

rendered unnecessary when herbicides were introduced that could control weeds between trees, thereby allowing growers to plant trees closer together down the row. Tree densities rose slightly to 100 to 120 trees per acre, and efficiencies improved because orchards reached full production more rapidly. Closer plantings mean that trees do not have to grow as large as those that are wide-spaced. Therefore, they can reach their ultimate "design size" more quickly, and consequently also reach full production more quickly. The trees are closer together but also smaller, so that each tree produces less on a per-tree basis but per-acre yields are usually the same.

In the 1960s, the first high-density orchard plantings were introduced to California. These were based on European hedgerow systems in which row width was reduced to 12 to 15 feet, and tree distance within each row was reduced to 6 to 12 feet, thereby increasing tree densities from about 240 to 605 trees per acre. In addition, smaller tree shapes were used, usually either upright central-leader/spindle forms (without the cone), or very upright palmette or parallel-V forms (with a much more narrow cone than the open vase). It was hoped that these high-density planting systems would increase yields — both early in the life of the orchard and at maturity. They were also expected to reduce labor costs since smaller trees mean that many orchard operations such as pruning, thinning and harvesting can be performed either mechanically or with mechanically assisted devices.

To test the hypotheses that high-density orchard plantings would increase yield and reduce labor costs, the first UC orchard-systems trial at Kearney was planted in 1972 (Gerdts et al. 1979). This trial tested four tree varieties (three peaches and one nectarine, ranging from early- to late-season in maturity) in three different training systems: the standard open vase (19-feet-by-22-feet spacing) versus two high-density systems (central leader [8-feet-by-15-feet spacing] and parallel-V [10-feet-by-15-feet spacing]). The results of this demonstration block confirmed that the high-density central-leader and parallel-V systems did indeed have greater cumulative yields than the standard open-vase system through the first 7 years of orchard life, when all the trees had matured (table 1).

Based on these encouraging results, another trial orchard was planted in 1982 (DeJong et al. 1991). This trial compared open vase to central leader and parallel-V, and also included a new type of high-density system called perpendicular-V. This new system maintained a "standard" (18 feet) row spacing but used a close (6.5 feet) spacing down the row, thereby achieving a tree density of 373 trees per acre. Equipment designed for an 18-foot row

TABLE 1. Cumulative fruit yields (1974–1978) for initial high-density planting trials at Kearney Research and Extension Center (peach and nectarine trees planted in 1972)

Variety	System*	Cumulative yield
		tons/acre
Springcrest	Central leader	42.6
	Parallel-V	44.1
	Open vase	23.7
June Lady	Central leader	54.6
	Parallel-V	46.4
	Open vase	28.0
Fantasia	Central leader	76.3
	Parallel-V	58.8
	Open vase	42.0
O'Henry	Central leader	72.3
	Parallel-V	65.5
	Open vase	38.3

* Central leader = 8'×15' spacing, 363 trees/acre; parallel-V = 1'×15' spacing, 290 trees/acre; open vase = 22'×19' spacing, 104 trees/acre.
Source: Gerdts et al. 1979.

TABLE 2. Cumulative fruit yields for four training systems, first 10 years after planting

Variety	System*	Cumulative yield
		tons/acre
Flavorcrest peach	Central leader	88.4
	Kearney-V†	110.1
	Parallel-V	96.1
	Open vase	107.4
Royal Giant nectarine	Central leader	145.9
	Kearney-V	186.4
	Parallel-V	148.9
	Open vase	169.5

* Central leader = 6.5'×18', 372 trees/acre; Kearney-V = 6.5'×18', 372 trees/acre; parallel-V = 10'×18', 242 trees/acre; open vase = 20'×18', 121 trees/acre.
† Kearney-V was originally called "perpendicular-V."
Source: DeJong et al. 1991.


Jack Kelly Clark

A trial orchard planted in 1982 introduced another alternative for high-density stone fruit orchards, the perpendicular V. This system maintained standard 18-feet row spacing but planted trees about 6 feet apart, affording the advantages of early high yields without the additional cost of new equipment for maneuvering in narrow row middles.

generally did not fit easily into a 12- to 14-foot row, often forcing growers converting to the close-row systems to purchase new equipment.

The results of this trial showed that like central leader and parallel-V, the new perpendicular-V system (later known as the Kearney-V or KAC-V) significantly improved the early yield (table 2). Most importantly, perpendicular-V allowed growers to adopt a high-density system without changing row spacings or buying new equipment.

Another benefit of this trial was the discovery of the importance of tree uniformity in orchard management. Open-vase orchards have a great deal of variation in tree shapes: the central trunk of each tree typically has three or four primary scaffolds (a major, permanent "branch" of a tree), and each of these then develops into as many as two or three secondary scaffolds, which in turn can branch into perhaps eight to 14 tertiary growing points by the time the tree reaches its ultimate height. In contrast, trees in the perpendicular-V system — where every tree is allowed to develop only two scaffolds and these are not allowed to branch — are more uniform.

Because an orchard can typically support only a given amount of fruit per acre, systems that use available light and labor most efficiently are generally most profitable. Just having more branches, scaffolds or growing points does not inherently make trees more productive. In the perpendicular-V orchard, every tree has exactly the same number of scaffolds and the variation between trees is reduced, thereby increasing the labor efficiencies. Uniformity also allows growers to better estimate, plan and develop the crop in an orchard; at the same time, every scaffold projects into the row middle, improving equipment usage and spray efficiency (Jack Dibble, UC Extension Entomologist [retired], personal communication).

Perpendicular-V was the first high-density system that was similar enough to open vase to be easily understood by growers, managers and workers. Perpendicular-V rapidly gained in popularity in the mid-1980s and soon became known as Kearney-V, or KAC-V. The system's primary drawback was tree cost, because three to four times more trees were initially planted. To address this, a variation of the Kearney-V called the Quad-V was soon developed and tested at Kearney (Day et al. 1993). In Quad-V, trees were planted slightly farther apart (9 to 10 feet) down the row and had four scaffolds instead of two. The Quad-V retained the uniformity aspects of the Kearney-V, but allowed for approximately a third fewer trees per acre — a significant savings. Both systems (with 'MayGlo' and 'Sparkling May' nectarines) quickly and efficiently filled their allotted spaces, had similar light interception (data not shown) and therefore similar yields (table 3). The Quad-V eventually became very popular.

TABLE 3. Yields in Kearney-V and Quad-V trial at Kearney Research and Extension Center (nectarine trees planted in 1990)

Variety	System*	1991	1992	1993	Total
		tons/acre			
Mayglo	Kearney-V	1.06b†	5.36ns‡	7.25a	13.67ns
	Quad-V	0.37a	5.65	7.53a	13.55
Sparkling May	Kearney-V	0.72ab	5.76	8.87ab	15.35
	Quad-V	0.37a	6.78	10.22b	17.38

* Kearney-V = 6'×18', 403 trees/acre; Quad-V = 9'×18', 269 trees/acre.
† Mean separation within columns by Duncan's multiple range test, $P \leq 0.05$.
‡ ns = not significant.
Source: Day et al. 1993.

During the 1980s and 1990s, fresh-market stone-fruit growers were most likely to use high-density systems because the quick (5 to 9 years) varietal turnover meant that fruit harvested early in the life of the orchard was of relatively greater value than that harvested toward the end of the variety's life. And while the developmental costs of high-density plantings were higher than those of standard plantings, this risk would likely be offset by the increased profit potential of these high-value commodities.

Profitability of systems explored

The aforementioned studies confirmed that high-density orchards have the potential to achieve full production earlier in their lives than standard open-vase orchards. These studies also showed that given equitable light-interception characteristics, high-density orchards are no more productive at full maturity than standard-density plantings.

However, these studies did not satisfactorily answer the growers' basic question of which system is most profitable. And as the California tree-fruit industry became more sophisticated in the closing decade of the 20th century, it was more important to focus on eco-

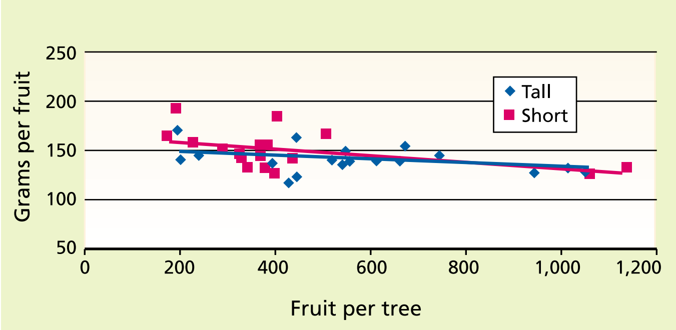

Fig. 1. Relationship between fruit size and crop load for short (limited height) and tall (standard height) 'Summer Bright' nectarine trees pruned to a Quad-V conformation.

TABLE 4. Cumulative yields and economic efficiency of four training systems of 'Ross' cling peaches after 5 years in the orchard

System*	Yield	Crop value	Costs	Profit
	tons/acre	. . . .	$	
Cordon	58.05c†	12,035	6,477	5,558
KAC-V	67.78b	14,133	5,813	8,320
HiD KAC-V	77.22a	16,149	8,125	8,024
Open vase	51.46c	10,430	4,355	6,075

* Cordon = 8'×13', 419 trees/acre; KAC-V = 6.5'×18', 372 trees/acre; HiD KAC-V = 5.5'×15', 528 trees/acre; open vase = 16'×18', 151 trees/acre.

† Mean separation within columns by Duncan's multiple range test, $P \leq 0.05$.

Source: DeJong et al. 1999.

nomics rather than on simply trying to maximize production.

Cling peaches trial. To explore the economics of orchard systems, in 1990 a replicated block of 'Ross' processing (cling) peaches was planted at Kearney (DeJong et al. 1999). This trial orchard compared four planting systems with different spacings: KAC-V (6.5 feet by 18 feet), high-density (HiD) KAC-V (5.5 feet by 15 feet), cordon (8 feet by 13 feet, and height limited to 7 feet) and open vase (16 feet by 18 feet). The HiD KAC-V system is even more closely planted than the KAC-V, with the goal of even more rapid full production. The cordon system consists of a single tall trunk, about 3 feet high; scaffolds are bent down off of the trunk in the first and second growing season and tied to a temporary support rope that is suspended down the row at a height of 4 to 5 feet. By tying the scaffolds down, earlier fruiting is induced and tree height is reduced, with the goal of maintaining a tree height in which all labor operations can be performed from the ground without a ladder. The orchard was 8 acres total, with four replications of each system in 0.5-acre experimental units. All associated costs and yields were recorded annually for the first 5 years after planting.

In this experiment, the two KAC-V systems were the most productive and profitable despite having the highest establishment, development and production costs (table 4). It is important to note, however, that this trial also vividly demonstrated that the development and initial production costs of these high-density systems were 50% to 100% greater than those of the traditional open-vase system. Due to the detailed record-keeping, this trial also provided tools that growers could use to estimate relative orchard profitability given particular price, cost and yield scenarios.

One surprising result of this study was that although the limited-height cordon system eliminated the use of ladders, this system still did not have lower per-acre labor costs. One of the primary beliefs in fruit production is that ladders add appreciably to the cost of labor since they are heavy and awkward to maneuver, and any time spent ascending or descending them is time lost for the primary tasks of pruning, thinning and harvesting. Since labor accounts for the majority of the orchard costs associated with fruit production — often $2,000 to $3,000 per acre annually — eliminating ladders should represent a potentially significant labor savings.

However, a physiological analysis of the cordon systems in this experiment indicated that potential economic efficiencies from lowering tree heights were not realized because training cordons to a horizontal position stimulated excessive vegetative growth (Grossman and DeJong 1998). This both increased pruning costs and decreased the trees' allocation of dry matter into fruit, reducing fruit yields. It became clear that if tree heights were to be reduced, it must be done in a manner that does not stimulate vegetative growth (vigor) at the expense of fruit growth.

Nectarine trial. To better understand the relationship between tree height and labor costs, a study with the KAC-V and Quad-V systems was begun at Kearney in 1995 (Day et al. 2003), with a replicated block of 'Summer Bright' nectarine trees growing as either two-leader (scaffold) KAC-Vs or four-leader Quad-Vs (6-feet-by-18-feet and 9-feet-by-18-feet spacing, respectively). Tree height was either allowed to develop to the common standard of 12 to 13 feet or limited to 8 to 9 feet, which meant that much of the hand labor could be performed without ladders. In order to get comparable planar bearing area between the two system heights, the limbs of the shorter trees were flattened by tying them to an angle of 50 degrees from horizontal, thereby achieving a shorter, flatter tree than is typical for California.

The results demonstrated that the labor costs for the short trees were an average of 20% to 30% less, depending on the activity, than those of tall trees. In addition, the yield potential was similar for short and tall trees (fig. 1), which was somewhat surprising and defied conventional wisdom. However, due to the flattened limb orientation, both systems had similar planar volumes and virtually identical light-interception characteristics, making it not unreasonable to assume that yields should be similar as well. Additional research will be necessary to explore the role of these factors in other locations and with different tree varieties.

As noted, one of the concerns associated with short trees is that of excess vigor. In this study, care was taken to ensure that the trees were not overwatered or overfertilized, and there was no problem with excessive vigor. However, this may not always be possible under all growing conditions and with all cultivars. The ultimate solution to the problem of excess vigor lies in developing adequate dwarfing root-

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California's tree fruit industry developed shortly after the Gold Rush of the mid-nineteenth century. For many years the state's dominant orchard system was the open vase, with trees trained into a wide "V" shape and ample spacing, allowing for 70 to 90 trees per acre. *Above*, long-time UC technician Jim Doyle stood next to a standard peach tree in the late 1970s.

stocks to fit a range of orchard needs such as variety, season of ripening, soil type and pH.

Maintaining competitive orchards

To remain competitive in an increasingly global market, the California fruit industry must develop orchard systems that (1) are simple and easily understood by managers and workers, (2) are of appropriate cost relative to the potential return on investment, (3) minimize reliance on ladders, which increase labor costs and (4) ensure the production of high-quality and high-value fruit.

Regimented systems such as the KAC-V and the Quad-V are quickly becoming the norm for many growers. These systems can be successfully planted without having to alter row-spacings or purchase new equipment. There is also a trend toward somewhat reduced tree heights as growers come to understand the importance of light and its relationship to tree height and form. Just because a tree is tall does not ensure that it is inherently more productive or intercepts light more efficiently than a shorter tree. Furthermore, fresh-shipping tree fruits are somewhat unique in that there is frequently an economic reward for increased quality rather than just an emphasis on total production. The Kearney research efforts have helped shape grower understanding of the relationship between potential yield and the most profitable yield.

The stone-fruit industry needs the development of a proven dwarfing rootstock that can be relied upon to ameliorate the problem of excessive vigor in short trees. Currently, growers still question whether tree heights can be dramatically reduced in a simple, effective and sustainable manner. Research at Kearney is now focusing on developing such dwarfing rootstocks, which could potentially revolutionize production in the stone-fruit industry just as they did in the apple industry (Ferree and Carlson 1987). Next, additional research will be needed to develop sensible and successful training systems that match the growth and production characteristics of trees on these dwarfing rootstocks.

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Labor costs may be reduced . . .

Research yields size-controlling rootstocks for peach production

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Photos: Jack Kelly Clark

UC Davis pomologist Ted DeJong and a team of researchers have identified three new rootstocks for peaches to limit tree size and therefore costs for pruning, thinning and harvesting. *Clockwise from top left*, the industry standard Nemaguard, P30-135, Hiawatha and K146-43 cultivars. Hiawatha is already available through commercial nurseries while the other two have been licensed by UC and USDA.

Production costs in peaches are highly dependent on the cost of labor to prune, thin and harvest trees — costs that would drop if growers had rootstocks that decreased tree size. Collaborating researchers from UC Davis and the U.S. Department of Agriculture's (USDA) Horticulture Crops Research Laboratory in Parlier screened several promising clonal, size-controlling rootstocks for California peach production. In field tests, two peach scion cultivars ('Flavorcrest' and 'Loadel') on five interspecific hybrid rootstocks yielded positive results. After 8 years in the orchard, they performed well compared with trees on 'Nemaguard' rootstock (the California standard for peaches), with reduced trunk circumferences (60% to 95%), reduced dormant (22% to 80%) and summer (40% to 80%) pruning weights, and acceptable fruit size and crop yields (54% to 98%), since smaller trees will be planted at higher densities. This project has identified three new dwarfing rootstocks with commercial potential for California peach production. One rootstock ('Hiawatha') is already available through commercial nurseries and UC and USDA have jointly licensed the two others for commercial use.

The annual production costs for peaches grown in California are heavily dependent on the costs of hand labor for pruning, fruit thinning and harvest, which is often done from ladders because of large tree sizes (DeJong et al. 1999). It is widely recognized that production costs could be substantially decreased if the size of peach trees were reduced enough to eliminate the need for ladders. Such benefits have been clearly demonstrated with apples; the availability of commercially acceptable size-controlling or "dwarfing" apple rootstocks has revolutionized that industry (Webster 2001).

Until recently, the primary factor limiting the widespread use of size-controlling rootstocks for peach (*Prunus persica* L. Batsch) production was the lack of commercially acceptable rootstocks compatible with a broad range of scion cultivars (Rom and Carlson 1987). In 1986, a rootstock screening experiment for peaches and plums was initiated at the UC Kearney Research and Extension Center (KREC). More than 120 *Prunus* genotypes from a range of genetic backgrounds were evaluated for their ability to root from hardwood cuttings, size-controlling characteristics and compatibility with peach ('O'Henry') and Japanese plum ('Santa Rosa'). At the conclusion of that experiment, we selected 19 size-controlling rootstocks as having commercial potential for California peach production. In 1996, a second trial involving the most promising eight (based on ease of propagation and consistency of tree characteristics) of those 19 rootstocks was initiated to test their growth and production characteristics under semicommercial field conditions.

Rootstock field trial

In February 1996, a rootstock field trial was established at KREC. The research block consisted of two peach scion cultivars, 'Loadel' (clingstone) and 'Flavorcrest' (freestone), June-budded onto eight experimental and two control rootstock genotypes. The rootstocks tested were Alace, Hiawatha, Sapalta (open-pollinated seedlings of Sapa, a *Prunus besseyi* × *P. salicina* hybrid), K-145-5, K-146-43, K-146-44, P-30-135 (*P. salicina* × *P. persica* hybrids), K-119-50 (*P. salicina* × *P. dulcis* hybrid) and two control rootstocks, Citation (*P. salicina*

TABLE 1. In-row tree spacing and trees/acre for KAC-V and open-vase systems in rootstock trial

	KAC-V		Open vase	
Rootstock	Tree spacing	Trees/ac (ha)	Tree spacing	Trees/ac (ha)
	feet (meters)		*feet (meters)*	
Nemaguard	6.5 (1.98)	418 (1,035)	16 (4.88)	170 (420)
P-30-135	6.5 (1.98)	418 (1,035)	16 (4.88)	170 (420)
K-119-50	6.0 (1.83)	452 (1,120)	14 (4.27)	194 (480)
Alace	6.0 (1.83)	452 (1,120)	14 (4.27)	194 (480)
Hiawatha	6.0 (1.83)	452 (1,120)	14 (4.27)	194 (480)
Sapalta	6.0 (1.83)	452 (1,120)	14 (4.27)	194 (480)
K-145-5	6.0 (1.83)	452 (1,120)	14 (4.27)	194 (480)
K-146-44	6.0 (1.83)	452 (1,120)	12 (3.66)	226 (560)
K-146-43	6.0 (1.83)	452 (1,120)	12 (3.66)	226 (560)

TABLE 2. Trunk circumferences of 'Flavorcrest' and 'Loadel' scion cultivars at the end of the seventh growing season (January 2003)

	Loadel		Flavorcrest	
Rootstock	Open vase	KAC-V	Open vase	KAC-V
	cm			
Nemaguard	62 ± 1.0*	44 ± 1.2	70 ± 0.9	50 ± 1.5
P-30-135	58 ± 0.7	41 ± 1.3	68 ± 1.2	47 ± 1.8
K-119-50	51 ± 1.0	37 ± 1.1	59 ± 1.4	41 ± 1.0
Hiawatha	50 ± 0.8	37 ± 1.0	55 ± 1.1	40 ± 1.4
K-146-44	39 ± 0.4	31 ± 0.8	47 ± 1.1	32 ± 0.7
K-146-43	40 ± 0.2	29 ± 0.8	46 ± 0.7	30 ± 0.7

* Values represent the mean (SE) of measurements of the four replications in the high-density KAC-V and standard-density open vase parts of the trial.

× *P. persica*) and Nemaguard (*P. persica* × *P. davidiana*, the California standard). In all, we planted 36 trees of each rootstock/scion combination in two different training systems. Four replications of five trees each were planted and trained to the two-scaffold KAC-V system (DeJong et al. 1994), and four replications of four trees each were planted and trained to the standard multiscaffold open-vase system (Micke et al. 1980)(see page 75). Between-row spacing was 16 feet (4.88 meters) for all rootstock/scion/training-system combinations, but in-row spacing varied according to expectations of the final tree size (table 1).

We randomized replication of the rootstock/scion combinations within training-system/scion cultivar subplots. In-row tree spacing between replications in the open-vase system was the shortest tree distance within the replications plus one-half of the spacing difference between the replications. For example, when a 'Nemaguard' replication was planted adjacent to a K-146-43 replication, the in-row spacing between replicates was 14.0 feet (4.27 meters).

The soil at the site was a well-drained Hanford fine sandy loam. The trees were flood-irrigated to maintain 100% of the potential evapotranspiration prior to harvest and about 80% after harvest. Fertilizer and pesticides were applied according to standard horticultural practices. Weeds were controlled by mowing the row middles and applying herbicides to maintain a 4.9-foot (1.5-meter) weed-free strip down the tree rows.

Trees were pruned during midsummer and during the dormant season according to standard recommendations for the two systems for each year, except in years 1, 4 and 7 when they were only dormant-pruned (DeJong et al. 1999). We adjusted the severity of pruning according to the growth characteristics of each rootstock/scion combination to optimize crop production while developing or maintaining the desired tree shape. The first significant fruit set occurred in the third leaf. We also adjusted crop load for tree size by hand-thinning to maintain a minimum spacing between fruit. Because patterns of fruit maturity varied somewhat with rootstock, fruit were harvested in several picks but the data were combined from all harvests to calculate the mean fruit yield. We also recorded data on crop load (fruit per tree and fruit size) but do not report it here.

The objectives of this research were to find rootstock-scion combinations with reduced trunk size, reduced pruning weights and acceptable fruit size and crop yields. *Above*, the clingstone Loadel scion grafted onto rootstock K146-43 was one of the more successful combinations in a trial orchard, producing a tree circumference 61% of current industry standard, Nemaguard.

Rootstock-related differences

Rootstock-related differences in tree size and vigor were apparent after the first year of field growth. As expected, 'Nemaguard' was clearly the most vigorous rootstock, followed in descending order by K-119-50, P-30-135, Hiawatha, K-145-5, Alace, Sapalta, K-146-43, K-146-44 and Citation. However, in the fall of the first year in the field, several trees of the Citation, K-145-5, Alace and Sapalta rootstocks appeared unhealthy, with premature leaf fall and leaf "boating" and "bronzing." During the subsequent spring several of these trees died while others appeared to recover. But by the following fall, more trees became unhealthy and died. As a consequence, these scion/rootstock combinations were eliminated from the formal experiment and we collected no further data on them. This paper therefore only reports data from the remaining six rootstocks in the trial (Nemaguard, K-119-50, P-30-135, Hiawatha, K-146-43 and K-146-44).

Trunk circumference. After 7 years in the orchard, overall tree size, as indicated by trunk circumference, was consistently decreased across all scion/training-system combinations by each size-controlling rootstock (table 2). The trees on the two most size-controlling rootstocks (K-146-43 and K-146-44) had trunk circumferences that were 61% to 72% of the trees on 'Nemaguard', while mean trunk circumferences of the oth-

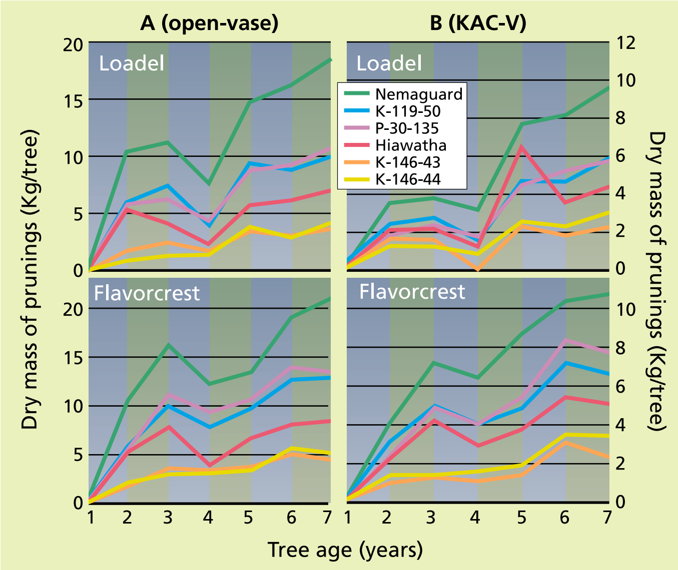

Fig. 1. Comparisons of pruning weights (summer and dormant season combined) for 'Loadel' and 'Flavorcrest' peach trees on six different rootstocks during the first 7 years in the orchard, in (A) open-vase and (B) KAC-V training systems.

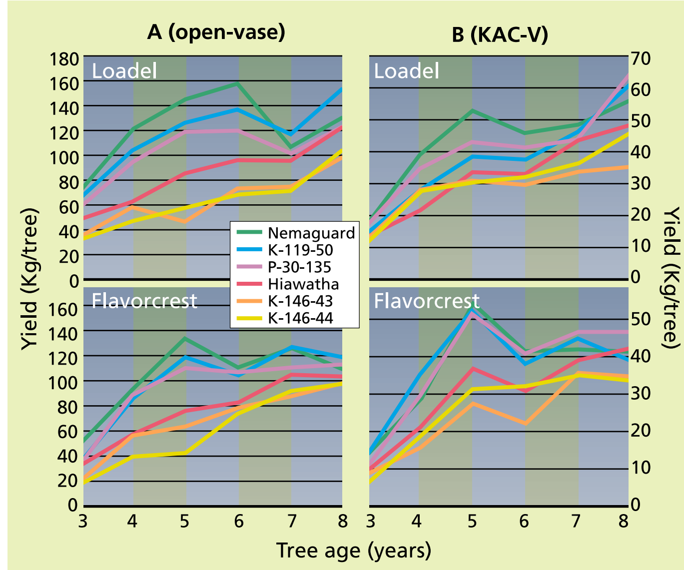

Fig. 2. Fruit yields (fresh weight) for 'Loadel' and 'Flavorcrest' peach trees on six different rootstocks in years 3 through 8 in the orchard, in (A) open-vase and (B) KAC-V training systems.

ers ranged from 76% of 95% of trees on 'Nemaguard'.

Pruning weights. Because of the differences in size and vigor, we pruned the trees to maintain the optimum fruiting potential for each scion/rootstock/training-system combination. Although there were yearly variations in the amount of brush pruned from each combination, the effectiveness of each rootstock in reducing vegetative growth — compared with trees on 'Nemaguard' — was apparent when the annual pruning weights were plotted for each rootstock/scion/training-system combination over the 7 years of the trial (fig. 1).

The effectiveness of the size-controlling rootstocks for reducing the amount of dry matter that needed to be removed during pruning relative to trees on the vigorous control ('Nemaguard') was greater in the larger open-vase trees than the higher density KAC-V system. Similarly, the effects of the size-controlling rootstocks on reductions in pruning weights were greater with the more vigorous scion cultivar ('Flavorcrest', an early fresh-market peach) compared with the weaker one ('Loadel', an early processing clingstone peach). Perhaps the most interesting aspect of this data was the relatively large reductions in cumulative pruning weights with the size-controlling rootstocks over the seventh year of pruning compared with the more modest differences in trunk circumference, which is also a cumulative measurement. For example, the cumulative pruning weights for trees on K-146-44 over 7 years were 17%, 23%, 32% and 26% of trees on 'Nemaguard' for 'Loadel'/KAC-V, 'Flavorcrest'/KAC-V, 'Loadel'/vase and 'Flavorcrest'/vase, respectively, while differences in trunk circumferences ranged from 61% to 72% of trees on 'Nemaguard'. Similarly, cumulative pruning weights for trees on P-30-135 ranged from 57% to 70% of trees on 'Nemaguard', while trunk circumferences on the same rootstock ranged from 92% to 95% of trees on 'Nemaguard'.

Yields and tree size

The patterns of tree yield during years 3 through 8 in the orchard followed patterns of relative tree size in each combination (fig. 2). Trees on the more-size-controlling rootstocks appeared to reach full yield potential at about the same time as trees on the more vigorous rootstocks in the higher density KAC-V system. However, they lagged behind the vigorous rootstocks in the open-vase systems. As a result, it was difficult to judge the final relative yield potentials of the various rootstock/scion combinations in each system, other than to note that annual as well as cumulative crop yields per tree on the size-controlling rootstocks ranged from 54% to 98% of 'Nemaguard'. Crop yields of 'Flavorcrest' peaches on the K-119-50 and P-30-135 rootstocks tended to be more similar to those on 'Nemaguard' than for 'Loadel' peaches with the same rootstocks. Although no fruit-size data is presented here, mean fruit sizes among the three most vigorous cultivars were very similar, but the three more-size-controlling cultivars tended to have somewhat smaller mean fruit sizes. At this time, it is not clear if the fruit size trends are a real function of the rootstock or the result of the fruit thinners' tendency to leave more fruit on the smaller trees relative to the size of the trees.

The relatively high variability in yield from year to year after the first couple of years was due to variability in pruning and fruit-thinning practices as well as the biological variability inherent in the combinations tested. However, general trends in the data indicate that the size-controlling rootstocks have the potential to increase the partitioning of dry matter to fruit, relative to vegetative growth. If training systems and tree densities can be adjusted so that the total annual accumulation of dry matter in an orchard is comparable to what is currently achieved with trees on

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'Nemaguard', it should be possible to maintain or increase crop yields with smaller trees using these size-controlling rootstocks.

Intensive studies of the growth characteristics of trees on the various rootstocks indicate that the primary differences between the scions on the size-controlling rootstocks and trees on 'Nemaguard' are related to shoot internode length and shoot extension growth rate (Weibel et al. 2002). Furthermore, these factors appear to be related to differences in diurnal patterns of stem water-potential (Basile et al. 2003), root hydraulic conductance (Basile, Solari, et al. 2003) and the dormant-season starch storage capacity of the various rootstocks (Solari and DeJong, unpublished data).

Commercial applications

Three rootstocks from this trial are currently being recommended for commercial use as size-controlling rootstocks for California peach and nectarine production. 'Hiawatha' is a public domain cultivar and is already being commercially propagated. K-146-43 and P-30-135 are being licensed jointly by UC and USDA for commercial use and will be marketed as "CONTROLLER 5" and "CONTROLLER 9," respectively. These are anticipated to be the first in a series of size-controlling peach rootstocks developed at KREC that will eventually be made available to California growers to reduce labor costs and improve the production efficiency of California peach orchards.

It is widely recognized that production costs could be substantially decreased if the size of peach trees were reduced enough to eliminate the need for ladders.

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Methyl bromide alternatives . . .

Soil solarization provides weed control for limited-resource and organic growers in warmer climates

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Richard H. Molinar
Kris Lynn-Patterson
Stuart K. McFeeters
Anil Shrestha

Jack Kelly Clark

Soil solarization is a "perfect fit" for small-scale specialty crop growers like Ong Lee Yang (right), according to Richard Molinar, Fresno County small farms advisor (middle). Central Valley strawberry growers can take advantage of hot summers to tarp their fields in July and August between production cycles. Interpreting for the Hmong farmer is Michael Yang (left), a UC small farms program representative.

Organic farmers and limited-resource growers in the San Joaquin Valley and other agricultural areas in California — many of whom are ethnic minorities — encounter limited options and environmental constraints when seeking economically viable pest management methods. Over the past 8 years, we have conducted weed research and implementation projects on soil solarization at the UC Kearney Research and Extension Center and on farms in the surrounding San Joaquin Valley. In the Kearney studies, small-scale solarization in parsley reduced weed biomass 94% to 99% over the untreated control. Furthermore, in an on-farm study, solarization provided effective weed control for strawberries at a much lower cost than methyl bromide, with comparable yields. This research has provided guidelines and technical support for growers wishing to implement solarization and related techniques for nonchemical soil disinfestation in a wide variety of specialty crops.

More than 80% of California farms are small family operations, making less than $250,000 in annual gross income, according to the U.S. Department of Agriculture's definition. Of these, 85% gross less than $100,000 annually. Classified as limited-resource farms, these comprise 72% of all California farms. To survive economically, small farms must depend on high-value specialty crops, specialized marketing programs or specific market windows. In many San Joaquin Valley counties, minorities, including Asians, Latinos, blacks, American Indians and others, operate almost 50% of the small farms. Fresno County's farmers are more diverse than those in any other California county, with a large proportion of Asian and Latino farmers. The Asian farmers are primarily Hmong, Lao and other groups that have emigrated to the United States since 1979. Although the total number of small farms in California decreased by 9.5% between 1997 and 2002, the number of minority farm operators increased by 52% (USDA 2004), with the largest proportional increases in Latinos (65%) and American Indians (70%).

Although only about 2.5% of all California small farms are registered organic, statewide farmland in production for the organic market totals more than 175,000 acres (CDFA 2002). Limited-resource growers and organic farmers in the San Joaquin Valley and other agricultural areas confront limited choices and environmental constraints when seeking economically viable pest management options. Many specialty crops have few labeled pesticides, due to the high development and support costs and low returns for the manufacturers. Organic growers are at an additional disadvantage due to the restrictions on pesticides allowable under organic certification programs. Also, many of the farms are located at the urban-agricultural interface, and the use of pesticides and fumigants is further restricted in fields close to occupied buildings. In general, weed management is the most pervasive problem for San Joaquin Valley specialty crop and organic growers.

Strawberries have been an important specialty crop for San Joaquin Valley small farmers, with the majority of the acreage located in Fresno and Merced counties. The Fresno County Agricultural Commissioner reported 137 acres of strawberries worth nearly

All of the solarization treatments were equally effective in providing weed management, with weed numbers reduced by 86% to 94% and weed biomass reduced by 94% to 99% over the untreated control.

$1.5 million in 2002, albeit less than 1% of the statewide total. The cultivation of strawberries in the San Joaquin and Sacramento valleys is quite different from that of the major strawberry production areas along the California coast, with a short, split, fall-spring harvest season and most fruit destined for processing and roadside sales, rather than fresh-market shipping. Most San Joaquin Valley strawberry farmers are Hmong immigrants who produce much of the crop at the urban-agricultural interface, often on rented land in close proximity to occupied buildings.

Historically, most strawberry fields in the San Joaquin Valley are fumigated every 2 to 3 years, depending on weed pressure and the availability of funds, while coastal plantings are usually fumigated every year. However, many of the strawberry fields in the San Joaquin Valley are close to shopping centers and residential homes, so growers may find fumigation impractical. Pesticide regulations require that growers maintain buffer zones between fumigation areas and occupied dwellings (Carter et al. 2005).

Also, while most fumigations in the past were done with methyl bromide/chloropicrin, the regulatory phase-out of methyl bromide has increased the cost of the remaining supply to the point of being prohibitive. In 2003, many San Joaquin Valley strawberry fields were fumigated with metam sodium, a moderately effective alternative fumigant that is significantly less expensive than methyl bromide (Richard Molinar, UC Farm Advisor, personal communication).

An alternative to chemical fumigation is soil solarization, a hydrothermal soil-disinfestation process that utilizes clear plastic mulch to trap solar radiation in moist soil. Solarization during the hot summer months can increase soil temperatures to levels that can kill soilborne disease, nematodes and weeds (Elmore et al. 1993). As with methyl bromide, plants often grow faster and produce higher yields when grown in solarized soil, as a result of weed and disease control, the increased solubility of nutrients, and changes in the microbial composition of the soil (Stapleton, Elmore, et al. 2000). Soil solarization can be a safe and effective method for controlling soil pests, and its effectiveness can be improved by combining it with other treatments such as fertilizers, cruciferous crops and other chemical treatments including metam sodium.

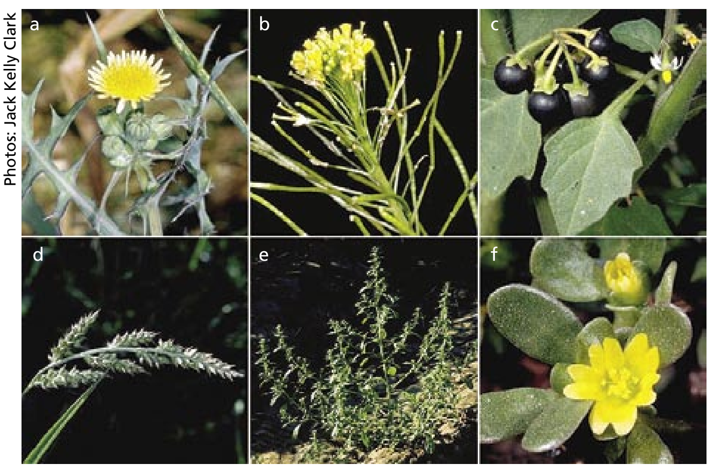
In this report, we describe solarization technology for weed management. This project, conducted at the UC Kearney Research and Extension Center (KREC) over the past 8 years, consisted of laboratory development, small-plot experimentation and on-farm validation of data in San Joaquin Valley specialty crops.

Preliminary laboratory studies

As a first step, earlier laboratory work done at KREC from 1997 to 1999 developed threshold treatment dosages for estimating weed management by soil heating (Stapleton, Prather, et al. 2000). In a series of experiments, we subjected the seed of six important weed species — barnyardgrass *(Echinochloa crus-galli)*, London rocket *(Sisymbrium irio)*, common purslane *(Portulaca oleracea)*, black nightshade *(Solanum nigrum)*, annual sowthistle *(Sonchus oleraceus)* and tumble pigweed *(Amaranthus albus)* — to timed heat treatments at 102, 108, 114, 122, 140 and 158°F (39, 42, 46, 50, 60 and 70°C). The weed species were selected to represent a range of thermal sensitivities and summer versus winter growing habits. Percentages of viability were determined 14 days after removal from the heat treatments.

At 158°F (70°C), the seeds of all species were dead within 20 minutes, and at

Photos: Jack Kelly Clark



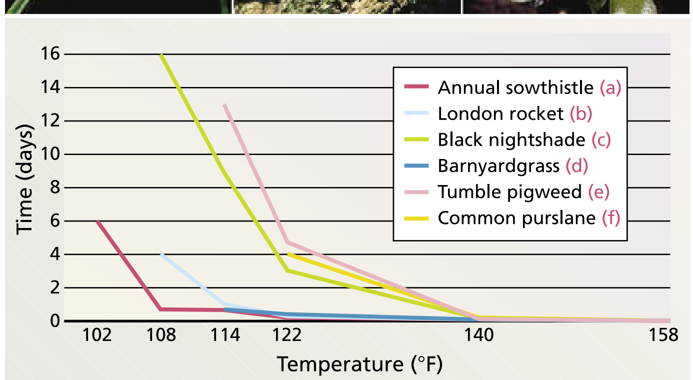


Fig. 1. Estimated lower threshold temperatures and times for isothermal inactivation of seed of six weed species from laboratory experiments (adapted from Stapleton, Prather, et al. 2000).

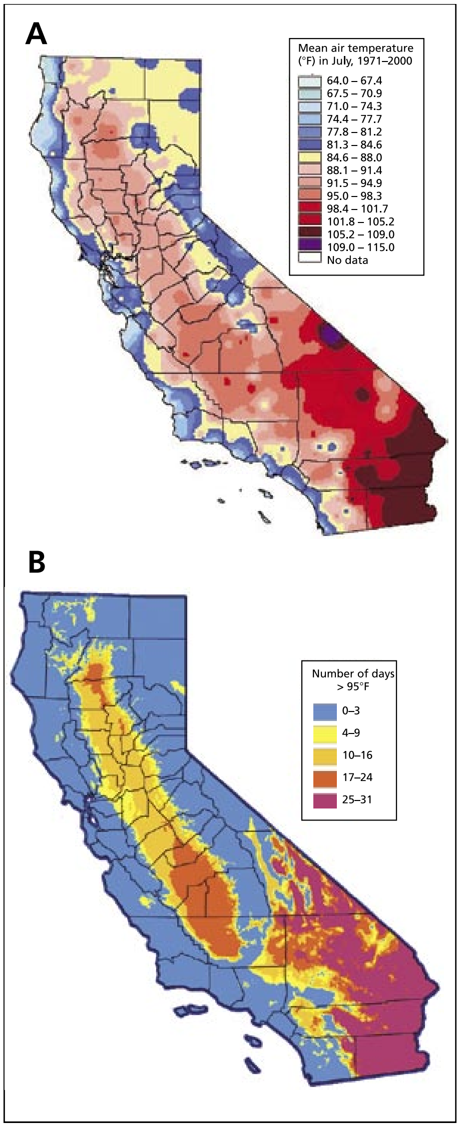


Fig. 2. Air-temperature maps of California in July, showing (A) mean daily maxima (30-year average); and (B) mean number of days in the month with maxima greater than or equal to 95°F (10-year average). Raw data source: National Climatic Center, NOAA.

One of the challenges facing many small-scale farmers in California is their close proximity to urban areas. This strawberry field is adjacent to a baseball field at Sunnyside High School in Fresno. Solarization affords a safe, nonchemical alternative for dealing with certain pest problems.

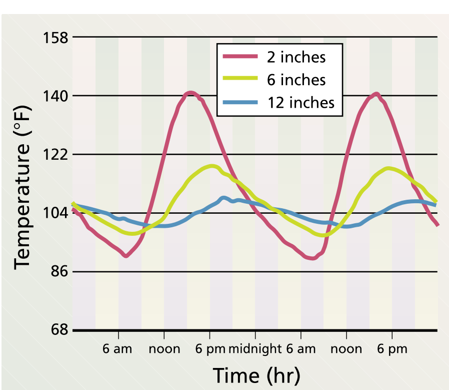


Fig. 3. Typical diurnal soil-temperature curves during solarization in the San Joaquin Valley, at three depths.

140°F (60°C) all species were dead within 3 hours. At 122°F (50°C), complete seed destruction occurred between 4 hours (annual sowthistle) and 4.7 days (tumble pigweed). At 114°F (46°C), thermal death occurred at a range of 15 hours (annual sowthistle) to 13 days (tumble pigweed). At 108°F (42°C), barnyardgrass, tumble pigweed and common purslane germinated inside the jars during the heat treatment. Barnyardgrass, tumble pigweed and common purslane were not studied at 102°F (39°C), since 108°F (42°C) had no effect on their viability (fig. 1). Additionally, the portion of this laboratory study conducted at 140°F (60°C) and 158°F (70°C) was used to assist in developing guidelines for the weed disinfestation of container nursery soil using a specialized solarization technique (Stapleton et al. 2002).

Developing guidelines using GIS

Solarization is a knowledge-based, rather than product-based soil disinfestation method. As such, end users are largely without the benefit and availability of the trained consultants and product support personnel associated with chemical pesticides. Many growers, pest control advisors and gardeners are often unsure as to the suitability of solarization for their particular geographic locations. To facilitate decision-making, we collaborated with the Kearney Agricultural Center (KAC) Geographic Information Systems (GIS) unit to create statewide air-temperature maps, using historical temperature databases obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center. These maps include both monthly air-temperature maxima (fig. 2A), and mean number of days warmer than minimum thresholds (a 95°F [35°C] minimum is depicted in fig. 2B), which can be accessed (www.uckac.edu/iwgss) by users who wish to estimate the suitability of their area for solarization.

Within the next few months, soil temperature models will be added to the Web site, to provide additional decision support for users (fig. 3). At the present time, however, users should conduct tests with soil thermometers or other temperature-sensing equipment to assess the potential for using solarization on their own land and for their particular climatic niches.

Small-plot field studies

Several small-plot studies were conducted at KREC to support the weed-seed inactivation studies conducted in

TABLE 1. Effects of solarization treatments on weed management and marketable yield of parsley foliage

Treatment*	Weed control			Parsley yield
	Number	Dry wt.	Weeding rate	Fresh wt.
	No./0.25 m²	*g/0.25 m²*	*Person-min./2 m row*	*kg/2 m row*
A	8.0a†	8.7a	0.4a	1.3b
B	17.3a	8.6a	0.5a	1.1b
C	14.7a	43.1a	0.4a	1.6b
D	16.0a	19.6a	0.3a	1.2b
E	18.7a	19.1a	0.6a	1.9b
F	13.3a	30.6a	0.2a	2.9a
G	12.0a	30.9a	0.7a	1.0bc
Untreated control	133.3b	721.5b	8.7b	0.1c

* A = 1 mil polyethylene on 40-inch bed, buried-drip irrigation; B = 0.6 mil high-density monolayer + UV inhibitor on bed, buried drip; C = 1.4 mil nylon five-layer virtually impermeable film on bed, buried drip; D = 1 mil polyethylene, on multiple bed (three), buried drip; E = 1 mil polyethylene on flat ground, left flat, buried drip; F = 1 mil polyethylene on flat ground, beds formed after treatment; G = 1 mil polyethylene on bed, surface drip.

† Values followed by different letters are statistically different (LSD test; $P < 0.05$).

Solarization is an effective tool against many shallowly distributed soilborne nematodes and diseases such as Verticillium wilt, as well as most weeds. The $150 to $300 per acre cost for a row application, *above*, is much cheaper than methyl bromide fumigation.

the laboratory. In the study described here from the 2003-2004 growing season, variations of solarization techniques (three plastic formulations; single bed, multiple bed and flat ground application; surface versus subsurface drip irrigation) were compared in a randomized complete block design to an untreated control for weed management efficacy and effects on yield of parsley (*Petroselinum crispum* cv. Italian dark-green plain leaf).

Beds, where used, were formed and shaped on 40-inch centers in an east-west orientation on the Hanford fine sandy loam soil. Three replications of each of the eight treatments were done, and soil temperatures were continuously monitored in one replication of each treatment. Each replication was three beds wide by 30 feet long. Plastic was laid on July 9, 2003, irrigated via the surface or subsurface drip systems, and removed on Sept. 4. Following plastic removal, parsley was planted on Oct. 2. A 6.6-foot (2-meter) row length of each replication was subjected to timed hand-weeding on Jan. 23, 2004. Additionally, subsamples (2.7 square feet = 0.25 square-meter quadrats) of emergent weeds from each plot were counted and separated by species on Feb. 19. To assess the effects of treatments on the yield of parsley foliage, two cuttings were made on Feb. 12 and March 22.

At the time of the initial evaluation on Jan. 23, 2004, *Conyza* sp., henbit *(Lamium amplexicaule)*, swinecress *(Coronopus didymus)*, redmaids *(Calandrinia ciliata)*, groundsel *(Senecio vulgaris)* and annual bluegrass *(Poa annua)* were the most numerous of the emergent weeds, and redmaids and common chickweed *(Stellaria media)* comprised the bulk of the weed biomass. Results showed that all of the solarization treatments were equally effective in providing weed management ($P < 0.05$), with weed numbers reduced by 86% to 94%, and weed biomass reduced by 94% to 99%, as compared with the untreated controls (table 1). Similarly, the timed hand-weeding showed that all of the solarization treatments reduced the labor time necessary to maintain commercial weed control in the plots by 92% to 97%.

This data clearly demonstrated that for specialty and organic crops grown in the San Joaquin Valley where chemical herbicides are not available or allowable, solarization can provide excellent control of winter weeds. In terms of the yield of the parsley foliage, the untreated control was so choked with weed growth that little parsley could be harvested. In a commercial situation, the field would have been abandoned with weed growth this extensive. All of the plots receiving solarization treatments provided an economic yield of parsley foliage, ranging from 6.7-fold to more than 20-fold increases over the untreated control. Yields from each of the solarization treatments were significantly different from the untreated control, except the one testing surface drip rather than subsurface drip irrigation (table 1).

On-farm comparisons near Fresno

To test and compare the herbicidal and strawberry fruit yield effects of solarization and standard soil fumigants under commercial field conditions, two on-farm field experiments were conducted in the Fresno-Clovis area of the San Joaquin Valley from 1997 to 1999. Field histories and pre-experiment soil assays confirmed that weeds were the only major soilborne pest problem of concern. The first experiment (A) was located in the midst of an urbanized area, with residential housing less than 100 feet from the edge of the field, and was in the third year since the previous fumigation using methyl bromide. Plot design was a randomized complete block with three replications. Each replicate consisted of three beds (double-row planted) on 54-inch centers, 130 feet long. Bed orientation was north-south, and soil type was Greenfield coarse sandy loam.

The preplant soil-disinfestation treatments included: (1) methyl bromide/chloropicrin (applied by a commercial applicator on July 30, 1997, using an 80/20 mixture at 300 pounds per acre plus plastic tarps left on 2 weeks); (2) methyl bromide/chloropicrin as above plus plastic left on only 5 days; (3) solarization with clear plastic for 4 weeks (July 26 to Aug. 26); (4) metam sodium (Vapam, 42% a.i.) at 40 gallons per acre (applied via drip irrigation as a bed treatment; application rate expressed as the broadcast rate injected through drip lines on Aug.

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In 2002, more than 65 "minor" or specialty vegetable and fruit crops worth more than $75 million were grown on 17,000 acres in Fresno County. Among the producers of those crops is Will Scott, Jr. (left) and his brother Melvin (on tractor), who grow turnips, peanuts, squash and other crops, and truck them to Oakland for sale at a local farmers market. Scott is working with Cooperative Extension in field trials to demonstrate solarization to fellow members of the African American Farmers Organization he helped found.

TABLE 2. Effects of soil solarization and fumigation treatments on weed management and marketable yield of strawberry, Clovis

Treatment*	Weed control: Weeding rate	Weed control: Weed density	Strawberry yield: Marketable fresh wt.
	Person-min./40 row ft.	*number/m²*	*kg/40 row ft.*
Experiment A			
Metam sodium + solarized	7.6a†	nd‡	42.0
Solarized	8.9a	nd	41.7
MBC (+ 14-day solarized)	12.9a	nd	40.6
MBC (+ 5-day solarized)	13.4a	nd	43.9
Metam sodium	14.1a	nd	40.5
Untreated control	26.9b	nd	30.9
Experiment B§			*kg/30 row ft.*
Solarized (+ mulch)	nd	2.5a	36.5a
Metam sodium	nd	2.0a	32.8ab
Solarized (– mulch)	nd	1.3a	29.7b
Metam sodium + solarized	nd	1.3a	28.4bc
Untreated control	nd	41.5b	23.5c

* MBC = 80/20 methyl bromide/chloropicrin at 300 lb. per acre; solarized = solarization for 4 weeks (July 26–Aug. 26); metam sodium = Vapam (42% a.i. @ 40 gal./acre).

† Values followed by different letters are statistically different (LSD test; $P < 0.05$).

‡ nd = no data collected.

§ Solarized = solarization for 4 weeks (Aug. 19–Sept. 18).

12) plus solarization for 4 weeks; (5) metam sodium plus plastic left on only 48 hours; and (6) the untreated control. Soil moisture was applied by preirrigation. Strawberry (*Fragaria × ananassa* cv. Chandler) plants were set out on Aug. 28 and drip-irrigated. Plant spacing down the row was 12 inches, and a standard fertilizer and insect management program was followed according to the grower's preferences. Yields were taken from 40-foot lengths of the middle beds only.

The second experiment (B) also was located in a residential area, on Ramona sandy loam soil. The site had been fumigated with methyl bromide/chloropicrin one season earlier. Bed spacing was 54 inches from center to center, and treatment plots were 30 feet long. Again, the plot was laid out as a randomized complete block, but with four replications of each treatment. Treatments were the same as in experiment A, except that methyl bromide/chloropicrin fumigation was not included, and single-bed replications were used. Soil in planting beds was solarized for 4 weeks later in the year than in experiment A (Aug. 19 to Sept. 18, 1998) using clear, 1-mil (0.025 mm) polyethylene film. Metam sodium (Vapam; 42% a.i.) was applied in the same way as in experiment A. The film was left on the ground and plants transplanted through it after solarization in one of the treatments. Following the soil disinfestation treatments, 'Chandler' strawberry plants were set out on Sept. 18 at an in-row spacing of 12 inches, two rows per bed, and the fertilization and insect management practices of the grower were followed. Soil temperatures were monitored in both experiments, and the data collected included weed management parameters and marketable berry yields.

Weeding costs, person hours

Experiment A. All plots in experiment A were hand-weeded on four different dates (Oct. 6 and Nov. 10, 1997; Jan. 23 and Feb. 17, 1998), based on the weediness of the untreated control, which was moderate at the time of each weeding. The time taken to hand-weed a 40-foot-long strip of each replication was recorded and totaled. All treatments required 48% to 72% ($P < 0.01$) less time to weed than the untreated control (table 2). None of the costs for solarization and/or chemical fumigant treatment were different from each other. When the hand-weeding labor cost, estimated at $7.90 per hour, was extrapolated to an entire field, use of the soil disinfestation treatments would have saved the grower $127 (metam sodium alone) to $190 (metam sodium plus solarization) per acre, compared to the control.

The same weeds that were comparatively resistant to chemical fumigation (cheeseweed [*Malva parvifolia*], burclover [*Medicago* sp.], Spanish clover [*Lotus purshianus*], red and white stem filaree [*Erodium* sp.] and birdsfoot trefoil [*Lotus corniculata*]) also were more tolerant of solarization. The weeds in the untreated control were much more variable, and included the above weeds plus shepherdspurse *(Capsella bursa-pastoris)*, cudweed *(Gnaphalium* sp.*)*, common chickweed, panicled willow herb *(Epilobium brachycarpum)*, London rocket, annual bluegrass, puncturevine *(Tribulus terrestris)*, prickly lettuce *(Lactuca serriola)* and crabgrass *(Digitaria* sp.*)*.

Experiment B. As only a single season had passed after the previous soil fumigation with methyl bromide, weed growth was relatively light in experiment B, even in the untreated controls. For this reason, timed hand-weedings were not made, and weediness in the experimental plots was expressed as the number of weeds per 30 feet of bed row. As with the previous experiments, all soil disinfestation treatments provided better weed control than the untreated control, but none of them differed significantly from each other (table 2).

The predominant weeds were subjected to analysis of variance separately. Results showed that the control of cheeseweed was improved by all soil disinfestation treatments by about 50% over the control. All other annual weeds, including yellow blossom sweetclover *(Melilotus officinalis)*, chickweed, annual bluegrass, shepherdspurse, crabgrass and spotted spurge *(Euphorbia maculata)*, were reduced by nearly 100% by the various treatments. None of the treatments provided satisfactory control of yellow nutsedge *(Cyperus esculentus)*.

Marketable yield of strawberries

Experiment A. Yield data was taken twice weekly for 12 weeks in experiment A, 3 weeks during the short fall season, then 9 weeks in the spring. As the harvest data was collected, it became apparent that as air temperatures increased in late May and June, production dropped off and the differences in yield among the different soil treatments became less marked and more variable. Over the entire season, increases in marketable yields from the soil treatments ranged from 32% to 42% ($P < 0.08$), as compared with the untreated control. As with the weed management data, no differences among the five solarization or fumigation treatments were found. Apart from weed growth, the only apparent pest problem during strawberry production was root damage caused by the feeding of *Hoplia callipyge* beetle grubs, which occurred in the untreated control plots only. Care was taken during harvest to select strips from untreated control plots that were not affected by the insect-feeding damage.

Experiment B. Berries were harvested twice weekly for 11 harvests in experiment B. Total yield per plot was taken and culls separated out for marketable yields. As opposed to experiment A, significant differences in yield ($P < 0.05$) were observed among some of the treatments (table 2). Soil disinfestation treatments increased berry yields 21% to 55% over the untreated control. Solarization with the plastic film left in place as a mulch during plant growth resulted in the highest marketable berry yield.

However, yields following metam sodium application plus solarization were not different from the untreated control (table 2). Most of the higher yields resulted from the first five harvests. The yield results are somewhat different from those of experiment A, and may have resulted from the solarization process starting about 4 weeks later in the year and resulting in fewer solarization heat units. In addition, the harvest season was terminated at least a week early because of an unseasonable hailstorm in June.

Benefits to users

The results of the KREC field study with parsley, along with the two on-farm experiments with strawberry, showed that solarization is an efficacious weed control option for fall/spring specialty and organic crops in the San Joaquin Valley. Also, there are economic advantages to using solarization: the $150 to $300 per acre cost of using solarization (row application) is much cheaper than methyl bromide fumigation. End users should be aware that certain weeds, such as yellow and purple nutsedge *(C. rotundus)*, are not consistently controlled by solarization.

The advantages of solarization include ease of use by the grower, relatively low treatment costs, and no hazards to the grower, workers or public, which is important at the urban-agricultural interface. Solarization is acceptable for use in organic production, and no permits or pesticide reporting is required. As an option, the film can be kept in place after treatment as a bed mulch to improve the cost/benefit ratio.

On the other hand, disadvantages include the unavailability of land for 3 to 4 weeks during the summer, and maintenance of the plastic (patching holes when necessary). Solarization must be timed soon after the spring harvest is completed but before planting for the next crop. Furthermore, little expert consultation is available (as opposed to chemical pesticide representatives). Combining solarization with chemical fumigants such as metam sodium is another attractive option for commercial users, but may be no more effective and cost more than solarization alone.

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Mulches reduce aphid-borne viruses and whiteflies in cantaloupe

Charles G. Summers
Jeffrey P. Mitchell
James J. Stapleton

We compared reflective plastic and wheat straw mulches with conventional bare soil for managing aphid-borne virus diseases and silverleaf whitefly in cantaloupe. The occurrence of aphid-borne virus diseases was significantly reduced with both mulches as opposed to bare soil, and reflective plastic performed better than wheat straw. Silverleaf whitefly numbers, both adults and nymphs, were reduced equally by plastic mulch and wheat straw, and were significantly lower than with bare soil. Reflective plastic produced mature melons sooner and more cartons per acre than the other production systems. The reflective plastic system also produced a greater number of large-size melons, which are favored in the late-season market. Plants grown over straw mulch produced higher overall yields, including large-size melons, than those grown over bare soil.

Aphid-borne viruses and silverleaf whitefly can completely devastate cantaloupe crops, causing serious economic losses to growers. The California Melon Research Advisory Board (2003) lists the management and control of aphid-borne viruses and whitefly as a top pest-management research priority. At the UC Kearney Research and Extension Center (KREC), we studied the use of reflective plastic mulch and straw mulch to manage aphid-borne viruses and silverleaf whitefly in cantaloupes without the use of pesticides.

Late-season cantaloupes are grown on approximately 5,000 acres on the West Side of the San Joaquin Valley (John LeBoeuf, Pest Control Advisor, California Melon Research Advisory Board, personal communication). While susceptible to a number of diseases and insect pests, by far the most important problem over the past several years has been the complex of aphid-borne viruses, primarily cucumber mosaic virus (CMV), watermelon mosaic virus (WMV) and zucchini yellow mosaic virus (ZYMV), which vary in severity by season (Hartz et al. 1996). Disease severity increases as the growing season progresses, and fall is the worst time of the year for all of the viruses. The viruses kill and stunt plants, reducing yield.

These diseases are transmitted by several aphid species (Kennedy et al. 1962) that are commonly found in the San Joaquin Valley, and they are characterized by leaf symptoms including severe distortion (crinkled, puckered and misshapen), yellowing, and light- and dark-green mottling (mosaic symptoms). These viruses may occur singly or in combination and can only be distinguished from each other serologically. We did not attempt to distinguish between the viruses in this study.

Recently, the silverleaf whitefly (*Bemisia argentifolii* Bellows and Perring) has emerged as a serious late-season pest, resulting in a 13% decrease in cantaloupe acreage in Fresno County (Jetter et al. 2001). Whiteflies damage cantaloupe by sucking the juices out of the plants, which can kill young plants and severely stunt older ones, resulting in almost no fruit set. While silverleaf whitefly transmits a number of viruses (Gemini viruses) in other parts of the United States, no whitefly-borne viruses have been found so far in California.

Currently, there are no cantaloupe varieties resistant to the aphid-borne viruses (CMRAB 2003). In addition, insecticides offer little relief because the viruses are acquired by the aphids and transmitted to the plants within seconds, long before the aphid vector acquires a lethal dose of insecticide

Jack Kelly Clark

Kearney-based entomologist Charlie Summers, *left*, has been studying the use of mulches to limit damage to melons from silverleaf whitefly and virus-carrying aphids. Reflective plastic mulch with a lattice network cut down the center, *right*, can be applied following machine-planting. The plants emerge through the holes in the lattice network.

Reflective mulch, *top*, is made from a thin coat of aluminum adhering to a sheet of polyethylene. Unlike black or clear plastic mulches, UV light is reflected back into the sky and canopy, repelling insects and boosting plant growth. Wheat straw mulch, *middle*, also reduced virus diseases and whitefly infestations over plants grown on bare soil with no mulch, *bottom*.

When grown over reflective plastic mulch, cantaloupes can produce both acceptable yields and sizes even under heavy pressure from aphid-borne viruses and silverleaf whitefly, without multiple insecticide applications.

(Gibson and Rice 1989). Insecticides may actually enhance the spread of aphid-borne viruses by stimulating vector activity (Ferro et al. 1980). Many insecticides stimulate the aphid's nervous system, causing it to move from plant to plant very rapidly. This results in the infection of more plants than would occur in those visited by a nonintoxicated aphid, which settles down and feeds on one plant before moving to another one. This occurs before the insecticide has a lethal impact on the aphid. In contrast, whitefly infestations can be somewhat relieved by imidacloprid, a systemic insecticide. However, the development of resistance to imidacloprid and other insecticides among whiteflies is a major concern (Prabhaker et al. 1998; Elbert and Nauen 2000; CMRAB 2003).

Mulches reduce crop viruses

Reflective, metalized plastic mulch, formed by adhering a thin coat of aluminum ions to a sheet of polyethylene, has been shown to help control other types of aphid-borne viruses as well as whiteflies. This control is due to the fact that reflective plastic mulch reflects ultraviolet (UV) wavelengths, unlike black or clear plastic mulches. Flying aphids and whiteflies are repelled by these UV wavelengths. The outcome is to delay and reduce the incidence of aphid-borne viruses. Stapleton and Summers (2002) showed that the onset of virus disease symptoms was delayed by 3 to 6 weeks in plants grown over this mulch, which was critical for normal flowering and fruiting. In addition, reflective plastic mulch delayed and reduced the severity of silverleaf whitefly infestations in zucchini squash, pumpkins and cucumber (Summers and Stapleton 2002). This mulch was as effective as a preplant application of imidacloprid in managing whiteflies.

Reflective plastic mulch can be applied with ordinary mulch-laying equipment or by hand, and holes are then cut into the mulch to accommodate hand-planting. In addition, a version of this mulch has a lattice network of openings down the center and can be applied following machine planting; the plants then emerge through the openings. (Reflective plastic mulch is slightly more expensive than black plastic mulch, but the latter does not work to repel aphids or whiteflies.)

As part of a conservation tillage study, we also found that wheat straw mulch can help manage aphid-borne viruses and whitefly in cucurbits. In zucchini squash grown over straw mulch, yields were as high and the incidence of aphid-borne virus diseases was no greater than in plants grown over reflective plastic mulch (Summers et al. 2004b). Plants grown over straw mulch produced higher yields than those grown over plots that had received a preplant application of imidacloprid. Straw mulch also deterred colonization by silverleaf whitefly and reduced the incidence of squash silverleaf (Summers et al. 2004b).

Field study, sampling protocols

In studies at KREC, we compared the effectiveness of reflective plastic and wheat straw mulches for the management of aphid-borne viruses and silverleaf whitefly in cantaloupe. We also compared both strategies to conventional bare soil production.

The study field was prepared for planting using conventional procedures: disking, preirrigation, fertilizer application (500 pounds per acre of 15-15-15 [nitrogen-phosphorus-potassium]), herbicide application (soil incorporated bensulide [Prefar] at 6.5 quarts per acre) and bed shaping (60-inch beds). The reflective plastic mulch was applied using standard mulch-laying equipment. Surface drip-tape was laid down the center of each bed under the plastic. Drip tape was also placed down the center of all remaining beds. The wheat straw was spread by hand. To accommodate seeding, holes were cut every 30 inches into the plastic mulch and the straw was "scratched" aside every 30 inches down the center of the beds.

Each treatment consisted of three beds with two unplanted beds between

Photos: Jack Kelly Clark

***Left*, a complex of different mosaic viruses can cripple crop production by stunting plant growth and reducing yield or killing cantaloupe plants outright. *Middle*, silverleaf whitefly has emerged as a serious late-season pest, contributing to a 13% decline in Fresno County cantaloupe acreage. *Right*, the cotton/melon aphid is a highly efficient vector of three mosaic viruses (cucumber, watermelon and zucchini yellow).**

treatments. Plots were 220 feet long and replicated five times in a randomized complete block design. Three seeds were planted per hill, and following seedling emergence, the stand was thinned to one plant per hill for an average of 88 plants per bed. 'Top Mark' melons were planted on July 21, 2002, and 'Ovation' were planted on July 31, 2003.

Biomass. Biomass was sampled in 2003 as a measure of plant growth. Beginning 1 week after seedling emergence, one plant from a guard row of each plot (one of two rows on either side of the data-collection row) was selected at random, cut at the soil surface and placed in a paper bag. It was then returned to the laboratory, dried at 160°F and weighed.

Insects and disease. Following seedling emergence, 10 plants in the middle of each center row were marked with surveyor's flags. Beginning approximately 2 weeks after seedling emergence, the newest fully expanded leaf on each marked plant was carefully turned over and the winged aphids and adult silverleaf whiteflies were counted. At approximately 4 weeks after emergence, a 3-week-old leaf from each marked plant was removed, placed in a locking plastic bag and returned to the laboratory. A 1-square-inch plug was removed from each leaf and the number of silverleaf whitefly nymphs present was counted. The 10 marked plants were visually examined weekly for virus disease symptoms.

Yields. Melons from the center row of each plot were harvested at full slip (when the melon separates from the stem with a very slight pressure). Harvesting occurred over a 10- to 14-day period. Melons were sorted by size, and the number in each size category was determined. Then weights in each size category were taken. The number of cartons per acre for each size category was then calculated.

Statistical analysis. All data presented in the text and figures were analyzed by analysis of variance. Means followed by the same letter(s) are not significantly different at $P = 0.05$, using Fisher's protected LSD.

Plant growth compared

During the first 2 weeks of the 2003 study, plant growth was identical across all three production systems (reflective plastic mulch, wheat straw mulch and bare soil)(fig. 1). However, at 2 weeks the plants grown over the reflective plastic mulch began a rapid growth spurt; at 3 weeks, they had accumulated twice as much dry matter as plants grown on bare soil, and more than three times as much by 4 weeks.

The large increase in weight per plant observed on Sept. 21 reflects the earlier development of fruit in plants grown over plastic. Similarly, plants grown over straw mulch also accumulated dry matter more rapidly than those grown over bare soil. However, this dry matter increase was not as rapid as that in plants grown over reflective plastic. In earlier studies, we found that compared to straw mulch and bare soil, reflective plastic reflects a significantly higher rate of photosynthetically active radiation (PAR) back into the plant canopy (Summers et al. 2004a). This reflected PAR is intercepted and absorbed by the canopy, resulting in increased photosynthesis, which in turn results in increased plant growth. While not as efficient as reflective plastic, straw mulch still reflects twice as much PAR back into the canopy as bare soil (Summers et al. 2004a). We believe that this reflected PAR from the plastic and the straw mulch confers a growth advantage to plants.

Aphid numbers and virus incidence

In 2002 and 2003, the cotton/melon aphid *(Aphis gossypii)* was the only aphid species present. This aphid is a highly efficient vector of all three viruses. In 2002, there appear to have been two aphid flights (a large number of winged aphids flying for a period of time) after seedling emergence, in mid-August and mid-September. During mid-August 2002, the number of winged aphids per leaf was significantly higher on plants grown over bare soil than on those grown over plastic or straw mulch (fig. 2A). The higher aphid counts in plants grown over bare soil resulted in a significantly higher incidence of virus disease in late August and early September (fig. 2B). At the same time, significantly lower aphid counts in plants grown over straw and plastic mulch resulted in lower virus incidence. The reflective plastic mulch maintained virus incidence below 10% through mid-September.

In 2003, a major aphid flight occurred in early August and populations of

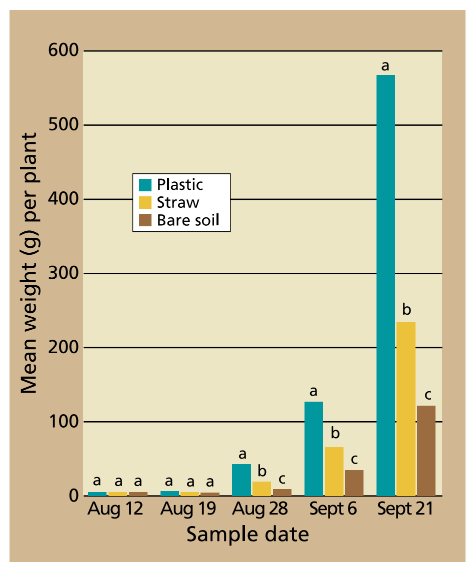

Fig. 1. Biomass accumulation in cantaloupe plants grown under three production systems, 2003.

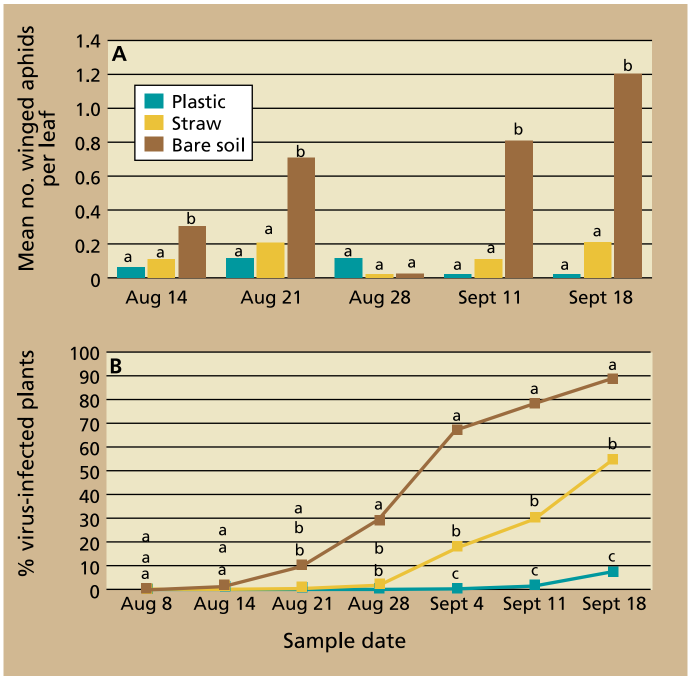

Fig. 2. Populations of (A) winged aphids and (B) virus disease incidence and in cantaloupe plants grown under three production systems, 2002.

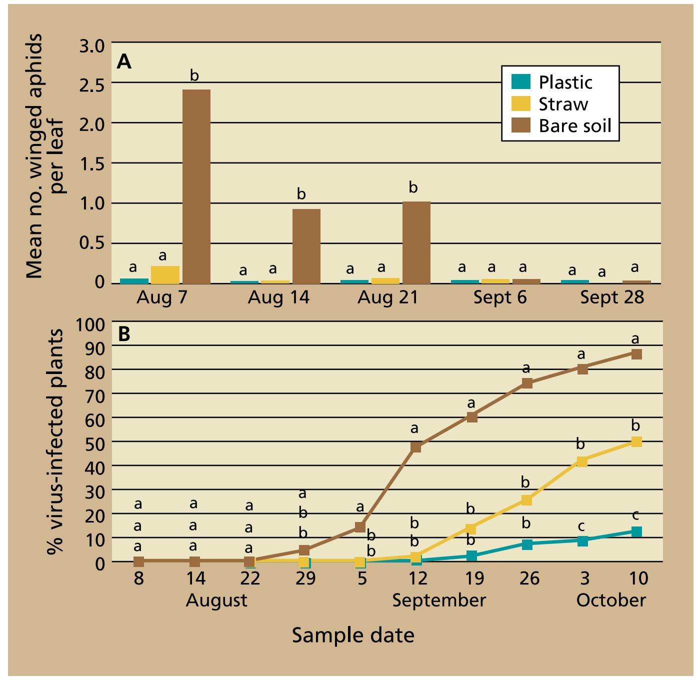

Fig. 3. Populations of (A) winged aphids and (B) virus disease incidence in cantaloupe plants grown under three production systems, 2003.

winged aphids were very high a week after seedling emergence. Maximum aphid numbers again occurred in plants grown over bare soil (fig. 3A). The incidence of virus-infected plants closely followed that of winged aphids per leaf, with the highest percentage of infected plants grown over bare soil (fig. 3B). Disease incidence in plants grown over bare soil increased rapidly beginning in early September and peaked near 100% by early October. The infection rate in plants grown over straw mulch remained under 50%, while those grown over reflective plastic reached only 15%.

Whitefly populations

In both 2002 and 2003, adult whitefly numbers were significantly higher in plants grown over bare soil (fig. 4). Whitefly numbers per leaf in 2002 were approximately twice those observed in 2003 with both mulches and bare ground. Whitefly numbers were significantly ($P < 0.05$) fewer, however, in plants grown over both reflective plastic and straw mulch in both years. While whitefly densities increased as the season progressed, numbers in plants grown over reflective plastic and straw mulch remained low (fig. 4A). Even in mid-September, the number of adults per leaf in plants grown over these mulches was less than those in bare soil in mid-August (fig. 4A).

The number of whitefly nymphs per square inch of leaf surface closely paralleled the adult counts, with populations in plants grown over reflective plastic and straw mulch significantly ($P < 0.05$) below those in bare soil. This trend persisted throughout the season (fig. 4B). The overall density of nymphs in 2003 was double that in 2002 for both mulches

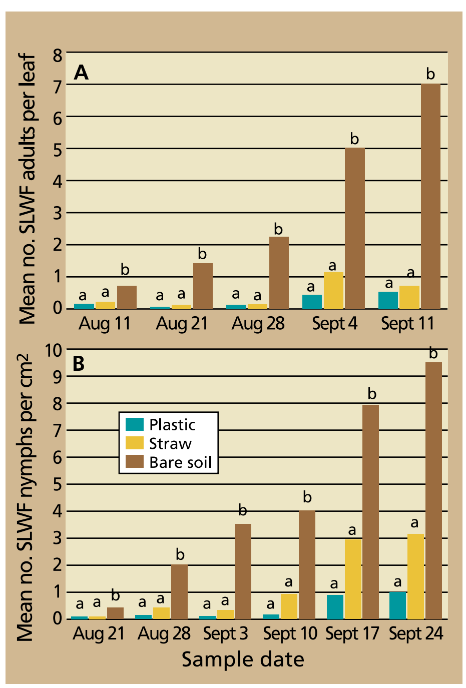

Fig. 4. Populations of silverleaf whitefly (SLWF) (A) adults and (B) nymphs in cantaloupe plants grown under three production systems, 2002.

and the bare ground plots, although adult densities were just the reverse. Adult densities were higher in 2003 because the temperatures in August and September were considerably warmer, with daily maximums 3°F to 5°F higher than in 2002 (National Weather Service 2004). This resulted in an additional one-half generation of whitefly (eggs were laid and immature insects developed but did not reach the adult stage) in 2003. Unlike squash and pumpkin, cantaloupe does not show symptoms of squash silverleaf.

Earlier, greater yields with mulch

Melon plants grown over reflective plastic mulch produced ripe fruit 7 to 10 days earlier than those grown over either straw mulch or bare soil. In 2002, yields (cartons per acre) were significantly lower in all size categories in all three production systems. There were no large-size melons (#12) in any production system in 2002. Among the remaining sizes, production was significantly ($P < 0.05$) higher in plants grown over plastic mulch, followed by those grown over straw mulch. Both production systems resulted in significantly higher yields than the conventional bare soil system (fig. 5).

While yields were significantly higher in all sizes in 2003, the same general trend was observed in 2002. Total

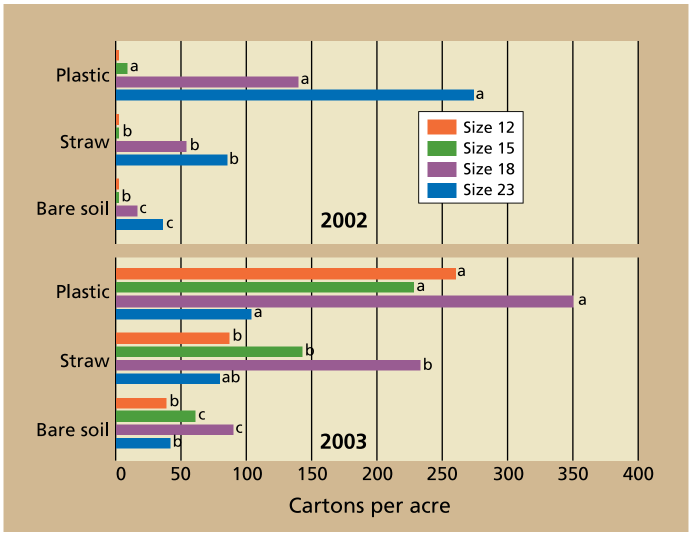

Fig. 5. Cantaloupe yields in cartons per acre, 2002 and 2003.

production was highest in plants grown over plastic and second highest in straw. Yields from plants grown over straw were only equal to those from the bare soil control in the largest and smallest sizes (#12 and #23). In all other size categories, yields from the straw mulch plots were significantly ($P < 0.05$) higher than bare soil.

Fewer insecticide sprays needed

When grown over reflective plastic mulch, cantaloupes can produce both acceptable yields and sizes even under heavy pressure from aphid-borne viruses and silverleaf whitefly, without multiple applications of insecticide. The plastic mulch must be present when the plants emerge from the soil, otherwise they may become infected with one or more virus diseases while in the cotyledon stage. In our experiments, the reflective mulch reduced the landing of winged aphids and delayed the incidence of aphid-borne virus diseases by 2 to 4 weeks. The reduced incidence of aphid landing resulted from the reflection of UV light from the mulch surface. The UV light repels incoming aphids, preventing them from landing and transmitting the viruses. Wheat straw mulch also reflects certain UV wavelengths, preventing aphids from landing.

Both mulches also reduced the incidence and severity of silverleaf whitefly colonization. As with winged aphids, the reflected UV light repels the adult whitefly, leading to fewer colonizing adults. This leads to lower numbers of immature whiteflies compared with plants grown over bare soil.

Reductions in both the incidence of virus diseases and the severity of whitefly infestation in plants grown over these mulches contributed to the higher yields. Plants grown over these mulches also produced more large-sized fruit, which are at a premium late in the season. In our studies, these higher cantaloupe yields and larger sizes were accomplished without the use of insecticides. We are currently working with growers to increase the adoption of this strategy for growing cantaloupes in situations where aphid-borne virus diseases and silverleaf whiteflies are problems.

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Jack Kelly Clark

UC technicians Albert Newton (left) and Matt Milton conduct an aphid count at an early cantaloupe trial using plastic reflective mulch (silver) and spray mulch (white).

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RESEARCH ARTICLE

Large bugs damage pistachio nuts most severely during midseason

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Raksha Malakar-Kuenen, a postdoctoral researcher, whacks a dormant pistachio limb with a mallet to dislodge overwintering stink bugs onto a beating tray, one of the primary field monitoring methods. California pistachios, once considered virtually pest free, are now under attack from a variety of insects, especially "true" bugs of the Hemiptera order.

"Large bug" damage to pistachio nuts varies by season, as well as among insect species and development stages, with larger bugs typically causing more damage than smaller bugs. We investigated pistachio damage by three large bug species (leaffooted bug, redshouldered stink bug and flat green stink bug) at different development stages and throughout the season, using field surveys and cage studies. Before fruit set occurs in June, most damaged nuts are dropped from the cluster without reducing fruit load. The midseason period (June to July) is the most critical because the damaged nuts remain in the cluster. After shell hardening, the kernel is largely protected from bug feeding.

Though once considered virtually pest-free, California pistachios are now attacked by a variety of insects, especially the Hemiptera or true bugs. Most are native pests that built resident populations as pistachio orchard acreage increased. These pests are commonly grouped as "small" and "large" bugs. The small bugs (adults about one-quarter inch) include several species of Miridae and Rhopalidae, most importantly *Calocoris norvegicus* (Gmelin), *Phytocoris relativus* (Knight) and *Lygus hesperus* (Knight). The large bugs (adults about one-half inch) include some species of leaffooted bugs (Coreidae), such as *Leptoglossus clypealis* (Heidemann); and stink bugs (Pentatomidae), such as the redshouldered stink bug (*Thyanta pallidovirens* [Stål]), the flat green stink bug (*Acrosternum hilare* [Say]), Uhler's stink bug and *Chlorochroa uhleri* (Stål) species. All of these bugs use piercing-sucking mouthparts to feed directly on the nut. While small bugs are often abundant and can cause damage early in the season, they pose little threat after shell hardening (Michailides et al. 1987; Purcell and Welter 1991). Large bugs, on the other hand, have larger, stronger mouthparts and may continue to damage kernels until harvest time (Michailides et al. 1987).

Significant crop loss will occur only when early-season bug densities are so high that the number of dropped nuts exceeds the level that the tree will naturally compensate.

There are also seasonal differences in the type of feeding damage that occurs. Early in the season, when the nuts are small (less than 10 millimeters in diameter), feeding punctures through the fruit pericarp (the outer wall of the nut, comprised of the outer epicarp, the fleshy middle mesocarp and the inner endocarp) quickly result in darkened areas of the hull or epicarp lesions (Uyemoto et al. 1986; Bostock et al. 1987), and the damaged nuts often drop from the cluster (Purcell and Welter 1991). In midseason, fruit load is set but shell lignification (hardening) is not complete. The damaged nut remains in the cluster and the resulting epicarp lesion can stain the outer shell, lowering market value. During this time, the kernel is also developing and feeding punctures can result in necrotic spots on the nut meat (kernel necrosis), aborted nuts or fungal contamination (such as stigmatomycosis).

Therefore, both the bug species present and the seasonal period will affect pest control decisions. We investigated pistachio damage by three large bug species (leaffooted bug, redshouldered

Field guide to pistachio pest insects

Monitoring pistachio orchards is essential to determine the type of insect pest present and the nature of potential damage. Midseason is the most critical period, but damage can occur early and late in the season as well. The insects in this guide are among the most common.

LARGE BUGS

Large bugs (adults approximately 1/2 inch) have larger, stronger mouthparts and may continue to damage kernels until harvest.

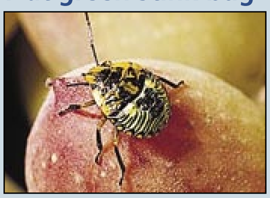
Redshouldered stink bug


Small nymph


Large nymph


Adult*

Flat green stink bug


Small nymph


Large nymph


Adult

Leaffooted bug


Nymphs emerging from egg mass


Medium nymph**


Adult**

All photos by author except *(Jack kelly Clark) and **(Richard E. Rice)

SMALL BUGS

Small bugs (adults approximately 1/4 inch), sometimes called "plant bugs," are often more abundant and can cause damage early in the season. Adults pose little threat after shell hardening.


Calocoris (adult)


Lygus bug (adult)


Phytocoris (adult)

Photos: Jack Kelly Clark

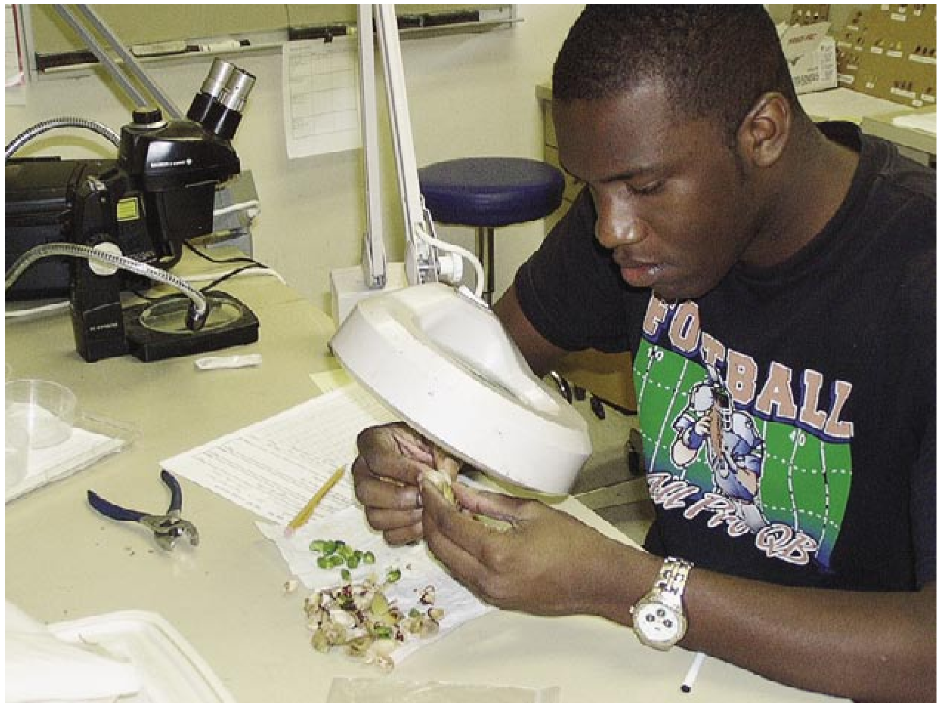
stink bug and flat green stink bug) at different development stages and throughout the season. Our work can improve pest control decisions by describing seasonal periods when large bug feeding results in greater crop loss.

Pistachio orchard studies

Field surveys. To compare seasonal changes in nut damage with changes in pest species, we sampled nine orchards in the San Joaquin Valley in 1998. To sample bugs in the pistachio trees, we took 350 beating-tray samples per orchard every 2 to 3 weeks from April to November. For a beating tray sample, a cloth tray is held under a section of the pistachio tree, and when the branch above is struck with a mallet, the dislodged insects are caught on the tray. To sample bugs in the cover crops, we took 350 sweep-net samples per orchard every 1 to 2 weeks from March to September. For this, a cloth insect net was swept through the cover crop, using 50 continuous sweeps while walking through the cover crop for each bag of collected insects (seven sections of each orchard were sampled). Feeding damage was determined by recording the number of epicarp lesions in 700 pistachio nut clusters per orchard every 7 to 14 days from May to September.

Cage studies — seasonal damage. In 1998, we conducted cage trials at the UC Kearney Research and Extension Center. After bud-break (when plant dormancy ends), pistachio branches with nut clusters were isolated in 3-gallon (11.4-liter) organdy cages. The number of nuts per cluster was recorded, and then a single bug was introduced for a 7-day feeding period. After that, the bugs were removed and the numbers of total, dropped and damaged (epicarp lesion) nuts were recorded. The cages were then resealed until harvest time, when the numbers of total, dropped and damaged nuts were again recorded. The nuts were then dissected and the kernel condition (clean, necrotic, stigmatomycosis-affected or aborted) was recorded.

The trials were conducted at three seasonal periods that correspond to changes in fruit susceptibility to bug damage: early season, as the fruit load is being set (May 1 to 8); midseason, dur-



Pistachio photos: Richard E. Rice

***Above right*, Gary Guelce, a research technician at KREC, examines pistachio kernels for evidence of damage. The most critical period for potential kernel damage occurs midseason, when large bug mouthparts can easily penetrate hardening shells. Damaged kernels may not become apparent until harvest. However, generalizing about bugs and nut damage is difficult because of regional and seasonal variations. Damage to the interior of the pistachio nut can range from blanks, *top left*, which can be caused by large or small bugs early in the season, to late season necrosis, *bottom left*, caused primarily by the larger bugs.**

ing shell hardening (June 10 to 17); and late season, after shell hardening (Aug. 13 to 21). We included the small bug *Calocoris* in some of the early trials as a comparable marker to previously published studies. The early-season treatments were adult redshouldered stink bug (RSSB), flat green stink bug (FGSB) and *Calocoris*. The midseason treatments were adult redshouldered stink bug, flat green stink bug and *Calocoris,* and the small (second or third instars) and large (fourth or fifth instars) stages of redshouldered stink bug and flat green stink bug. The late-season treatments were adult redshouldered stink bug, flat green stink bug and leaffooted bug, and small (second or third instars) and large (fourth or fifth instars) stages of redshouldered stink bug and flat green stink bug. We also did a no-insect control treatment. For each trial, treatments were set in a complete randomized block design, with five replicates (cages) per treatment (130 cages total). Blocks were individual or adjacent trees.

Cage studies — “hidden” damage. We call damage after shell hardening is complete “hidden,” because epicarp lesions will not form even though some of the bug’s probes can successfully penetrate the shell to feed on the kernel. In 2001, we further quantified bug damage after the midseason period by inoculating clusters with different bug species every few weeks. Pistachio branches were isolated with organdy cages, as described. At the beginning of the season, each cluster has more nuts than it will carry to harvest time, and there will be a natural nut drop to set the cluster load at about 15 to 20 nuts per cluster. After the natural nut drop was nearly complete (May 16), we recorded the number of nuts remaining in the cage and then randomly assigned cages to treatments.

To begin each trial period, a single bug was placed into each cage for a 7-day feeding period. Every 2 to 3 weeks thereafter, the cages were briefly opened and we recorded nut condition in seven categories: (1) new feeding wounds (small puncture with extruding fluid), (2) old feeding wound (dried puncture, no epicarp lesion), (3) new epicarp lesion, (4) old epicarp lesion, (5) dropped nuts with bug damage, (6) naturally dropped nuts and (7) no damage. We repeated the inoculation procedure with new bugs and cages every 2 to 3 weeks, for a total of seven trial periods with initial start dates of May 22, June 8 and 22, July 10 and 26, and Aug. 9 and 21. At harvest time (mid-September), nuts were evaluated for external and internal damage. We tested redshouldered stink bug, flat green stink bug and leaffooted bug adults and a no-insect control with 10 cages (replicates) for each treatment (210 cages total).

Statistical analysis. The results are presented as means per treatment (± SEM) and compared using analysis of variance (ANOVA), with treatment means separated with Tukey’s HSD test. When needed, data were transformed ($\sqrt{x}$) to normalize the variance. In the cage study of hidden damage, levels of kernel necrosis in each bug treatment were adjusted to the control (Abbott 1925).

Bugs found in field surveys

Overall, insect collections using the beating tray were low (less than 0.2 bugs per sample). In the surveyed orchards, *Phytocoris* was the most abundant small bug in the canopy, with three seasonal peaks in late April, mid-June and late August. Flat green stink bug was the most common large bug in the canopy and was found from mid-May

Field studies of pistachio nut damage and drop included a stink bug feeding trial. ***Bottom***, former UC lab assistant Cody Anderson ties off a 10-gallon organdy cage during dormancy to isolate pistachio clusters prior to insect damage. ***Top***, former UC staff research associate and study co-author Shawn Steffan opens one of the cages to inspect midseason nut condition.

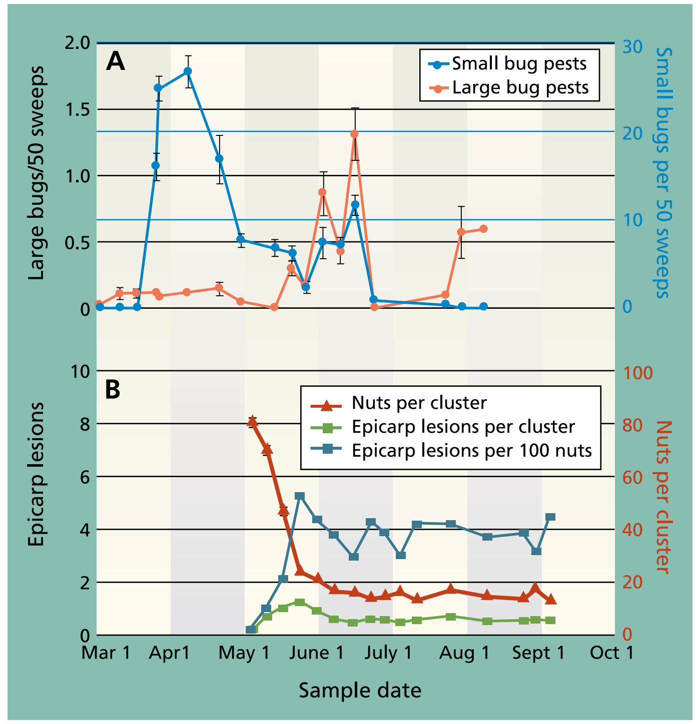


Fig 1. (A) Average (± SEM) number of small and large bugs collected from cover crops in nine sampled orchards in the San Joaquin Valley shows that small bugs, primarily *Calocoris*, were most common early in the season, while large bugs, most commonly stink bugs, were most common in June. (B) Average (± SEM) total and damaged nuts per cluster in the sampled orchards.

until harvest. Flat green stink bug commonly overwinters in the pistachio orchard and is often the first large bug found each year. We also collected redshouldered stink bug from July through harvest. There were no leaffooted bugs collected in the beating tray samples; however, we observed these bugs in the canopy from July through harvest.

From sweep-net samples of the ground covers, we identified 29,873 specimens of bug pests. Most bugs were collected in spring (fig. 1A), and were composed primarily of *Calocoris* (63%) and Lygus (21%). Large bugs were less common, collected most often in June, and composed primarily of redshouldered stink bug and flat green stink bug. The data on the seasonal changes in bug species in monitored orchards is presented in the following discussion on nut damage. However, it is difficult to generalize about bugs and nut damage because of seasonal and regional variations in small and large bug species. For example, while *Neurocolpus longirostris* (Knight) may be one of the more damaging bugs, it is also rare; and while Uhler's stink bug may be common in orchards on the West Side of the San Joaquin Valley, the redshouldered stink bug and flat green stink bug are more dominant on the East Side.

Nut drop and damage

When the nut cluster is formed in April, it has more nuts than it will carry to harvest. Therefore, the large number of dropped nuts per cluster observed in May resulted primarily from a natural drop as fruit load was set (fig. 1B). Nevertheless, there was also an impact from insect feeding. We observed Phytocoris and *Calocoris* feeding on newly formed nuts in April and most of these damaged nuts dropped within 24 hours, without any visible signs of insect damage. This is because it takes more than 24 hours for visibly darkened epicarp lesions to form (Bostock et al. 1987). The result is that insect feeding on nuts in their earliest development period is easily overlooked. Later, in late April and early May as the fruit load establishes, insect-damaged nuts (epicarp lesions) typically remain in the cluster for a short time. This visible sign of insect feeding can be used to monitor bug activity.

The number of visible epicarp lesions increased in late May and then declined, leveling off to about four per 100 nuts (less than one per cluster) in mid-June (fig. 1B). In July and August, there was essentially no change in the number of lesions (fig. 1B), even though there was an increase in the number of large bugs (fig. 1A). This is because insect wounds no longer cause epicarp lesions during fruit maturation and shell lignification (hardening), when peroxidase activity in the pericarp declines (Bostock et al.

1987). Therefore, most lesions found after mid-July were the result of earlier feeding wounds. We suggest that the subsequent feeding by large bugs presents potential "hidden" damage, since kernel necrosis may occur without the external sign (epicarp lesion) of insect feeding. Therefore, epicarp lesions cannot be used to monitor insect activity or damage after shell hardening.

The relationship between epicarp lesions in pistachio nuts and insect feeding was first reported for the leaffooted bug by Bolkan et al. (1984), and was further clarified for large bugs by Rice et al. (1985) and for small bugs by Uyemoto et al. (1986). Michailides et al. (1987) categorized the seasonal succession of bug species in a Sacramento County pistachio orchard and compared damage levels among bug species. The results from our field-sampling build upon these studies and show that the early-season feeding by small and large bugs is minimized because the damaged and dropped nuts will typically not affect fruit load. This results from early-season plant compensation of fruit load (fewer nuts are dropped naturally) in response to insect damage, which was first verified with *Phytocoris* (Beede et al. 1996). We also confirmed that while large bugs may be present in the orchard after shell hardening is complete, there will not be an increase in epicarp lesions, as first detailed by Bostock et al. (1987).

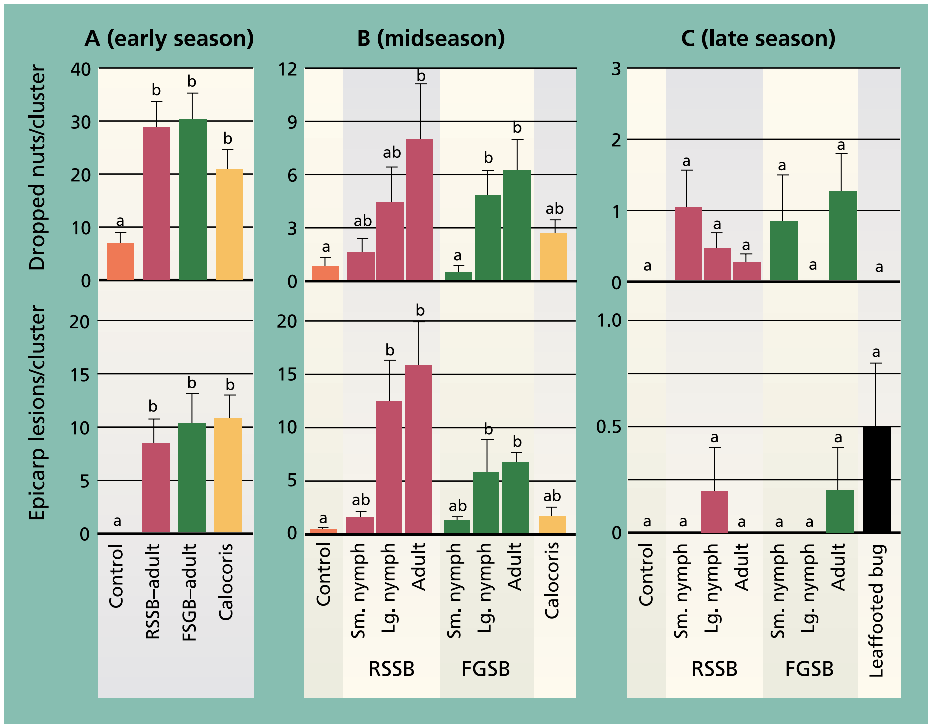


Fig. 2. Average (± SEM) number of epicarp lesions and dropped nuts after a 7-day exposure period to different bug species (RSSB = redshouldered stink bug, FGSB = flat green stink bug) or development stages, in (A) early season (May 1–8), (B) midseason, during shell hardening (June 10–17) and (C) late season, after shell hardening (Aug. 13–21). In each graph, different letters above each bar indicate a significant difference between treatments (Tukey's HSD test, $P < 0.05$).

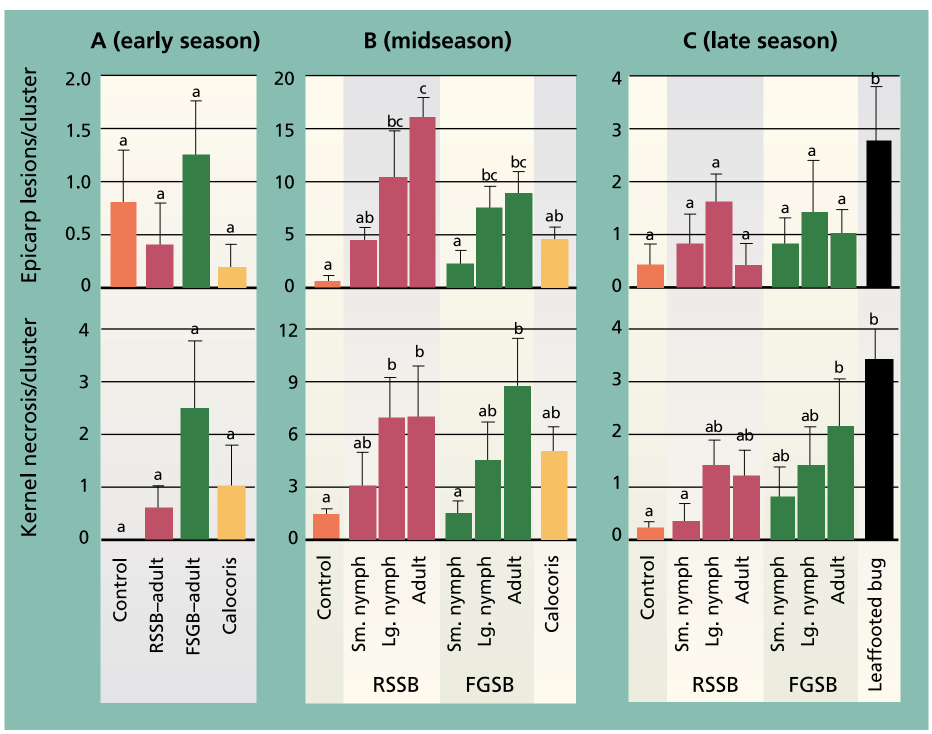


Fig. 3. Average (± SEM) levels of epicarp lesions and internal nut damage (kernel necrosis) at harvest time for different bug treatments (RSSB = redshouldered stink bug, FGSB = flat green stink bug) during (A) early season (May 1–8), (B) midseason, during shell hardening (June 10–17) and (C) late season, after shell hardening (Aug. 13–21). In each graph, different letters above each bar indicate a significant difference between treatments (Tukey's HSD test, $P < 0.05$). One replicate (cage) of the midseason *Calocoris* treatment was dropped from the analysis as an outlier.

Size and species affect damage

Initial damage. After the 7-day feeding period in the cage studies, the numbers of dropped nuts in the early-season trial were higher in all insect treatments other than the control (fig. 2). In the midseason trial, only the adult redshouldered stink bug and adult and large nymph flat green stink bug treatments were significantly higher than the control, and there were no treatment differences in the late-season trial (fig. 2). The pattern of dropped nuts among treatments in the midseason trial also suggests that bug size and species affect damage levels. In both

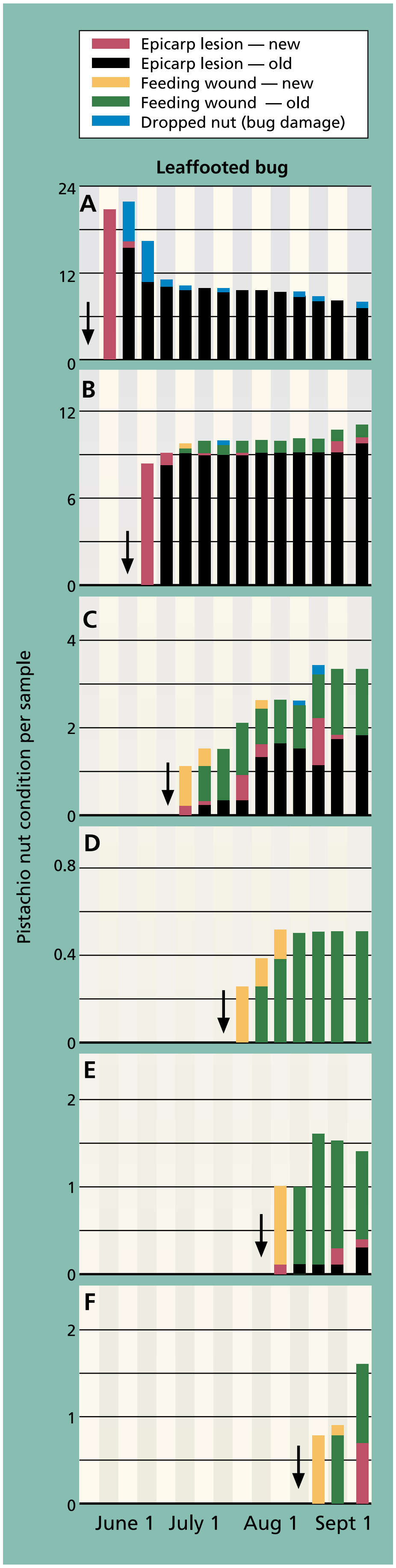


Fig. 4. Amount and type of external nut damage from a leaffooted bug exposed for a 7-day feeding period at mid- and late-season periods (A–F). Arrows indicate the date when the cages were inoculated. Each stacked bar represents averages for the number of nuts that showed the damage sign.

the redshouldered stink bug and flat green stink bug treatments, dropped nuts increased from the small nymph (and *Calocoris*) to adult stages. Adult redshouldered stink bug and flat green stink bug were tested in each trial period, and we used changes in these insects' damage levels to compare seasonal changes. For both the adult redshouldered stink bug and flat green stink bug, significantly more insect-damaged nuts were dropped in the early- than in the midseason trial, and in the mid- than in the late-season trial ($F = 14.80$, $df = 2, 12$, $P = 0.001$; $F = 26.00$, $df = 2, 12$, $P < 0.001$; respectively).

The number of epicarp lesions formed in the early-season trial was significantly greater in all insect treatments than the control, but not different among tested insect species (fig. 2). In the midseason trial, bug species and size had an impact on the formation of epicarp lesions. As with the number of dropped nuts, there were more epicarp lesions in treatments with larger insects, with the redshouldered stink bug large nymph and adult treatments significantly higher than the control. In the late-season trial there were no treatment differences. As with nut drop, differences in the adult redshouldered stink bug and flat green stink bug treatments were used to compare seasonal periods. We found a significant reduction in epicarp lesions for both adult redshouldered stink bug and flat green stink bug in the late-season trial compared to the early- and midseason trials ($F = 7.189$, $df = 2, 12$, $P = 0.009$; $F = 8.80$, $df = 2, 11$, $P = 0.005$; respectively).

Crop damage. At harvest time the impact of hemipteran feeding on crop damage is more evident. Across the trial periods, adult redshouldered stink bug and flat green stink bug feeding resulted in significantly more epicarp lesions at harvest time in the midseason trial than in either the early-season (in which damaged nuts are dropped) or late-season trial (in which epicarp lesions are not readily formed)($F = 60.54$, $df = 2, 12$, $P < 0.001$; $F = 12.99$, $df = 2, 12$, $P < 0.001$; respectively).

In the early-season trial, the number of epicarp lesions at harvest time was quite low (less than 1.5 per cluster) and was similar across all treatments (fig. 3). Most damaged nuts dropped from the cluster, as was evident from collected nuts in the cage bottom with feeding puncture wounds or epicarp lesions. Combined with data on dropped nuts (fig. 2), the results suggest that most insect-damaged nuts in the early-season period do not remain in the cluster, verifying there is crop compensation for early-season damage by redshouldered stink bug, flat green stink bug and *Calocoris*. In contrast, in the midseason treatment differences in epicarp lesions at harvest time were pronounced (fig. 3), with more damage associated with the larger insects. In the late-season trial, there were no treatment differences in the number of epicarp lesions in the stink bugs tested, while there was a significant difference in the leaffooted bug treatment. The few lesions found may have been the result of other pathogens that contaminated the insect feeding wounds.

The most critical measure of insect crop damage in pistachio nuts is kernel necrosis. In the early-season trial, the levels of kernel necrosis were low and not different among treatments, again a result of damaged nuts dropping from the cluster (fig. 3). In the mid- and late-season trials, there was more damage in treatments with larger insects, as previously described. Comparing trial periods, kernel necrosis in the redshouldered stink bug and flat green stink bug treatments was significantly higher in the midseason trial than in either the early- or late-season trials ($F = 11.32$, $df = 2, 11$, $P < 0.001$; $F = 17.29$, $df = 2, 11$, $P < 0.001$; respectively).

These results for the early- and midseason trials are comparable to those of previous studies (Michailides

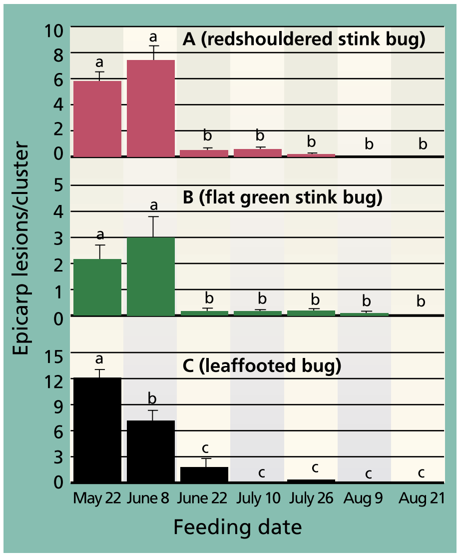


Fig. 5. Average (± SEM) levels of epicarp lesions for (A) redshouldered stink bug, (B) flat green stink bug and (C) leaffooted bug were significantly different among different feeding dates. For each insect, different letters above each bar indicate a significant difference between inoculation dates (Tukey's HSD test, *P* < 0.05).

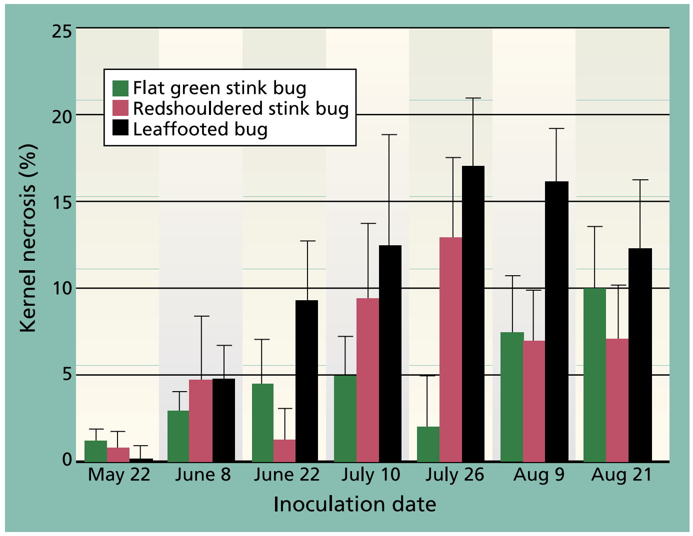


Fig. 6. Average (± SEM) levels of kernel necrosis for redshouldered stink bug, flat green stink bug and leaffooted bug for different 7-day feeding periods.

et al. 1987; Rice et al. 1985). However, the results for the late-season trial disagree with those of earlier studies on one critical point. While we found that larger bugs were better able to penetrate the hardened pistachio shell and feed on the kernel, we also found significantly less kernel damage in the late season, suggesting that the hardened shell provides some protection from even the largest bug tested, adult leaffooted bugs.

Still, there was some kernel damage, and a comparison of feeding locations provides an indication of how these large bugs are able to penetrate the pistachio shell. Michailides et al. (1988) suggest that late-season feeding by the leaffooted bug was successful when the insect's mouthparts penetrated the shell near the "Achilles heel" of the pistachio — the region near the peduncle (the nut's stem). To test this observation, we regressed the treatment means of kernel necrosis (which indicated that the bug had successfully penetrated the kernel) against epicarp lesions at the Achilles heel and epicarp lesions elsewhere. Indeed, the results confirmed that kernel necrosis was significantly and positively related to epicarp lesions at the Achilles heel ($y = 3.247x + 0.610$, $r^2 = 0.93$, $P < 0.001$).

Hidden damage from feeding

The experiment was designed to better understand the transition period between the visible signs of feeding damage (epicarp lesion) and "hidden" crop loss (kernel necrosis) in the mid- and late-season periods. Figure 4 shows the amount and type of external nut damage for leaffooted bug; we had similar results with redshouldered stink bug and flat green stink bug.

As with the previous cage study, the seasonal pattern of insect damage provided the most useful information. In the first trial (inoculation on May 22), insect feeding quickly resulted in new epicarp lesions. The number of new epicarp lesions per cluster was significantly different among tested insects, ranging from most to least severe in leaffooted bug (20.7 ± 1.7), redshouldered stink bug (8.4 ± 2.1) and flat green stink bug (2.1 ± 0.9)($F = 33.58$, df = 2, 27, $P < 0.001$). Fruit load was not complete during the May 22 inoculation period and some of the insect-damaged nuts dropped from the cluster, with significantly more nut drop per cluster in the leaffooted bug (5.3 ± 1.2) than in either redshouldered stink bug (1.8 ± 0.6) or flat green stink bug (0.6 ± 0.4)($F = 7.737$, df = 2, 27, $P = 0.002$). Most of the damaged nuts (which had visibly evident old epicarp lesions) remained in the cluster until harvest time (fig. 4A). The pattern of feeding damage in the second trial (inoculation on June 8) was similar to the first trial but had two important differences: there was now little fruit drop, and some of the new feeding wounds did not form epicarp lesions due to shell hardening (fig. 4B).

The third trial (inoculation on June 22) marks a period of considerable change in the expression of insect damage. Most important is that new and old feeding wounds did not lead to epicarp lesions for many weeks, if at all (fig. 4C). This pattern becomes more evident in the fourth, fifth and sixth trials (figs. 4D, 4E, 4F), when epicarp lesions rarely formed. To illustrate the change in damage levels during the time when shell hardening is completed, we compared the average number of old epicarp lesions (those that formed 2 to 4 weeks after inoculation) across inoculation periods and showed a significant reduction between the June 8 and 22 inoculation periods for redshouldered stink bug, flat green stink bug and leaffooted bug (fig. 5).

Levels of kernel necrosis were low in the May and early-June inoculation treatments, with levels increasing in later treatments to a peak in late July, followed by a slight decrease in August (fig. 6). We suggest that the lower lev-

The number of surface lesions to still-soft pistachio shells can be a good tool for monitoring insect feeding activity early in the season.

els found in May and June, when the shell hardening is not yet complete, is the result of an increase in aborted nuts (data not provided). Throughout all inoculation periods, adult leaffooted bugs caused more damage than the adult stink bugs tested. As suggested by Rice et al. (1985) and Michailides et al. (1987), it is clear that adult leaffooted bugs can feed on the kernel throughout the season. Still, these bugs were caged for 7 days on a single cluster and damage levels were less than 20%, and we suspect that the hardened shell significantly reduces insect feeding.

Practical applications

We showed that in the early-season period, before crop load is set, insect-damaged nuts are dropped from the cluster; due to the plant's natural compensation for these dropped nuts, such insect feeding will not result in crop loss in most years and orchards. Significant crop loss will occur only when early-season bug densities are so high that the number of dropped nuts exceeds the level for which the tree will naturally compensate. For this reason, from mid-April through May the developing nuts should be monitored for insect damage, and the pistachio canopy and orchard floor should be monitored for small and large bugs.

The midseason period, as the pistachio shell is hardening and the fruit load is set, is the most critical period since the large bug mouthparts can easily penetrate the shell and most of the damaged nuts remain in the cluster. During this period, not all damaged nuts will have the externally visible epicarp lesions, and some lesions may require up to 2 weeks to develop. Therefore, the damaged kernel may not be apparent until harvest, when nuts are processed and graded.

In the late-season period when the shell has hardened, bug damage was significantly reduced in our studies (but see Michailides et al. 1987). We suggest that mid- and late-season insect sampling should focus on large bugs in the pistachio canopy, especially the adult leaffooted bugs, which are most capable of penetrating the hard pistachio shell. Therefore, it is helpful to properly identify small and large bugs and monitor their corresponding damage.

Accurately sampling bug densities is difficult. Because reliable sampling methods and economic action thresholds that correlate to economic crop loss have not yet been developed, managers should use a variety of sampling tools (sweep nets, beating trays and visual inspection) to keep abreast of changes in insect densities. In addition, the number of epicarp lesions can be a good tool for monitoring insect feeding activity early in the season, when lesions may form within 48 hours of a wound. However, be more cautious when monitoring lesions during the midseason period, since there can be a 2-week period between the initiation of insect feeding and the development of lesions. After shell hardening is complete, insect-damaged nuts will not be readily visible and when found will indicate feeding that probably occurred weeks or even months before. Therefore, insecticide applications that target epicarp lesions may be applied long after the insect damage occurred. For this reason, if bugs are found in the orchard after shell hardening, the best way to assess crop damage is to inspect the kernel for signs of insect damage.

K.M. Daane is Associate UC Cooperative Extension (UCCE) Specialist, and G.Y. Yokota, R. Krugner, and S.A. Steffan were Staff Research Associates, Division of Insect Biology, UC Berkeley (currently, Krugner is Graduate Student, UC Riverside, and Steffan is Project Manager, Utah State University); P.G. da Silva was Postgraduate Student, Division of Insect Biology, UC Berkeley (and currently is Associate Professor, College of Marin); R.H. Beede is Farm Advisor, UCCE Kings County; W.J. Bentley is Areawide Farm Advisor, UC Statewide IPM Program, UC Kearney Agricultural Center; and G.B. Weinberger is owner, Weinberger & Associates, Visalia. We thank the California Pistachio Commission, UC Statewide IPM Program and Western Region SARE program for funding; and Louise Ferguson, UCCE Specialist, Department of Pomology, UC Davis, for technical advice with pomology horticulture. Farm managers at Sherman Thomas Ranch, Nichols Farm, Agri-World and Paramount Farms provided field sites. Comments from two anonymous reviewers greatly improved the manuscript.

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Early harvest delays berry skin browning of 'Princess' table grapes

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Table grapes commonly suffer from tissue browning during harvest, packing, storage and shelf life, resulting in lower prices and reduced access to markets. We evaluated the development of browning symptoms in 'Princess' table grapes. The berries had high skin browning but very low flesh browning incidences. The most skin browning was found in highly mature grapes and appeared after 3 weeks of cold storage. Skin browning was directly related to fruit maturity, but vineyard location had a greater impact on the incidence of skin browning than maturity. In all locations, the skin browning susceptibility of 'Princess' table grapes rapidly increased when the berries reached a titratable acidity of less than or equal to 0.60% and/or a soluble solids concentration greater than or equal to 18.0%. Based on this work, we recommend harvesting 'Princess' at a soluble solids concentration between 16.0% and 18.0%.

***Top and bottom right*, fresh-market table grapes are vulnerable to browning of skins and flesh during harvesting, packing, storage and shelf life. Research has shown that this browning can be reduced in 'Princess' table grapes, *left*, by harvesting when soluble solids range between 16.0% and 18.0%.**

Table grapes commonly suffer from variations of tissue browning including stem browning (Crisosto et al. 2001), internal flesh browning (Nelson 1969) and berry (skin and flesh) browning (Crisosto, Badr, et al. 2002; Vial 2003) during harvest, packing, storage and shelf life. Table grapes that suffer from browning disorders normally have a shorter postharvest shelf life and may not be utilized for long-distance markets, which are often the most profitable. In general, table grapes with browning problems garner lower prices than grapes without them.

We studied postharvest berry browning in 'Princess' (originally known as 'Melissa'), a white, seedless, table grape cultivar developed and released by the USDA's Agricultural Research Service in 1999 (Ramming 1999). 'Princess' resulted from the cross of 'Crimson Seedless' with 'B40-208' in 1988. 'B40-208' is a white, seedless selection and is a complex hybrid whose parents include 'Italia', which is well known to exhibit berry browning symptoms. According to the California Agricultural Statistics Service, in 2003 there were 1,329 acres (325 acres nonbearing) planted in the state. In 2000, we conducted a preliminary postharvest evaluation of 'Princess' and observed various berry browning symptoms similar to those seen in 'Italia'.

Berry browning occurred either as an irregular shape and scattering on the surface of the berries restricted to the skin, which we called "skin browning," or as partial or total browning restricted to the flesh, which we called "flesh browning." These berry browning symptoms were different from those described in a 1992 UC DANR bulletin (Luvisi et al. 1992) as "internal browning" for 'Thompson Seedless'. The 'Princess' berry browning symptoms are frequently expressed on white table grape cultivars, including 'Italia', 'Regal Seedless' and others. In the few cases where internal browning has been reported on 'Thompson Seedless', the browning started parallel to the vascular system in the center of the berry and never developed on the skin as it does in 'Princess'.

We investigated if the development of postharvest berry browning problems in 'Princess' was related to cluster maturity parameters such as soluble solids concentration (SSC), titratable acidity (TA), the SSC/TA ratio and juice pH.

Maturity and berry browning

To study the relationship between grape maturity and berry browning incidence, 'Princess' table grapes were harvested during the 2001 and 2002 seasons at three soluble solids concentration (SSC) ranges: low (13% to 16%), moderate (16% to 18%) and high (greater than 18%).

'Princess' table grapes were harvested at different maturity levels from three San Joaquin Valley vineyards. Researchers determined that vineyard location and management practices had a greater influence on tissue browning than maturity in this cultivar. Trellis systems, nitrogen fertilization, canopy management and rootstocks could play important roles in controlling excess sunlight and hence browning problems.

During the 2001 season, 'Princess' table grapes were harvested at three different maturities at California State University, Fresno, from research plots in a vineyard comprised of 6-year-old, cane-pruned vines. The vines were supported by a wide "V" trellis system, and vine and row spacings were 7 feet (2.3 meters) and 12 feet (3.7 meters), respectively. A drip irrigation system was installed at planting time in 1996. The entire block received a gibberellic acid (1.0 gram per acre) bloom-thinning treatment at 80% bloom. Standard cultural practices of irrigation, pest management and canopy management were applied to the entire block. Twelve healthy vines were selected and labeled for this experiment, with each vine serving as a replicate. Four clusters were harvested from each vine on July 19, July 27 and Aug. 2, 2001, and each cluster was labeled to identify its date of harvest and vine number.

During the 2002 season, 'Princess' table grapes were harvested at the same three levels of maturity from three commercial vineyards located in major table grape production regions of the San Joaquin Valley: Parlier (Fresno County), Delano (Tulare County) and Arvin (Kern County). These vineyards were carefully chosen based on their similar age, vigor (moderate to high) and management practices. At all three sites, the spacing was 12 feet (3.7 meters) between rows and 8 feet (2.4 meters) between vines, with drip irrigation; and clusters were tipped and the trunks girdled using a 3/8-inch knife immediately after berry set. Twelve healthy grapevines were randomly selected and labeled at each site for the study (Dokoozlian et al. 2001). In 2002, the 'Princess' grapes were harvested in Parlier on July 23, Aug. 1 and Aug. 16; Delano on July 19, July 30, Aug. 12 and Aug. 27; and Arvin on July 17, July 26 and Aug. 8.

In Parlier, 5-year-old 'Princess' vines were grown on their own rootstock in fine sandy loam soil. Six canes, along with four to six two-bud spurs, were retained on each vine at pruning. Gibberellic acid was applied at 1 gram per acre near full bloom to reduce berry set. Vine rows were oriented east-west.

In Delano, 8-year-old 'Princess' vines were grown on their own rootstock in clay loam soil. Vines were bilateral-cordon trained and were pruned using a combination of spurs and canes (approximately eight to ten two-bud spurs and six to eight 15-bud canes per vine) on a "V" trellis system. The vineyard was not treated with gibberellic acid, which is used to reduce berry set and/or increase size. The vines were adjusted to similar crop loads (approximately 20 clusters per vine). Vine rows were oriented east-west.

In Arvin, 8-year-old 'Princess' vines were grown on Freedom rootstock in sandy loam soil. Vine rows were oriented north-south. Vines were pruned using six to eight 12-bud canes and trellised to an open gable system. Gibberellic acid was applied twice. First, 1.5 grams per acre was applied at 80% bloom to reduce fruit set, then 20 grams per acre was applied at fruit set (0.2 to 0.3 inches [6 to 8 mm berry size]) to increase berry size. Clusters were tipped and the vines were adjusted to similar crop loads (approximately 35 clusters per vine).

During both seasons, four clusters were harvested from each replication (48 clusters per harvest date per location total) on each harvest date. Clusters were harvested in the morning (7 a.m. to 10 a.m.) and labeled with a code that included the harvest date, location, vine number and cluster position. Harvested clusters were placed into plastic boxes with cardboard pads in the bottom to reduce

Table grapes that suffer from browning disorders normally have a shorter postharvest shelf life and may not be utilized for long-distance markets, which are often the most profitable.

***Left*, clusters of 'Princess' table grapes were harvested between 7 a.m. to 10 a.m., labeled with a code indicating date, location, vine number and cluster position and placed in plastic boxes with cardboard pads. From the vineyards, grapes were taken in an air-conditioned vehicle to the F. Gordon Mitchell Postharvest Center at KREC for visual inspection and analysis, *right*.**

abrasion damage and were immediately transported to the F. Gordon Mitchell Postharvest Center at the UC Kearney Research and Extension Center in an air-conditioned vehicle.

Quality evaluation at harvest

During both seasons, each cluster was visually evaluated for skin browning upon arrival at the postharvest facility. When more than 15% of the berries were discolored (skin browning), clusters were considered visually unacceptable. After the visual quality evaluation, five berries per cluster were carefully removed to determine firmness, soluble solids concentration, titratable acidity and juice pH (Crisosto, Garner, et al. 2002), which are physical and chemical parameters used to assess berry quality.

These five berries from each replication were pooled (for a total of 60 berries for each set of 12 experimental vines) and pressed through cheesecloth to extract the juice. Soluble solids concentration was measured with a temperature-compensating refractometer (model ATC-1, Atago Co., Tokyo, Japan). Juice titratable acidity and undiluted pH were measured with an automatic titrator (Radiometer, Copenhagen, Denmark) at a final pH of 8.2 and reported as percentage tartaric acid, which is the predominant organic acid in grapes.

At the same time that these measurements were taken, labeled clusters from each harvest date were carefully packed using a plastic pad that slowly released sulfur dioxide (SO_2; 7 grams of sodium metabisulfite)(Tedmark, South Africa) — combined with a perforated, polyethylene box liner (1/4-inch hole, 3-inch center) — to reduce water loss and assure *Botrytis cinerea* control without causing bleaching (Crisosto et al. 1994). Clusters were placed inside a plastic cluster bag and packed in 15.7-by-19.7-inch (40-by-50-centimeter) fiberboard boxes as is done commercially. The slow release, one-phase sulfur-dioxide-generating pad was used in the top of each box, above the cluster plastic bags but inside the box liner. Finally, the boxes were labeled and stored at 32°F (0°C) and 80% relative humidity.

Storage quality evaluation

In the 2001 season, clusters from the three harvest dates were removed from cold storage at 12 weeks after harvest for visual browning evaluations. The number of berries in the sample with skin browning covering more than 25% of the berry's surface was recorded. If more than 15% of the berries in the sample had skin browning, the cluster was deemed "unacceptable" (cull).

In the 2002 season, clusters from each harvest date were removed from cold storage 1, 3, 5 and 7 weeks after harvest for visual browning evaluations. At 1, 3 and 5 weeks after harvest, incidences of berry skin browning and flesh browning were visually evaluated. Flesh browning incidence was the percentage of clusters with one or more berries showing symptoms. At about 7 weeks after harvest (7 weeks at 32°F [0°C] plus 2 days at 68°F [20°C]), all berries were removed and weighed, and skin browning incidence was expressed as a percentage of cluster weight. Flesh browning and internal browning were also expressed as a percentage of cluster weight after each berry was cut in half and examined internally.

Since harvest dates were different at each location, the interaction between harvest date and location was not studied. In both seasons, harvest date was used independently as a main treatment within each location. Twelve vines were used as replicates and four clusters from each replicate were harvested as experimental units. Data analysis was done by ANOVA, whereas mean comparison was carried out by LSD ($P < 0.005$) using SAS.

Harvest date and maturity

In Parlier, there were no significant differences in soluble solids concentration among samples collected on

TABLE 1. Soluble solids concentration (SSC), titratable acidity (TA), SSC/TA ratio and juice pH of 'Princess' table grapes

Vineyard location and harvest date (2002)	SSC	TA*	SSC/TA ratio	pH
	······ % ······			
Parlier				
7/23	17.2	0.70	24.7	3.2
8/1	17.7	0.70	27.8	3.3
8/16	19.7	0.50	42.1	3.6
P value	< 0.0001	< 0.0001	< 0.0001	<0.0001
$LSD_{0.05}$†	0.6	0.07	3.3	0.045
Delano				
7/19	13.8	1.00	14.4	N.A
7/30	15.2	0.70	23.1	3.3
8/13	17.0	0.50	36.8	3.5
8/27	18.9	0.40	48.6	3.7
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$LSD_{0.05}$	0.46	0.04	1.74	0.05
Arvin				
7/17	15.6	0.80	19.2	N.A.
7/26	16.6	0.60	27.1	3.4
8/8	18.4	0.50	37.5	3.7
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$LSD_{0.05}$	0.63	0.04	2.29	0.05

* Titratable acidity (TA) expressed as tartaric acid.

† $LSD_{0.05}$ = least significant difference at the 5% level.

TABLE 2. Skin browning and flesh browning after 7 weeks of storage at 32°F (0°C) for 'Princess' table grape berries

Location and harvest date (2002)	Skin browning*	Flesh browning†
	······· *% cull clusters* ·······	
Parlier		
7/23	0.0	0.1
8/1	23.5	0.5
8/16	58.2	0.8
P value	< 0.0001	0.5932
$LSD_{0.05}$‡	12.3	1.3
Delano		
7/19	0.3	0.1
7/30	3.1	0.0
8/13	33.0	1.0
8/27	55.5	2.0
P value	< 0.0001	< 0.0015
$LSD_{0.05}$	12.6	1.14
Arvin		
7/17	0.1	0.3
7/26	0.0	0.3
8/8	14.4	1.0
P value	< 0.0001	0.0700
$LSD_{0.05}$	5.05	0.69

* Clusters with more than 15% discolored (skin browning) berries were considered visually unacceptable (culls).

† Percentage of clusters having one or more berries with flesh browning. Berries were cut longitudinally to observe flesh browning.

‡ $LSD_{0.05}$ = least significant difference at the 5% level.

the first two harvest dates (17.2% and 17.7%), while samples collected on the third harvest date had a significantly higher soluble solids concentration (19.7%) than those collected on the first two dates (table 1). Titratable acidity decreased significantly between the first and third harvest dates (from 0.70% to 0.50%). The SSC/TA ratio also increased significantly during this period (from 24.7 to 42.1), but did not change significantly between the first two sampling dates. Similarly, juice pH increased between the first and third harvest dates (from 3.2 to 3.6).

In Delano, the soluble solids concentration increased significantly between the first and third harvest dates (from 13.8% to 18.9%)(table 1), as did the SSC/TA ratio (from 14.4 to 48.6). During this period, titratable acidity decreased significantly (from 1.00% to 0.40%). Juice pH increased significantly between the second and third harvest dates (from 3.3 to 3.7).

In Arvin, the soluble solids concentration increased significantly between the first and third harvest dates (from 15.6% to 18.4%)(table 1). During this period, titratable acidity decreased significantly (from 0.80% to 0.50%) and the SSC/TA ratio increased significantly (from 19.2 to 37.5). Juice pH increased significantly between the second and third harvest dates (from 3.4 to 3.7).

Harvesting late resulted in an increase in soluble solids concentration and a reduction in the titratable acidity, thus the SSC/TA ratio increased in the mature grapes.

Harvest maturity and storage time

In both seasons, skin browning was related to harvest date and in turn, grape maturity, but was very low at harvest for all three maturities. Flesh browning was so low that it was not commercially important (< 2.0%), and internal browning was not observed at all. Skin browning was related to grape maturity, because after 12 weeks of storage, grapes from the early harvest had significantly less skin browning than grapes harvested later (fig. 1). Significant changes in skin browning

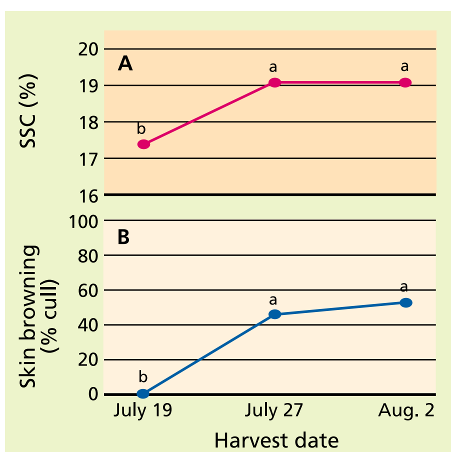

Fig. 1. Relationship between 'Princess' table grape harvest date and (A) soluble solids concentration (SSC) measured at harvest and (B) skin browning measured after 12 weeks of storage at 32°F (0°C), 2001 season.

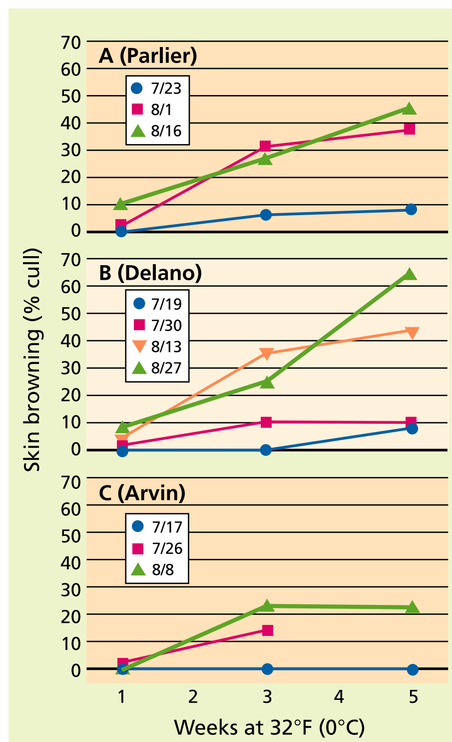

Fig. 2. Relationship between harvest date and the development of berry skin browning in 'Princess' table grapes grown in (A) Parlier, (B) Delano and (C) Arvin, during 5 weeks of storage at 32°F (0°C), 2002 season.

incidence occurred when the soluble solids concentration increased from about 18% to 19% (fig. 1A).

In Parlier, skin browning incidence was low after a week of cold storage, varying from 0% to 10.4% depending on the 2002 harvest date (fig. 2). After 3 weeks, skin browning incidence increased from 6.3% to 31.8%, and after 5 weeks reached 8.3% to 45.8%. Similarly, in Delano the incidence of skin browning was low after a week of cold storage, but increased dramatically after 3 weeks for the second harvest (35%) and reached up to 64.6% after 5 weeks for the fourth harvest. In Arvin, skin browning incidence was substantially lower than in Parlier and Delano but followed a similar pattern of development, increasing with time in cold storage.

After 7 weeks in cold storage, skin browning expressed as a percentage of cull clusters increased significantly in grapes from all three locations (table 2), increasing from the first to the last harvests from 0% to 58.2% in Parlier, 0.3% to 55.5% in Delano, and 0.1% to 14.4% in Arvin. Soluble solids concentration, SSC/TA ratio and pH were significantly positively correlated with skin browning, while titratable acidity was significantly negatively correlated (data not shown). Furthermore, the flesh browning incidence in grapes at all three locations was low after 3 weeks of cold storage but increased dramatically after 5 weeks (fig. 3).

There were no significant differences between harvest dates in a specific location and the duration of cold storage, but there was a clear trend of increasing flesh browning during storage on a specific harvest date. It is important to note that flesh browning during the first 5 weeks of cold storage was measured visually and is therefore subjective. However, even in these evaluations, flesh browning was not a major problem and only reached a maximum of 12.5% among all locations after 5 weeks in cold storage.

After 7 weeks in cold storage, flesh browning incidence expressed as a percentage of cull clusters did not increase significantly during the 2002 harvest period (table 2). Flesh browning incidence was so low (about half a berry per cluster) that it did not have commercial implications and was not related to maturity. In general, 'Princess' table grapes collected from the three locations in California during the 2002 season developed skin browning but not flesh browning during storage.

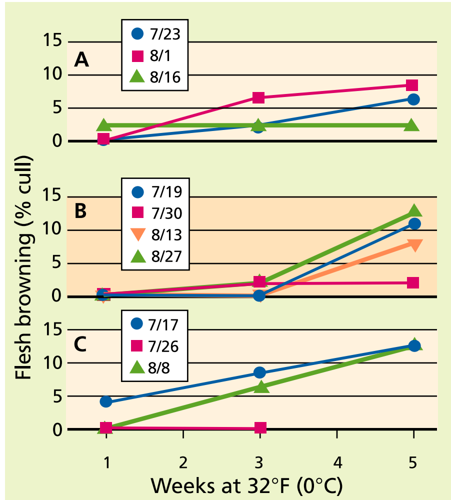

Fig. 3. Relationship between harvest date and the development of berry flesh browning in 'Princess' table grapes grown in (A) Parlier, (B) Delano and (C) Arvin, during 5 weeks of storage at 32°F (0°C), 2002 season.

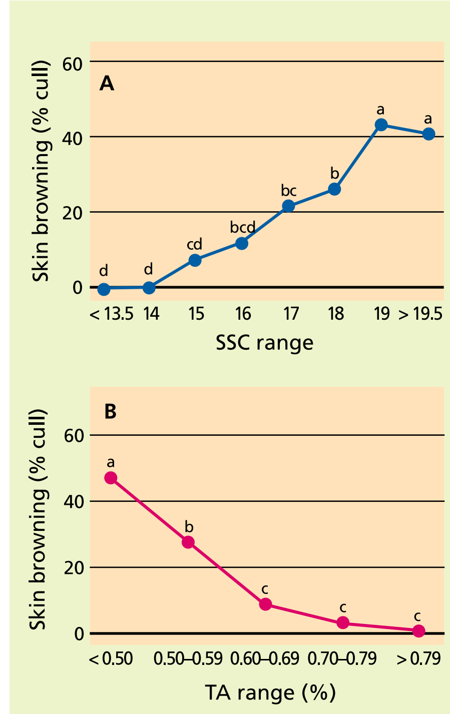

Fig 4. Relationship between 'Princess' table grape berry skin browning and (A) soluble solids concentration (SSC) and (B) titratable acidity (TA), 2002 season.

In contrast, our group reported a significantly higher flesh browning incidence in 2001 than 2002 (Crisosto, Badr, et al. 2002). The differences can be explained by the vineyard conditions in the 2002 study, which were carefully chosen for vines with well-balanced vigor and with healthy and shaded canopies. During the 2001 season, the 'Princess' table grapes were grown in sun-exposed and low-vigor vineyards and subsequently showed more browning problems.

Significant development of skin browning occurred during cold storage of 'Princess' table grapes from all three vineyards. Skin browning was observed after 3 weeks in cold storage and it was strongly correlated with maturity. This data agrees with our previous work (Crisosto, Badr, et al. 2002), in which the incidence of skin browning after 3 weeks at 32°F (0°C) was directly associated with increases in fruit harvest maturity. 'Princess' table grapes that were harvested at low soluble solids concentrations exhibited lower skin browning incidence than those harvested at values above about 18%. Skin browning increased sharply when soluble solids concentration was greater than 16.0% to 18.0% (fig. 4A). High values of titratable acidity concur with a low incidence of skin browning, and maturity was strongly correlated with titratable acidity. Grapes harvested at titratable acidity values between 0.60% and 1.00% showed significantly lower skin browning incidence than those harvested at titratable acidity values below 0.60% (fig. 4B). The degradation of organic acids, such as tartaric, citric and malic, occurred along with fruit maturation. SSC/TA ratios below 25 were associated with considerably lower skin browning than those above 25 (table 1).

However, vineyard location and management were more important than maturity in tissue browning in 'Princess' table grapes. There are many possible reasons for this. First, the phenolic concentration, type of phenolic compounds and polyphenoloxidase (PPO) activity vary for the same cultivar

Davis Krauter

Consumers have come to expect unblemished table grapes in the produce section. Postharvest research is helping growers to supply fresh, attractive produce for the marketplace.

among locations, and from year to year (Sapis et al. 1983). The browning capacity for a specific cultivar and among locations can also be affected by management practices such as irrigation, fertilization, rootstock, trellis system, pruning systems and canopy management (Sapis et al. 1983; Wissemann and Lee 1981). For example, trellis system, nitrogen fertilization, canopy management and rootstocks could play important roles in controlling excess sunlight and hence browning problems.

Growing location is important

Skin browning incidence at harvest was low but its level depends on the level of physical abuse during harvesting operation. The skin browning incidence reached its highest expression after 3 weeks in cold storage and was strongly related to maturity and vineyard location. The effect of location on skin browning incidence was more important than maturity. Flesh browning and internal browning incidences were not commercially important ($\leq$ 2.0%).

The skin browning susceptibility of 'Princess' table grapes increased when berries were harvested at titratable acidity levels less than 0.60% and/or soluble solids concentrations greater than or equal to 16.0%; grapes harvested at an advanced stage of maturity ($\geq$ 18.0% SSC) were more susceptible to tissue browning. To maximize storage potential and taste, 'Princess' grapes should be harvested at a soluble solids concentration between 16.0% to 18.0%.

Skin browning was highly influenced by vineyard location or management; 'Princess' table grapes grown under the specific management conditions of the plot located in Arvin had two to three times less skin browning incidence than those grown in Delano and Parlier.

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Reduced-risk fungicides help manage brown rot and other fungal diseases of stone fruit

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Project Scientist Helga Förster and Staff Research Associate George Driever run nectarines through an experimental packingline at the F. Gordon Mitchell Post Harvest Center at Kearney, to evaluate the performance of new reduced-risk fungicides under realistic postharvest conditions.

New reduced-risk fungicides are highly effective in managing both pre- and postharvest diseases of stone fruit crops in California, and they have replaced most previously registered materials. These fungicides have a low impact on the environment, high specificity to target organisms, and low potential for groundwater contamination and human health risks. In stone fruit, they can be successfully used to manage brown rot blossom blight in a new delayed-bloom fungicide application program for low-precipitation years. In our studies, we found that fungicide treatments applied 1 to 14 days before harvest were also effective against preharvest brown rot and protected fruit from fungal decays initiated during harvest. Practices such as mixtures and rotations can be implemented to prevent resistance from developing and to ensure the lasting efficacy of these reduced-risk fungicides.

IN 1996, the U.S. Congress unanimously passed the Food Quality Protection Act (FQPA). Among other things, the law formalized the U.S. Environmental Protection Agency's (EPA) Reduced-Risk Pesticide Program (initiated in 1993) and mandated that EPA continue to enhance it (EPA 2003, 2004). The FQPA expedited EPA's review and registration decision-making process for pesticides that are classified as less risky to human health and the environment than existing conventional products. The advantages of reduced-risk pesticides may include: low mammalian toxicity, and in turn fewer risks to human health; low toxicity to nontarget organisms (such as bees, birds, fish and plants); low potential for groundwater contamination; low use rates; and compatibility with integrated pest management (IPM) practices (Adaskaveg et al. 2002).

Concurrently, agrochemical companies were on the verge of developing a plethora of new fungicides and fungicide classes, many of which qualified for reduced-risk status. The simultaneous development of these new fungicides by several manufacturers was unparalleled in the history of fungicide or other pesticide discovery and registration (Hewitt 1998; Uesugi 1998).

At the same time, however, the ongoing reregistration of older fungicides and other pesticides — mandated by Congress with amendments to the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) in 1988 — made it financially prohibitive for agrochemical companies to reregister fungicides in the low-profit postharvest market. Postharvest fungicides that were not reregistered after 1996 included benomyl (Benlate), thiophanate-methyl (Topsin-M), triforine (Funginex) and iprodione

Top above, **George Driever inoculates fruit with an aqueous solution of fungal spores. *Above*, an untreated control shows obvious signs of a brown rot infection (top), compared with fruit inoculated 14 to 16 hours before fludioxonil treatment (middle) and fruit inoculated after fludioxonil treatment (bottom).**

Infections of wounds that occur in the field at harvest are effectively stopped by postharvest treatments, typically done the same day.

(Rovral). Our research goal at the UC Kearney Research and Extension Center (KREC) was to evaluate new reduced-risk fungicides for potential pre- and postharvest use on stone fruit crops, in order to proactively identify effective new fungicides and change the way they can be used.

The most important preharvest blossom and fruit disease of stone fruit crops in California is brown rot caused by *Monilinia fructicola* and *M. laxa* (Ogawa and English 1991). On fresh-market peaches, plums and nectarines, *M. fructicola* is the primary cause of blossom blight and pre- and postharvest fruit decay. Other diseases caused by the brown rot fungi include green shoot and mature shoot blights. Shoot blights, however, only occur in very wet environments and with high inoculum levels. Gray mold caused by *Botrytis cinerea* and Rhizopus rot caused by *Rhizopus stolonifer* also result in postharvest fruit losses every year. Thus, all three of these postharvest decays reduce crop yields and render commodities unmarketable (Eckert and Ogawa 1988).

Our trials with reduced-risk fungicides at KREC focused on these diseases. This work was done in cooperation with fungicide manufacturers and state and federal regulatory agencies including the Interregional Research Project No. 4 (IR-4 Project), which conducts residue studies for determining tolerances or maximum residues on "specialty" or "minor-use" crops (generally, those grown on 300,000 acres or less nationwide) such as stone fruit.

Several reduced-risk fungicides were included that have extremely low mammalian toxicity (LD_{50} values from 2,000 to more than 5,000 milligrams per kilogram [mg/kg]) and are not known or suspected as carcinogens (table 1). These materials are either derivatives of naturally occurring compounds (such as fludioxonil [Scholar] and pyraclostrobin [Cabrio]) or were discovered by random chemical synthesis and screening for biological activity (such as boscalid [Endura], fenhexamid [Elevate] and pyrimethanil [Scala or Penbotec]). We evaluated cyprodinil (Vangard), fenhexamid, pyrimethanil and the premixture of boscalid and pyraclostrobin (Pristine) in preharvest studies, and fludioxonil and all the other compounds except cyprodinil in postharvest studies.

For all data reported in the figures, values followed by the same number are not significantly different based on an analysis of variance and LSD mean-separation procedures of SAS version 8.2.

Brown rot blossom blight management

While brown rot–infected blossoms on the tree rarely reduce crop load significantly, they are important inoculum

TABLE 1. Conventional and reduced-risk fungicides for management of pre- and postharvest decays of stone fruit

Common name	Trade name	Class	Rates*	Year of federal registration: Preharvest	Year of federal registration: Postharvest
			oz. a.i./100 gal		
Reduced risk					
Boscalid/pyraclostrobin†	Pristine	Anilide/strobilurin	5.6	2004	Expected 2005
Cyprodinil	Vangard	Anilinopyrimidine	3.75, 7.5‡	2000	Not planned
Fenhexamid	Elevate	Hydroxyanilide	12	2002	2004
Fludioxonil	Scholar	Phenylpyrrole	4	Not planned	2003
Pyrimethanil	Penbotec	Anilinopyrimidine	11.4	Expected 2006	Expected 2006
Conventional					
Dicloran	Allisan, Botran	Dicarboximide	15.6–27.6		
Propiconazole	Orbit	SBI-triazole	1.8		
Tebuconazole§	Elite	SBI-triazole	3.6		

* Rates are ounces of active ingredient per 100 gallons of water/acre (preharvest) or 200,000 lbs. fruit (postharvest).
† Boscalid and pyraclostrobin (Pristine) are marketed as a premixture.
‡ Cyprodinil was applied at 3.75 oz. a.i./100 gallons water/acre in the brown rot blossom blight control trial (fig. 1) and at 7.5 oz. a.i./100 gallons water/acre in the preharvest study (fig. 2).
§ Only registered for use on sweet cherry.

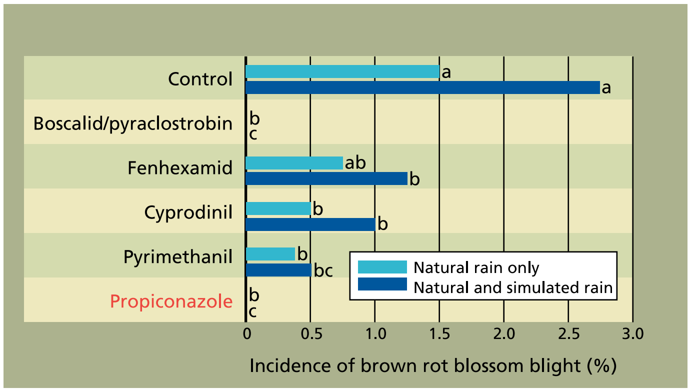

Fig. 1. Efficacy of reduced-risk, delayed-bloom fungicide applications for management of brown rot blossom blight in 'Elegant Lady' peaches with natural rain only (0.39 inches in 2003 and 0.79 inches in 2004), and natural rain plus simulated rain. Average of 2003 and 2004 data is shown. Conventional fungicide is shown in red type.

Without a postharvest fungicide treatment, fruit usually cannot be shipped to distant markets or displayed in the market at shelf temperatures without risking decay. Commercial, low-volume postharvest fungicide applicators include the "wigwag," *top*, and controlled droplet applicator, *bottom*, which are among the more popular methods because there is little to no fungicide runoff.

sources for fruit infections. The management of blossom blight involves integrating orchard sanitation with the judicious use of fungicides. Important sanitation practices include the removal of mummified fruit from trees and orchard floors after harvest as well as brown rot cankers during pruning. Previously, UC guidelines suggested a two-application program of fungicides at the phenological blossom stages of pink bud (5% bloom) and full bloom (80% bloom). The current updated guidelines (www.ipm.ucdavis.edu/PHG) are based in part on the research presented here. They indicate that a delayed, 20% to 40% bloom treatment should be made followed by a second application at 80% to 100% bloom, if heavy rain or other weather conditions (such as dense fog and warm temperatures) are conducive to fungal diseases.

In 2003 and 2004, we compared the efficacy of the new reduced-risk fungicides with that of older fungicides (which generally require higher application rates) in a stone fruit orchard at KREC. A single delayed-bloom application (20% to 40% full bloom) was done. Although blossom infections could have already occurred at this bloom stage, our intent was to evaluate the fungicides for their protective and postinfection activity. In addition to natural rain (0.39 inches in 2003 and 0.79 inches in 2004 during the 2-week bloom period when the trial was conducted), simulated rain was provided by two high-angle overhead sprinkler irrigations of 6 to 8 hours each, within 5 days after fungicide application. This was done to find out how treatments would perform under high rainfall and subsequent microclimate alterations associated with wet conditions — such as high relative humidity — which may occur in California during wet springs.

Similar trends were obtained for all treatments in both years. With simulated rain, the reduced-risk materials were effective in reducing brown rot incidence as compared with the untreated control, but some of them were more effective under ambient conditions (natural rain only)(fig. 1). With boscalid/pyraclostrobin or propiconazole, no disease was found under simulated or natural rain conditions. In addition, in years (2001 and 2002) when natural rainfall was low during the bloom period, no disease was detected in any of the treatments evaluated in our trials, whereas in the control, 1.5% of the blossoms were diseased. Although this blossom blight incidence may seem low, it is a moderate disease level considering the amount of new inoculum that can be produced to contaminate developing fruit in the current growing season. The reduced-risk fungicides performed as well as the conventional products tested, and one application was enough to reduce brown rot pressure in years when conditions were less conducive to disease.

Preharvest treatments

In California's semiarid climate, brown rot fruit decay before harvest is generally less severe than postharvest decay of untreated fruit, unless the fruit are mature and rain occurs at harvest time (similar to stone fruit production in high rainfall regions) or improper irrigation practices create favorable environments for disease. Decay may develop from conidia (spores) contaminating fruit surfaces or from recent infections or quiescent (latent) infections that occur with brown rot and gray mold. Inoculum from mummified fruit, twig cankers or blighted blossoms commonly contaminates fruit surfaces during the growing season. Quiescent infections (in which the fungus enters plant tissue but does not continue to grow or cause disease until later) are initiated much earlier in the season. Growth of the pathogen, however, does not continue because fruit are immature and resistant to fungal decay. As fruit ripen, rapid decay may result before or after harvest even when environmental conditions at harvest time are not conducive to infection. Still, quiescent infections are considered only a minor cause of fruit decay in most years (Emery et al. 2000).

In general, preharvest fungicide treatments reduce inoculum (preventing infections that later sporulate or inhibiting sporulation of existing infections) or prevent quiescent and active infections on

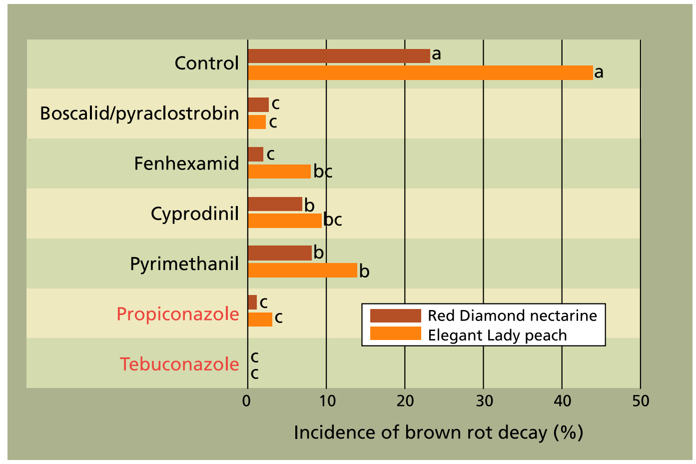

Fig. 2. Efficacy of reduced-risk preharvest fungicides to manage natural incidence of brown rot fruit decay. Treatments were applied using an air-blast sprayer (100 gal/acre) at 14 days and 1 day before harvest for 'Red Diamond' nectarines, and at 7 days and 1 day before harvest for 'Elegant Lady' peaches. Conventional fungicides are shown in red type.

fruit before harvest. Furthermore, these treatments can protect against wound infections that occur during harvesting operations. Fruit injuries may occur from contact with plant debris, soil particles or equipment surfaces, or from improper handling by harvesters. Preharvest fungicide treatments can reduce the incidence of postharvest fruit decay, which is especially important when fruit is exported to countries that do not allow the use of postharvest fungicides.

In all of our evaluations we tried to simulate standard commercial fruit-handling practices as closely as possible. In general, stone fruit are harvested, stored and shipped at low temperatures, and then marketed in grocery stores and ripened by consumers at ambient temperatures. Preharvest fungicide applications were evaluated over several seasons from 2001 to 2003 in 'Red Diamond' nectarine and 'Elegant Lady' peach orchards at KREC. Treatments were made at 14 days and 1 day before harvest, or at 7 days and 1 day before harvest, using an air-blast sprayer calibrated for 100 gallons per acre on four or five single-tree replications for each treatment in a randomized plot. Harvested fruit were evaluated either for the natural incidence of decay or for decay protection, after we manually wounded and inoculated the fruit with decay pathogens. For both evaluations, harvested fruit were refrigerated for 1 week at 33°F to 37°F and then transferred to an incubation room maintained at 68°F (approximately room temperature). Fruit were wounded (using a small, beveled-edged nail that simulated a fingernail scratch) and inoculated with conidia of the brown rot fungus *(M. fructicola)* or gray mold fungus *(B. cinerea)*.

In our studies, brown rot was the main natural decay that developed on the incubated fruit. On both stone fruit cultivars, all fungicides evaluated significantly reduced the incidence of decay (fig. 2), including the sterol biosynthesis inhibiting (SBI) fungicides (propiconazole and tebuconazole) and the reduced-risk materials (boscalid/pyraclostrobin, fenhexamid, cyprodinil and pyrimethanil). Decay incidence after wound inoculations on unwashed fruit was also significantly reduced by all treatments for both brown rot and gray mold (fig. 3A), but the efficacy of the reduced-risk materials was generally lower than in our studies on the natural incidence of decay.

In additional studies, preharvest-treated fruit were washed postharvest over a brush bed on an experimental packingline using chlorine water (100 parts per million [ppm] sodium hypochlorite), rinsed with plain water and treated with a postharvest fruit coating, again similar to commercial practices, and fruit were then wound-inoculated. This washing step further reduced the efficacy of the reduced-risk materials against brown rot decay, and this was correlated with a reduction of fungicide residues in fruit. In contrast, the SBI fungicide treatment (tebuconazole) was still highly active against brown rot. However, cyprodinil and pyrimethanil were still very effective against gray mold decay (fig. 3B).

These studies on preharvest fungicide applications demonstrated several characteristics of the new group of fungicides. First, some of the new fungicides — particularly boscalid/pyraclostrobin — performed as well as the SBI materials for managing natural decay. SBI fungicides set the standard for effective preharvest treatments of stone fruit after iprodione was cancelled for preharvest use in 1998. In addition, the new reduced-risk materials generally were less effective when fruit were wounded after treatments, indicating that there is little penetration into the fruit and

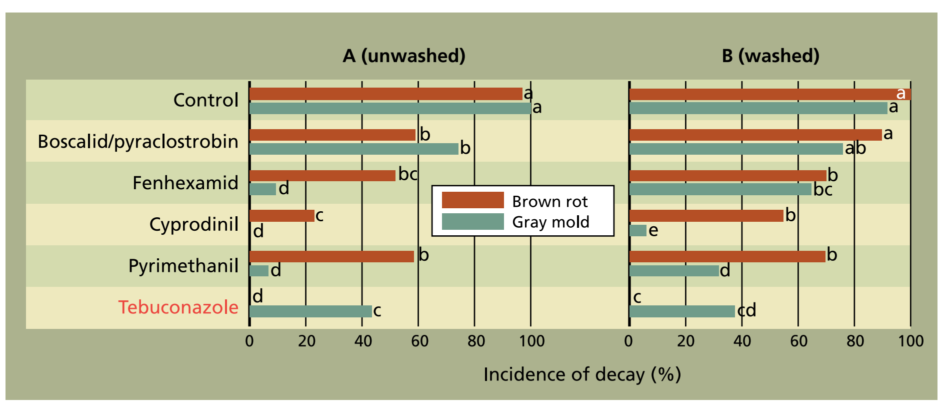

Fig. 3. Efficacy of reduced-risk preharvest fungicide applications for management of brown rot and gray mold fruit decay in 'Elegant Lady' peaches after wound inoculation. Treatments were applied using an air-blast sprayer (100 gal/acre) at 7 days and 1 day before harvest. After harvest, fruit were left (A) unwashed or (B) washed, and waxed on an experimental packingline and wound-inoculated with conidia of either decay fungus. Conventional fungicide is shown in red type.

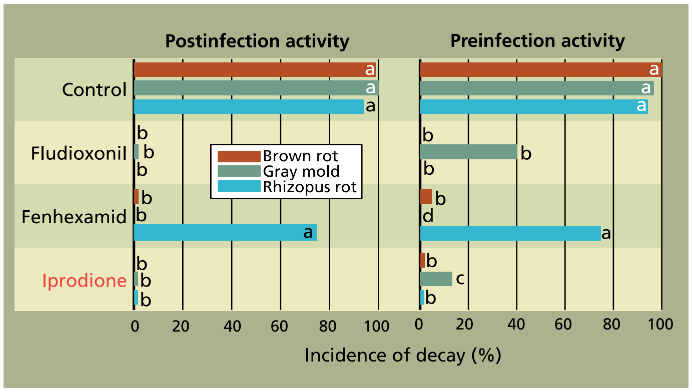

Fig. 4. Efficacy of reduced-risk postharvest fungicide applications to manage fruit decays of 'Red Diamond' nectarines. Treatments (postinfection, 12 to 14 hours after inoculation; and preinfection, before inoculation) were done in a diluted emulsified mineral oil–based fruit coating using a low-volume controlled droplet applicator (for rates, see table 1). Conventional fungicide is shown in red type.

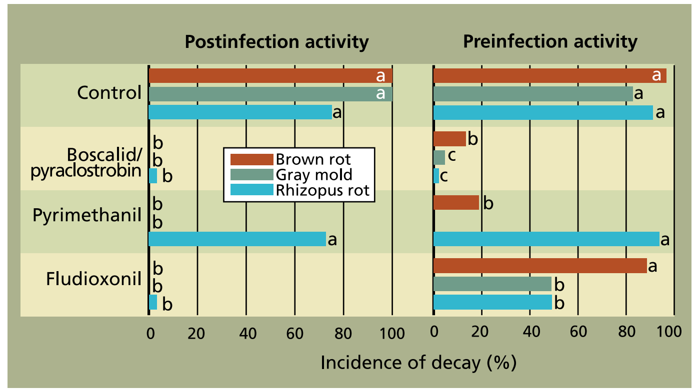

Fig. 5. Efficacy of reduced-risk postharvest fungicide applications to manage fruit decays of 'Red Diamond' nectarines. Treatments (postinfection, 12 to 14 hours after inoculation; and preinfection, before inoculation) were done in a diluted emulsified mineral oil–based fruit coating using a high-volume T-jet application system (for rates, see table 1).

demonstrating that these materials are mainly wound-protectants.

Furthermore, fungicide residues on the fruit surface can be removed to a large degree by washing, as shown by the reduced decay control that we found in our experiments (fig. 3). Although growers and packers find this less desirable, consumers want less pesticide residue on their fruit. Pesticides that have extremely low mammalian toxicity and are easily removed by washing will be more acceptable to the consumer than previously registered products.

Postharvest fungicide applications

Postharvest decay fungi infect stone fruit tissue through wounds that occur either before harvest or, more importantly, during or after harvest. The main goals of a postharvest decay management program are to: avoid fruit injuries, keeping the fruit healthy and nonsenescent; remove pathogen inoculum from the surface by sanitation; inhibit the pathogen in infections that may occur at harvest; and protect the fruit from infections during postharvest handling, shipping and marketing. In wet years conducive to disease, a large portion of the crop may be destroyed by postharvest decay. Without a postharvest fungicide treatment, fruit usually cannot be shipped over long time periods (2 to 3 weeks) to distant markets or displayed in the market at shelf temperatures without decay developing, making it difficult to ensure that high-quality fruit reaches the consumer (Adaskaveg et al. 2002).

Postharvest fungicides were evaluated on an experimental packingline at KREC. This packingline includes a brush wash bed, a drying area with sponge rollers, and low- and high-volume fungicide application equipment over brush and roller beds. The setup is similar to commercial treatment systems, albeit downscaled. We determined the spectrum of activity of the fungicide treatments, as well as the optimum application methods and compatibilities with the most commonly used fruit coatings, which improve appearance and prevent water loss from healthy, ripening fruit.

Fruit were either: (A) inoculated, incubated for 14 hours at 68°F, treated with fungicides and incubated for decay development at 68°F; or (B) treated, inoculated and then incubated. These schedules were used to obtain information on the post- (such as wound protection) and preinfection activity of the fungicides, respectively. We evaluated the efficacy of the treatments as the incidence of decay compared with the untreated control.

To control brown rot and gray mold, fenhexamid, boscalid/pyraclostrobin, pyrimethanil and fludioxonil showed excellent activity as postinfection treatments, while fenhexamid and pyrimethanil were not effective against Rhizopus rot (figs. 4, 5). The efficacy of the fungicides as preinfection treatments was generally lower and inconsistent for fenhexamid, boscalid/pyraclostrobin and fludioxonil. These fungicides are mainly wound-protection treatments that are highly effective in preventing decay from infections when initiated up to 16 hours before treatment. Infections of wounds that occur in the field at harvest are effectively stopped by postharvest treatments, typically done the same day. Our data also indicates that the new reduced-risk fungicides, particularly boscalid/pyraclostrobin and fludioxonil, have a spectrum of activity and efficacy comparable to the cancelled iprodione (table 2).

TABLE 2. Efficacy (+++ = most effective to – = ineffective) of conventional and reduced-risk postharvest fungicides as wound-protection treatments of stone fruit

Fungicide	Brown rot	Gray mold	Rhizopus rot
Reduced risk			
Boscalid/ pyraclostrobin	+++	+++	+++
Fenhexamid	++	+++	–
Fludioxonil	+++	+++	+++
Pyrimethanil	++	+++	–
Conventional			
Dicloran	++	+++	
Iprodione*	+++	+++	+/+++†
Tebuconazole‡	+++	++	+

* Iprodione was cancelled for postharvest use in 1996.
† Only highly effective against Rhizopus rot when used in a fruit coating.
‡ Only registered for use on sweet cherry.

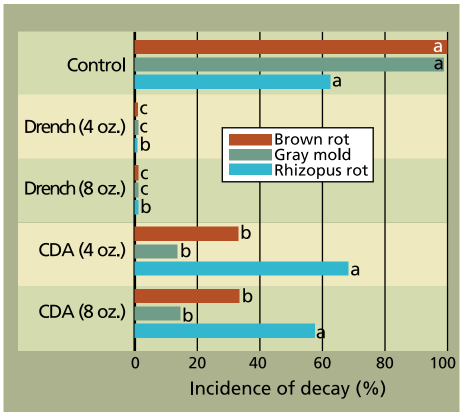

Fig. 6. Postinfection activity of fludioxonil treatment (14 to 16 hours after inoculation) to prevent fruit decays of 'Casselman' plums, with low-volume controlled droplet applications (CDA)(rate is per 10 gallons water, per 200,000 pounds fruit) on a roller bed, and drench applications in aqueous solutions (rates are per 100 gallons water per 200,000 pounds fruit) followed by CDA, both with diluted carnauba fruit coating.

Application methods compared

Postharvest application methods were evaluated to maximize fungicide efficacy and minimize disposal issues and costs. Among the application methods used commercially, low-volume and ultra-low-volume controlled droplet applications (CDA; 1 to 25 gallons of solution per 200,000 pounds of fruit) are currently the most popular because there is little or no fungicide runoff as compared with high-volume application methods (generally 100 gallons per 200,000 pounds of fruit). Fungicide runoff cannot be easily disposed of in the sewer systems of most municipalities. In peaches and nectarines, the low-volume fungicide treatment can be applied on a brush bed to the wet, washed fruit, dispersing it evenly over the surface. Treating smooth-skinned plums is more problematic because the waxy fruit surface often prevents sufficient uniform coverage. In addition, removal of the waxy bloom on plums by brushing may decrease their desirability in some markets.

As an alternative for plums, we evaluated recirculated, high-volume drench applications over a roller bed. Although this method uses a large volume of fungicide solution, any runoff is collected and recirculated for reuse. To prevent microbial contaminants from growing in the fungicide solution, a sanitizer must be added and the fruit must be thoroughly washed before treatment. Fludioxonil is particularly suited for this type of application because it is very stable in sodium hypochlorite solutions at 100 parts per million (ppm) active chlorine, while the recirculating application system makes this expensive material more cost-effective. In our studies, drench applications were significantly more effective wound-protection treatments than low-volume spray applications (fig. 6). In addition, we observed that fruit treated with aqueous fungicide drench applications over a roller bed followed by a CDA application with a carnauba-based fruit coating retained most of their natural bloom, for a higher market value.

Resistance management is key

Reduced-risk fungicides have an unparalleled safety profile and are equivalent or superior in their efficacy to previously and currently registered older fungicides for management of pre- and postharvest diseases in stone fruit. Cyprodinil, fenhexamid and boscalid/pyraclostrobin are fully registered for preharvest use (table 1). Fludioxonil was registered for postharvest use on all stone fruit in 2003. Due to its light-sensitivity with degradation in ultraviolet light and nonpersistence in the environment, fludioxonil will not be considered for a preharvest registration.

Because the new materials belong to different chemical classes with modes of action different from the older fungicides, resistance management programs can be designed that are based on mixtures and rotations of materials (Kendall and Hollomon 1998). In addition, good stewardship of these single-site mode of action compounds should include proper application procedures (Adaskaveg and Forster 1999) that leave adequate fungicide residues on the fruit and the appropriate disposal of fungicide runoff and fungicide-treated culls. Reduced-risk fungicides will not completely replace the older fungicides in the near future, but safer chemical control options will be available in many situations. The most important role of the older materials will be their inclusion in resistance management programs with the newer products. With appropriate strategies, the new reduced-risk tools should be available for years to come.

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REVIEW ARTICLE

Conventional and molecular assays aid diagnosis of crop diseases and fungicide resistance

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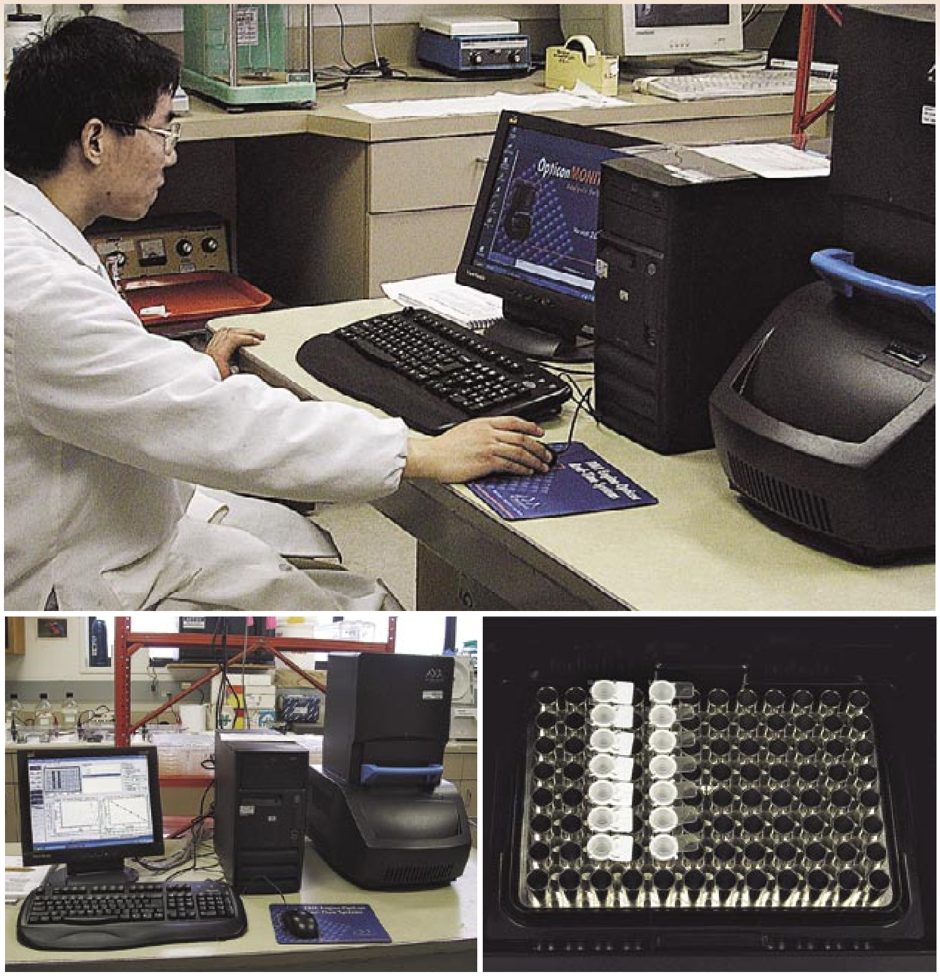
Zhonghua Ma
Yong Luo
Daniel Felts
Mark A. Doster
Heraclio Reyes

For the past decade, we have been developing techniques for monitoring pre- and postharvest diseases of tree fruit, nuts and vines at the UC Kearney Research and Extension Center (KREC). We have also advanced new methods to monitor pathogen resistance to fungicides, which growers can now use to make decisions on disease management. Although accurate, the conventional techniques are time-consuming and only provide results after 5 to 21 days. Molecular methods offer the possibility of faster, more reliable and efficient tests. We have developed such methods to monitor, diagnose and quantify crop pathogens. We have also used these new molecular techniques to answer complex questions on the biology of tree fruit and nut pathogens, the origin of their inoculum sources, changes in their population structures and the epidemiology of the diseases they cause. We are now working on molecular techniques that could supplement the conventional ones we have developed for vine diseases. Private diagnostic laboratories have been using a number of these conventional techniques and plan to adopt some of the molecular ones in the near future.



Kearney scientists, including post-doctoral associate Zhonghua Ma, *above*, are developing advanced diagnostic tools to more quickly and accurately predict pre- and postharvest diseases of tree fruits, nuts and vines. For instance, spore-trap tapes in the field capture tiny fragments of DNA from airborne fungal spores, which can be identified within hours in laboratory molecular assays, *bottom*, while conventional methods require a week or more.

Our research at the UC Kearney Research and Extension Center (KREC) seeks to expand epidemiological knowledge of fungal diseases of tree fruit, nuts and vines in order to predict disease risk during the growing season — at harvest and during postharvest storage — and to predict resistance to fungicides. Both conventional and molecular methods can provide powerful decision-making tools for growers, enabling them to predict the emergence of latent disease, identify the sources and structure of fungal populations, and detect the emergence of pesticide resistance in fungal populations. Although the conventional techniques can be accurate and less expensive, only minimal information concerning a few isolates becomes available 1 to 3 weeks after testing. This can be a critical period for growers, who must make disease management decisions such as when and how to spray fungicides and which resistance-management programs to employ in the field.

Currently, molecular methodology requires costly, specialized reagents and enzymes and expensive special equipment (PCR and RT-PCR machines) and is two or three times more expensive than the conventional methodology. Presently, none of the specific molecular methods are available to the average grower due to prohibitive costs and requirements for specialized lab facilities, equipment and specific training. Nor can UC research laboratories run samples for growers on a fee-per-sample basis. However, when afford-

'Howard Sun' plum fruit show quiescent (small black specks) and latent (invisible) infections by *M. fructicola*, to compare conventional and molecular diagnosis techniques.

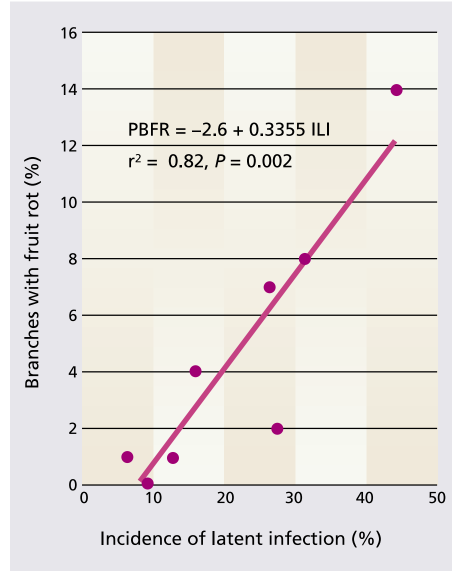


Fig. 1. Linear regression between incidence of latent infections (ILI) and percentage of branches with fruit rot (PBFR) caused by *M. fructicola* on prune, detected by the ONFIT technique. Each dot represents an average value of multiple locations and inoculations.

able, portable molecular instruments and simple protocols are developed, we expect the routine, accurate and quick diagnosis of many crop diseases to be possible, even in the field. Private diagnostic laboratories have been adopting molecular methods for detecting and identifying plant diseases, and we recommend that they adopt the methods described here.

For example, we have learned that latent infections are correlated with subsequent disease emergence in the field or postharvest. Although conventional methods can detect latent infections, they are based upon a 1- to 3-week process of subjecting infected tissues to tissue-damaging agents (such as paraquat) or conditions (freezing), followed by the incubation of samples. Additionally, there are many variations in the type, number, duration and sequence of these processes. Molecular techniques can provide the basis for the efficient, accurate and rapid detection of pathogen inoculum — and are already being used to supplement critical conventional methods.

Predicting disease risk

The dynamics of plant disease development include: (1) the absence or presence and quantity of the pathogen's inoculum, (2) the stage and susceptibility of the crop and (3) the environmental conditions that are conducive to disease. These three factors are continuously changing and make the development of accurate predictive models difficult, complex and time-consuming.

Although increasingly accurate weather predictions are available through the National Oceanic and Atmospheric Administration (NOAA), other aspects of the disease triangle require a large database of information. The pathogen's spore inocula can be quantified by trapping spores, or predicted based on disease incidence in previous seasons (historical disease data). The most susceptible stage of the crop can be determined experimentally by periodic inoculations with the pathogen.

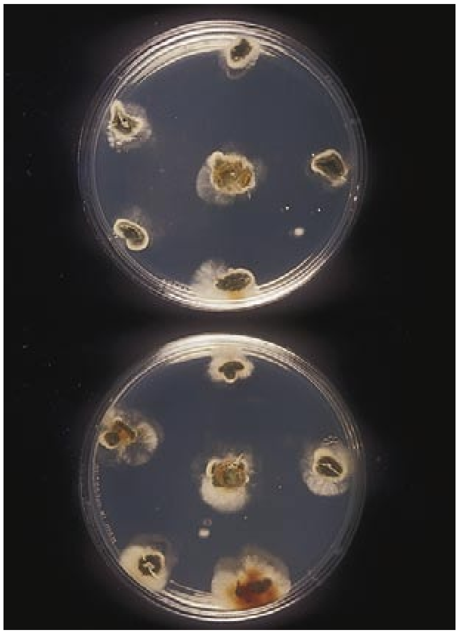
In many plant diseases, latency is an important epidemiological stage. In latent infections, the host and parasite coexist for a period with minimal damage to the host; latency involves an asymptomatic parasitic phase that eventually gives rise to visible symptoms if conditions are favorable for disease development (Verhoeff 1974). If latent infections are at high levels and develop into active symptoms, then a disease epidemic can occur. Latent infections of grapes, kiwifruit, stone fruit and nut crops remain inactive or may not survive until these fruit start to mature and environmental conditions become favorable for disease development. In most cases, the incidence of latent infections correlates with disease incidence in the field at harvest of tree fruit and nut crops (Michailides et al. 2000) or with the incidence of decays that develop in storage (Michailides and Morgan 1996).

The management of tree fruit diseases depends on the level of disease itself, environmental conditions, effective cultural manipulations, knowledge of pathogens' sensitivity to fungicides, and the proper selection and timing of fungicide sprays. If growers had access to timely information on the presence of disease, the structure of fungal populations and the presence of fungal resistance to fungicides, they could make correct decisions on resistance management programs to avoid failures of disease control in the field or a buildup of resistance in the pathogen's population.

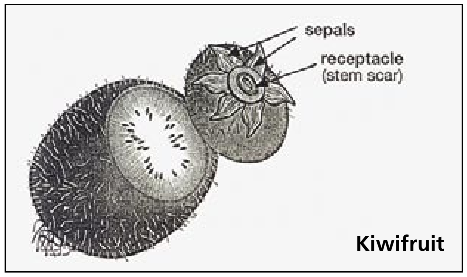
Conventional techniques take time

The accurate identification and early detection of plant pathogens are the cornerstones of successful disease management. The morphological identification of plant pathogens is often difficult and time-consuming and requires extensive knowledge of taxonomy and experience in recognizing detailed fungal features.

Direct agar plating technique (DAPT). This technique isolates fungal plant pathogens from symptomatic plant tissues. The agar medium commonly used for the DAPT in our laboratory is acidified potato dextrose agar (APDA) adjusted to an acid pH of 3.5 by amending 2.5 milliliter of lactic acid (25% strength) per liter of medium. The



The conventional BOTMON technique can reveal *Botrytis cinerea* in sepals of kiwifruit plated in Petri dishes containing acidified potato dextrose agar.



acid pH is inhibitory to the majority of bacteria, but allows most fungal pathogens to grow when the Petri plates are incubated at 68°F to 77°F (20°C to 25°C) for 4 to 7 days. The DAPT can also be used to isolate latent infections from asymptomatic fruits and nuts using parts of tissues and contact areas (Michailides and Morgan 1997).

***Botrytis* monitoring (BOTMON).** This technique detects latent infections by *Botrytis cinerea* of kiwifruit *(Actinidia deliciosa)* sepals in the field. The incidence of latent infection is a good predictor of gray mold in cold storage (Michailides and Morgan 1996; Michailides and Elmer 2000). BOTMON involves the collection of fruit samples with stems attached, and the removal and plating of sepals or stem ends in APDA. We found that 1 month before harvest is the best time for sampling immature fruit to perform BOTMON and gray mold prediction. The results of the colonization of sepals and/or stem ends by *B. cinerea* become available 9 days after plating, and growers can use standardized tables to predict the levels of gray mold in cold storage.

In California, kiwifruit growers are increasingly using the BOTMON technique to make decisions on the need for preharvest fungicide sprays. Also, packinghouse operators and shippers use the results to determine needs for sorting and repacking fruit, to minimize secondary spread of disease in storage and to plan for fruit marketing. If growers spray only when needed (only vineyards with high incidence of latent infection), they reduce cost, increase revenue and reduce environmental contamination. The only disadvantage of the technique is that it is time-consuming.

Bud monitoring of *Botryosphaeria* (BUDMON). In the last two decades, we have seen more diseases caused by *Botryosphaeria dothidea.* In pistachios *(Pistacia vera)*, it caused severe epidemics in 1998 with major yield losses. *B. dothidea* produces a multitude of spores in flasklike structures (pycnidia) that overwinter on the tree. Rains during summer, fall and winter spread the pathogen spores from infected parts of the trees to newly formed buds. As soon as buds develop, *B. dothidea* can infest them in latent form, allowing them to appear healthy, or can infect and kill them (Michailides and Morgan 2004). We developed a technique based on DAPT, which is used to reveal latent infections caused by *B. dothidea* in floral and vegetative healthy-looking buds of pistachio (Michailides 1991). Results are available 5 to 7 days after plating and incubation.

Overnight freezing incubation technique (ONFIT). This technique is frequently used in our laboratory to detect and quantify latent infections of *Monilinia fructicola* and *Monilinia laxa*, which cause brown rot in stone fruit (fig.1); *Botrytis cinerea* in grapes, which causes bunch rot preharvest and gray mold postharvest; and *B. dothidea* and *Alternaria* species, which cause blight diseases in pistachio. The test takes advantage of the fact that killing the fruit and leaf tissues at a stage when they do not favor disease development triggers the development of latent infections into active disease symptoms or accelerates the growth of hidden plant-tissue colonists. Our laboratory developed the ONFIT technique as an alternative to the use of the herbicide paraquat, which triggers the same events. Freezing and incubation eliminate the use of this toxic substance. While this is an improvement, the test still requires up to 7 days (Luo and Michailides 2003), during which an orchard could incur significant damage.

Molecular assays quick, accurate

We have developed several molecular methods that can supplement and may someday replace the slower conventional techniques. The polymerase chain reaction (PCR), which revolutionized molecular biology when it was first described in 1985, has been used to identify pathogens and determine their population structures, taxonomy and classification. This sophisticated yet increasingly common technology can definitively determine, for example, whether a piece of plant includes the genetic material of a microbe. Additionally, in the last several years we have applied techniques to quantify pathogen DNA, and these can be very useful to predict disease risk when the relationship between quantities of pathogens' DNA in latent infections

Molecular technology increases understanding of the biology and population structures of plant pathogens, provides quick and accurate answers to epidemiological questions about plant diseases, and supports disease-management decisions.

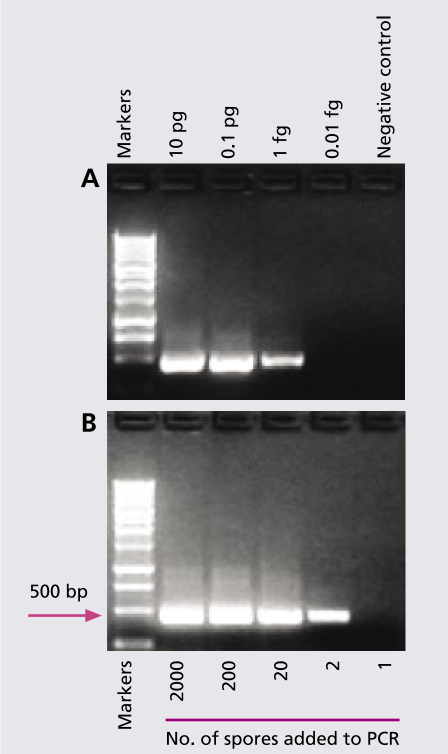


Fig. 2. (A) A sensitive molecular method (species-specific polymerase chain reaction) that can detect a fentogram (0.000000000000001 gram) of DNA from *M. fructicola*, the pathogen causing brown rot in stone fruit. (B) Another molecular technique (nested-PCR) can detect DNA of two spores of the pathogen. The tall column (gel) is a marker of the known molecular weight, which is used as a reference to quantify the amounts of the short columns (gels). Base pairs (bp) is a unit showing the size of DNA; the larger the bp, the heavier (or longer) the DNA; pg = picogram (10^{-12} g); fg = fentogram (10^{-15} g).

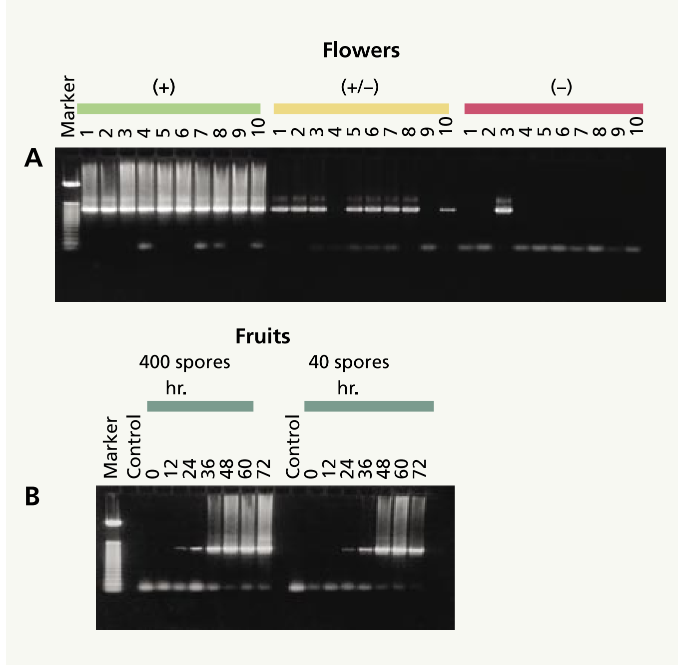


Fig. 3. Molecular techniques can detect *M. fructicola* in (A) plum flowers collected from the field and (B) fruit inoculated with different concentrations of spore suspension of the brown rot pathogen and after various hours of incubation.

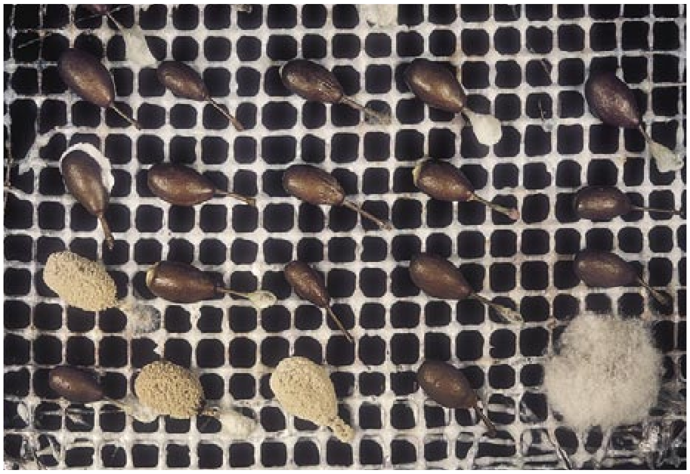
and disease levels has been established. Many plant pathologists are working toward establishing these relationships (the quantity of pathogen DNA to disease levels), especially now when recent advanced technology can quantify the pathogens' DNA in plant tissues with great accuracy. However, because disease levels depend on weather conditions, it takes several years to establish such relationships. These techniques could aid in estimating disease potential and levels of latent infections relevant to disease in the field or during postharvest storage.

Brown rot in stone fruit

Brown rot, caused by *M. fructicola* or *M. laxa*, is a destructive disease of stone fruit (*Prunus* spp.) in California. The infected mummies of stone fruit harbor spores of brown rot pathogens, known as conidia and ascospores. Ascospores, produced only by *M. fructicola*, develop in cuplike structures (apothecia). (*M. fructicola* and *M. laxa* both produce conidia; however, conidia are not produced in apothecia.) The spores disperse in the air and infect blossoms, causing blossom blight. Subsequently, young fruit can become infected and eventually rot. When fruit bearing latent infections are thinned, they develop numerous conidia — especially under high relative humidity. Conidia can disperse and cause additional fruit infections in midseason. As fruit matures, a number of latent infections may develop into fruit rot. The inoculum potential (amount of a pathogen's spores) in orchards is an important factor in blossom blight and fruit infection (Luo and Michailides 2001, 2003). Determining inoculum potential in early- and midseason is critical for predicting brown rot accurately and managing it effectively.

However, inoculum potential is the most difficult disease parameter to determine in a stone fruit orchard. Currently, spore traps are used to determine the density of airborne disease agents, including *M. fructicola*. Because samples from traps require microscopic examination, this method is time-consuming and requires special training to recognize, count and culture spores, making it impractical for recording the large number of samples necessary for a large-scale disease management system.

PCR-based assays have the potential to monitor airborne inoculum levels of plant pathogens because they are highly specific and sensitive. Initially, we developed species-specific primers for the detection of *M. fructicola* in California stone fruits and flowers (Boehm et al. 2001). And recently, we developed a special PCR (nested-PCR), which is a very sensitive method for the detection of *M. fructicola* on spore-trap tapes (Ma, Luo, et al. 2003). First, sensitivity tests in the laboratory showed that the nested-PCR assay could detect the specific DNA piece in as little as 0.000000000000001 gram (or 10^{-15} gram) of *M. fructicola* DNA (fig. 2A) or in DNA from only two spores of *M. fructicola* (fig. 2B), which is a much higher degree of sensitivity than was previously possible. However, in a spore-trap tape sample from the field, the nested-PCR method can only detect 200 or more spores because of various inhibitors. Using these species-specific primers, we can also detect latent infections in fruit caused by *M. fructicola* within hours, while the DAPT or



Prune fruit show brown rot symptoms after processing with the overnight freezing incubation technique (ONFIT) and incubating for 7 days at 74°F (23°C).

Brown rot grows on prune fruit (without freezing) after sterilization and incubation with latent infections of *M. fructicola* for 2 to 3 weeks at 74°F (23°C) under 95% relative humidity.

ONFIT would require at least 1 week (table 1). Since the nested-PCR assay cannot quantify the exact number of *M. fructicola* spores on a spore-trap tape, we are now working on a real-time (RT)-PCR technique that can do so.

Comparison of methods. In March and April 2001, hundreds of flowers of 'Royal Diamond' plum were collected from a commercial orchard in Reedley, Calif. A subsample of 30 flowers was divided into three groups based on visual symptoms: flowers heavily infected with *M. fructicola* and showing obvious signs of fungal sporulation on the stem and calyx surface, and designated (+); flowers displaying brown patches on the petals but no external signs of fungal sporulation (+/–); and flowers without any evidence of brown discoloration or fungal infection (–). Using these flowers, the PCR detected the DNA of *M. fructicola* in all (100%) of the (+) flowers, 80% of the (+/–) and only in 10% of the (–) flowers (fig. 3A).

These results were confirmed as accurate by plating (on APDA) another subsample of 30 flowers, providing a potentially useful method for assessing disease risk and blossom blight incidence and developing pre- and postharvest chemical control strategies against brown rot. This study took about 8 hours for collecting and testing the flowers. However, results from the plating of flowers became available after 4 days. Private laboratories could take this technology and offer it to growers right now. The PCR technique could supplement or replace the flower incubation technique (FIT), which provides an estimate of inoculum potential in stone fruit orchards in about 4 to 5 days.

In a second experiment conducted in an orchard with 'Howard Sun' plums, the presence of numerous visible quiescent infections suggested the presence of even more latent (invisible) brown rot infections. We decided to compare the DAPT of visible quiescent infections with the ONFIT of invisible latent infections and a species-specific PCR technique. In mid-May, fruit were observed in the field, and their fruit-to-fruit contact surfaces were marked with a permanent pen. All these fruit were then collected and brought to our KREC laboratory, surface-disinfected in 10% bleach solution for 3 minutes, rinsed with sterile water twice, and placed on clean paper towels. The fruit samples were split into three subsamples.

Using the PCR technique, 7.9% of the samples with invisible latent infections were positive for DNA of *M. fructicola*, and 6.7% of the fruit processed with ONFIT developed brown rot (table 1).

TABLE 1. Techniques to detect *Monilinia fructicola* in 'Howard Sun' plums

Technique	Latent infections (invisible)	Quiescent infections (visible symptoms)	Time required for results
	. . . . %		*days*
PCR	7.9	60.5	1.25*
ONFIT	6.7	—	7–9
DAPT	—	54.3	5–7

* Time includes 1-day preincubation of sample.

Similarly, as expected when visible quiescent infections were used, 60.5% were positive for *M. fructicola* with the PCR technique and 54.3% of those plated on APDA developed colonies of *M. fructicola.* Most importantly, the traditional techniques required 5 to 9 days while the PCR technique provided the results within only 30 hours (table 1).

Pistachio fungi inoculum sources

As the pistachio industry in California has matured, fungal diseases have become a major threat, sometimes causing significant losses. One of these diseases, panicle and shoot blight caused by *B. dothidea*, was recorded for the first time in summer 1984 in a commercial orchard in Butte County. This disease infects shoots, branched flower clusters, leaves and panicles throughout the season. By 1999, it had spread to pistachio orchards throughout the state, causing yield losses of 40% to 100% (Michailides and Morgan 2004).

B. dothidea has been recovered from more than 35 native and introduced plant species (Michailides and Morgan 2004), suggesting that these hosts may serve as inoculum sources and threaten commercial plantings, since pistachio was only recently (early 1970s) introduced as a commercial crop in California. In greenhouse and field inoculation tests, we found that all *B. dothidea* isolates recovered from other hosts were capable of infecting pistachio.

Although multiple applications of the new strobilurin fungicides have provided excellent control of

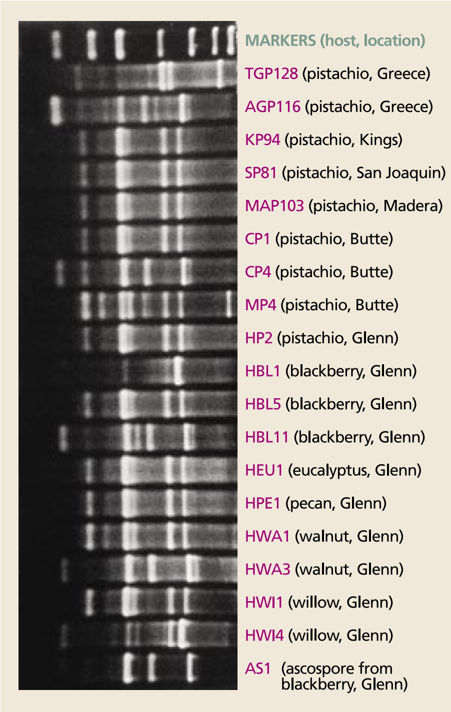


Fig. 4. DNA fingerprints of *B. dothidea* isolates (the pathogen causing panicle and shoot blight of pistachio) collected from hosts at different locations in California counties (shown in parentheses) and Greece.

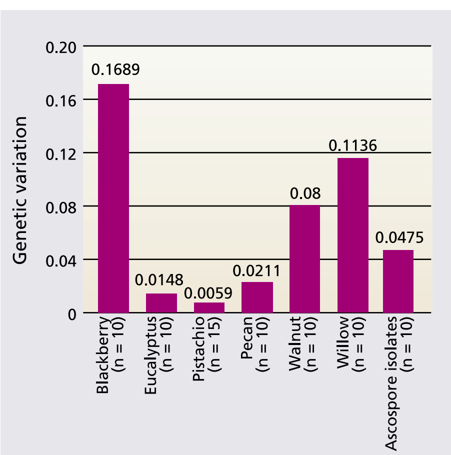


Fig. 5. Genetic variation within populations of *B. dothidea* from pistachio and other hosts next to a pistachio orchard in Glenn County. The taller the bar, the larger the genetic variation of isolates. Scale is from 0 to 1, where 0 = no variation and 1 = entirely (100%) different (1/5th of full scale is shown).

TABLE 2. Resistance to fungicides in some pathogens of California tree fruit, nuts and vines detected by the plating or molecular assays

Pathogen	Fungicide (category)	Resistance detected
Monilinia fructicola	Benomyl, thiophanate-methyl (benzimidazoles)	Yes
M. laxa	Benomyl, thiophanate-methyl (benzimidazoles)	Yes
Botryosphaeria dothidea	Benomyl, thiophanate-methyl (benzimidazoles);	No
	iprodione (dicarboximide);	Yes*
	azoxystrobin (strobilurin)	No
Fusarium moniliforme	Benomyl (benzimidazole)	Yes
Botrytis cinerea	Benomyl, thiophanate-methyl (benzimidazoles);	Yes
	fenhexamid (hydroxyanilide)	Yes*
Alternaria alternata,	Azoxystrobin, pyraclostrobin,	
A. tenuissima, A. arborescens	trifloxystrobin (strobilurins);	Yes
	iprodione (dicarboximide)	Yes*

* Laboratory-induced resistance only.

the disease in recent years, the potential development of fungicide resistance in *B. dothidea* is a significant concern. The use of resistant pistachio cultivars is the ultimate goal of any disease management program, but the judicious development and deployment of resistant cultivars depends on the population structure of the pathogen. To improve understanding of the pathogen's genetic diversity and how it has changed over the years at diverse locations, we conducted several studies that will eventually advance pistachio breeding programs (Ma et al. 2004).

Genetic variation. The genetic makeup of *B. dothidea* populations has remained homogeneous since it was first detected in 1984. We took samples of *B. dothidea* from infected pistachio orchards at diverse locations, some more than 600 miles (960 kilometers) apart, and over the course of several years. Our findings, as well as the pathogen's lack of propensity to form a sexual stage on this host, suggest that a program to breed resistant pistachio cultivars has a high chance of success. However, the interactions of a genetically uniform yet highly virulent pathogen population and the monoculture of the highly susceptible pistachio cultivars ('Kerman' and 'Peters') still pose a serious threat to the California pistachio industry.

DNA fingerprints. The DNA fingerprints of *B. dothidea* isolates collected from pistachio were identical to those of some *B. dothidea* isolates collected from other hosts (Ma et al. 2001), which suggests that native and introduced hosts for *B. dothidea*, other than pistachio, have historically served as potential inoculum sources for panicle and shoot blight of pistachio (fig. 4). (Forensic science uses similar DNA fingerprinting techniques in criminal investigations.)

Nonpistachio hosts. Although *B. dothidea* obtained from California pistachio are primarily asexual and very homogeneous, relatively high levels of genetic diversity were observed in *B. dothidea* isolates collected from nonpistachio hosts (fig. 5). These can infect pistachio. Consequently, if we are to select durable disease-resistant cultivars these cultivars should be tested with *B. dothidea* isolates that represent various genotypes from both pistachio and nonpistachio hosts.

Monitoring fungicide resistance

Fungicides are commonly used to manage plant diseases. However, the frequent use of fungicides with a single mode of action incurs a high risk of selecting resistant genotypes of plant pathogens. To determine levels of resistance to fungicides, the most common traditional technique is direct-plating single-spore isolates in media amended with various concentrations of fungicides and determining inhibition of growth and/or spore germination (table 2). The entire test can take 1 to 3 weeks — longer if the time required to isolate the pathogen from infected plant tissues is included. This conventional technique is time-consuming but critical, since growers rely on the results to decide on fungicide programs for their orchards.

In 2004, a new technique was reported using the spiral plate gradient-dilution method. Though an improvement, the method still requires 1 to 5 days for mycelial growth assays, followed by 14 to 20 hours for the spore inhibition studies to reveal results, plus 2 to 5 days for sporulation of fungi in culture (Förster et al. 2004).

DNA assays for fungal resistance

Strobilurin resistance. Alternaria late blight caused by *Alternaria* spp. in the *alternata*, *tenuissima* and *arborescens* species-groups (Pryor and Michailides 2002) is one of the most common fungal diseases of pistachio in California, and affects foliage and fruit. The disease can cause severe premature defoliation, staining of nutshells and molding of the kernels, which reduce fruit quality. Controlling Alternaria late blight requires a combination of cultural practices (irrigation management and pruning to reduce humidity) and multiple fungicide sprays.

The strobilurin fungicide azoxystrobin (Abound) provided excellent efficacy against this pistachio disease for some years. However, azoxystrobin-resistant populations of *Alternaria* have been detected in a fungicide experimental orchard and commercial pistachio orchards after multiple sprays for only 3 to 4 years, which caused failures of disease control in the field (Ma, Felts, et al. 2003).

Because azoxystrobin-resistant *Alternaria* populations appeared rapidly in pistachio orchards, it became urgent to incorporate effective antiresistance strategies when this or other strobilurins (because of cross-resistance) were used to control Alternaria late blight. The first important step is determining the sensitivities of pathogen populations to fungicides. Using the current conventional method, one person can examine only about 30 isolates in 2 work days, assuming that mature *Alternaria* spores are available for plating in fungicide-amended media. Obtaining spores requires 4 to 5 days for the incubation of cultures at optimum growth temperatures. It is almost impossible to produce results in a timely fashion.

Molecular markers by their potential nature are stable, not specific to

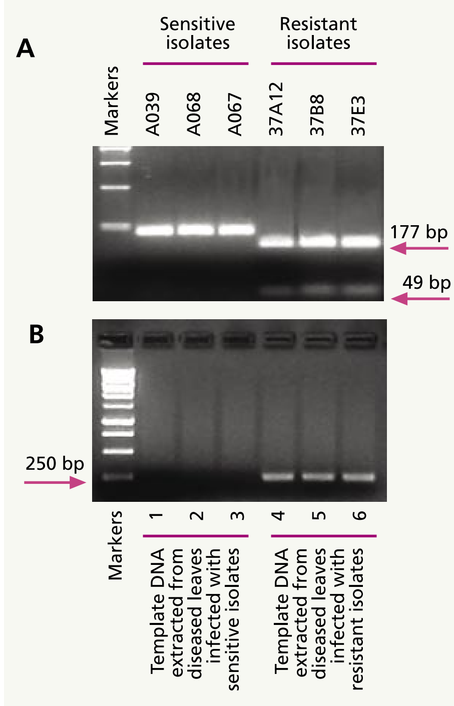
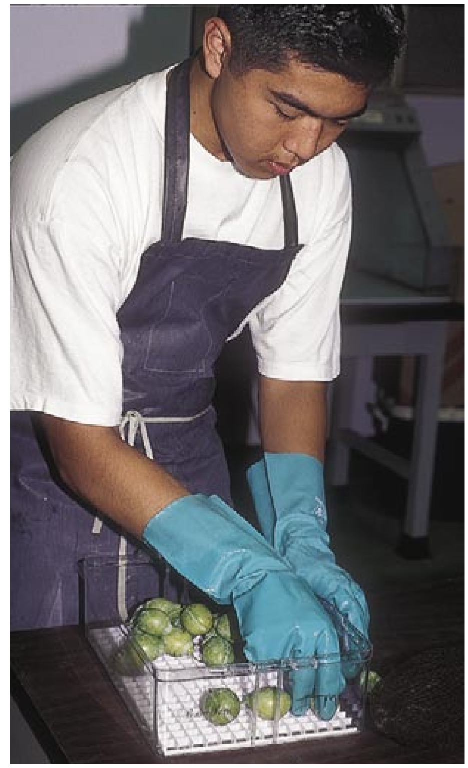


Fig. 6. (A) A change (mutation) in a specific gene of *Alternaria* spp. helps distinguish azoxystrobin-sensitive from azoxystrobin-resistant *Alternaria* isolates from pistachio; (B) A specific molecular technique (allele-specific PCR assay) can detect azoxystrobin-resistant *Alternaria* form lesions on pistachio leaves infected only by azoxystrobin-resistant and not by azoxystrobin-sensitive *Alternaria* isolates.



Surface sterilization of immature prune fruit with latent infections by *M. fructicola* is conducted by UC San Diego undergraduate Bobby Koja, by placing it in a container for the overnight freezing incubation technique (ONFIT).

the growth stage of the pathogen, and not influenced by the environment. If a DNA marker linkage with fungicide resistance is established (identification of the mechanism of resistance), it can be used to detect fungicide resistance in natural fungal populations.

In 2003, we found that azoxystrobin resistance in *Alternaria* from pistachio was correlated with a single-point mutation in the mitochondrial cytochrome b gene (Ma, Felts et al. 2003). Based on this mutation, we developed a PCR restriction fragment length polymorphism (PCR-RFLP) marker that detects DNA only from azoxystrobin-resistant isolates of *Alternaria*, but not from azoxystrobin-sensitive isolates (fig. 6A). Using this molecular method, one person can examine as many as 100 samples in a workday. Because many samples can be processed in a day, the cost for this test is not prohibitive. In fact, it is ready to be offered by private diagnostic laboratories that are willing to adopt and offer this new procedure (based on protocols provided by our UC laboratory).

Since the PCR-RFLP assay requires two steps and is still time-consuming if a larger sample must be tested, we further developed a one-step, allele-specific PCR (AS-PCR) method to rapidly detect azoxystrobin-resistant *Alternaria* in pistachios (Ma and Michailides 2004a). This AS-PCR method is being used in our laboratory now to rapidly detect the percentage of lesions caused by azoxystrobin-resistant *Alternaria*, making the results available to the grower within a day.

The AS-PCR assay was not quantitative per se and only detected the presence of azoxystrobin-resistant *Alternaria*. However, after purchasing a real time (RT)-PCR machine, the new RT-PCR technique can be used to accurately determine the frequency of azoxystrobin-resistant *Alternaria* isolates. Because 96 samples can be run simultaneously by the RT-PCR machine, the method is not expensive and is ready to be used by private diagnostic laboratories. However, a private lab has to first buy the expensive RT-PCR machine (about $35,000).

***Above*, apothecia of *M. fructicola* as observed in the field and *right*, blossom blight in prunes caused by *M. fructicola.* New molecular technology can help growers to detect and better manage resistance to fungicides.**

Larger laboratories are equipped with RT-PCR machines, and we expect that within a few years smaller laboratories will adopt this technique.

Based on the AS-PCR assay described above, we developed an allele-specific, real-time PCR assay to quantify the amount of azoxystrobin-resistant *Alternaria* DNA in a sample extracted from disease lesions (such as 50 disease lesions collected from a commercial pistachio orchard)(Ma and Michailides 2004b). Using this method, we can now detect frequencies of azoxystrobin-resistant *Alternaria* populations from at least 60 orchards (50 disease lesions per orchard) in 2 work days, while the conventional spore germination technique would require at least 200 work days for processing the same number of samples/isolates.

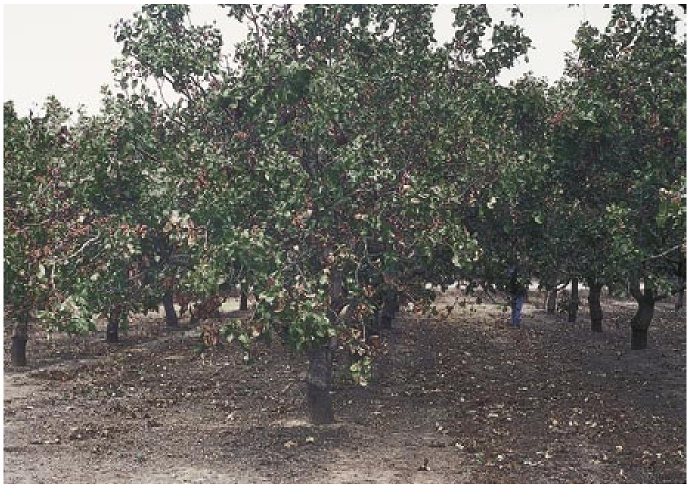
Benzimidazole resistance. Since benzimidazole resistance in *M. fructicola* and *M. laxa* has been shown to be genetically related to point mutations in the β-tubulin gene (Ma, Yoshimura, et al. 2003), we developed an allele-specific RT-PCR method for rapidly detecting benzimidazole-resistant *M. fructicola* in stone fruit and *M. laxa* isolates in almonds, in a manner similar to that used for the detection of *Alternaria* resistance to azoxystrobin. This technique used blossoms collected from peaches and almonds in March 2004 and successfully detected the level of resistance to benzimidazole in *M. fructicola* (peaches) and in *M. laxa* (almonds). These protocols are available to private diagnostic laboratories, which are free to use the techniques at any time. Obviously, such rapid and quantitative detections of fungicide resistance in the fungal pathogen populations will be valuable for California growers to manage fungicide resistance in stone fruit and almond orchards, especially since the benzimidazole fungicide thiophanate methyl (Topsin-M 70WP) is still registered and recommended by the UC disease management guidelines to control brown rot diseases in stone fruit and almonds.

Future prospects

In general, molecular technology increases understanding of the biology and population structures of plant pathogens, provides quick and accurate answers to epidemiological questions about plant diseases, speeds up fungicide-resistance detection, and supports disease-management decisions. For example, in summer 2002 a pistachio grower in Kern County noticed that azoxystrobin had failed to control *Alternaria* late blight in his fields. Within 2 days of collecting *Alternaria* isolates from leaf lesions in his field, we cautioned that 80% of the *Alternaria* isolates were resistant to azoxystrobin and cross-resistant to other registered strobilurins. The grower avoided using any additional strobilurin sprays and instead he used chlorothalonil, which has a wide mode of action.

Future goals of our research are to develop techniques that can supplement or replace DAPT, BOTMON, BUDMON, FIT (flower incubation technique) and the conventional quantification of pathogen inoculum using spore traps in orchards and vineyards, with efficient, accurate and rapid molecular procedures using RT-PCR. In the near future, we plan to emphasize research on molecular techniques to provide results more quickly than the BOTMON and BUDMON techniques, especially since we have good evidence of the quantitative relationships of BOTMON with gray mold in cold storage and BUDMON with panicle and shoot blight of pistachio in the field. Furthermore, the goal of our laboratory is to reduce the cost of protocols that incorporate molecular tech-

Right, **symptoms of severe *Alternaria* late blight in pistachio; *below right*, leaf lesions caused by *Alternaria* isolates are used to determine the incidence of azoxystrobin-resistant isolates of *Alternaria* species. *Below*, pistachios severely infected with panicle and shoot blight caused by *Botryosphaeria dothidea;* DNA fingerprints of the fungus collected from pistachio and other hosts suggest that nonpistachio hosts serve as inoculum for the disease.**



niques, by developing the capacity to process large numbers of samples at our laboratory and providing the protocols to private laboratories.

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REVIEW ARTICLE

Deep vadose zone hydrology demonstrates fate of nitrate in eastern San Joaquin Valley

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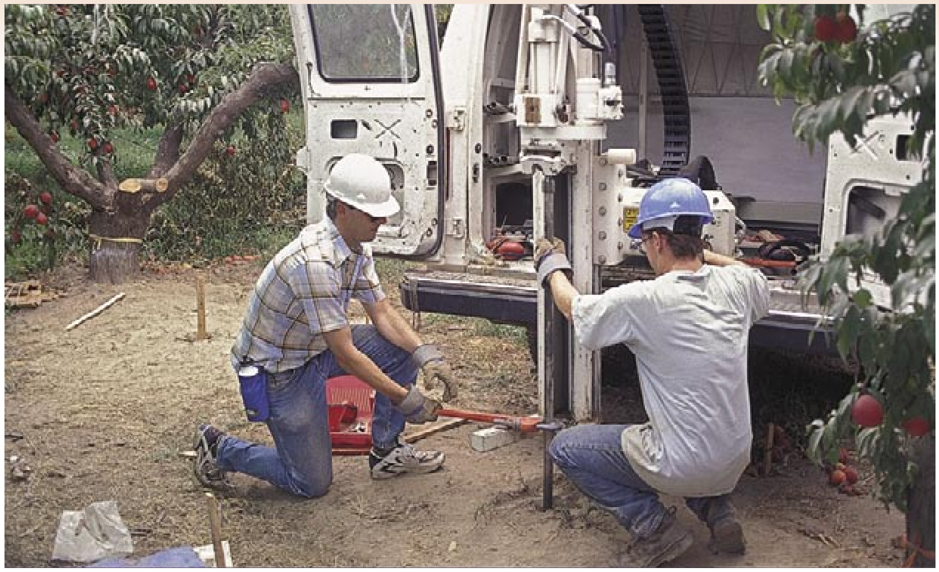


Nearly 3,000 feet of continuous soil cores were obtained between July and October 1997 using the Geoprobe direct-push drilling method. This method allowed for complete recovery of undisturbed cores throughout the 52-foot deep vadose zone. *Above*, UC Davis vadose zone hydrology professor Jan Hopmans (left) and Fresno State geology undergraduate Anthony Cole operate the coring equipment.

The sustainability of water resources is key to continued prosperity in the San Joaquin Valley and California. The vadose zone is an often-ignored layer of wet but unsaturated sediments between the land surface and the water table. It plays an important role in groundwater recharge and in controlling the flux and attenuation of nitrate and other potential groundwater contaminants. In a former orchard at the UC Kearney Research and Extension Center, we investigated the processes that control the movement of water, nitrate and other contaminants through the deep vadose zone. These processes were found to be controlled by the alluvial sedimentary geology of the vadose zone, which is highly heterogeneous. This heterogeneity should be considered when interpreting soil and deep vadose zone monitoring data and assessing of the leaching potential of agricultural chemicals. The transport of contaminants through the vadose zone may be significantly faster than previously assumed, while denitrification is likely limited or insignificant in the oxic, alluvial vadose zone of the eastern San Joaquin Valley.

For decades, the leaching of agricultural chemicals (fertilizer, especially nitrate, and pesticides) has been a concern of agronomists, soil scientists and hydrologists. Federal legislation first recognized the potential impacts to water resources in the early 1970s, when the Clean Water Act, the Safe Drinking Water Act, the Federal Insecticide, Fungicide, and Rodenticide Act and other legislation related to water pollution were enacted. Since then, countless efforts have been mounted by both the scientific-technical community and the agricultural industry to better understand the role of agricultural practices in determining the fate of fertilizer and pesticides in watersheds (including groundwater) and to improve agricultural management accordingly.

Much of the scientific work related to subsurface nitrate and pesticide leaching has focused on two areas: documenting the extent of contamination in groundwater; and investigating the fate of these chemicals in the soil root zone (including the potential for groundwater leaching) as it relates to particular agricultural crops and management practices. Rarely are these two research areas linked within a single study.

In California's valleys and basins, particularly in Central and Southern California, groundwater levels are frequently much deeper than 10 feet (3 meters) and sometimes as deep as 150 feet (45 meters) or more. Hydrologists refer to the unsaturated zone above the water table as the vadose zone. In general, only the uppermost 4 to 6 feet (1 to 2 meters) is described in soil surveys and investigated in soil studies; the deep vadose zone below the root zone remains largely outside the area of research and regulatory activity.

Yet, the vadose zone below the root zone stores significant moisture. All water and contaminant transport from the land surface to groundwater passes downward through the vadose zone. Few studies have investigated the fate or potential fate of, for example, nitrate and other contaminants in such deep vadose zones. Key questions include, What is the time of travel through the deep vadose zone? And, is there significant denitrification (natural attenuation) of nitrate in the deep vadose zone?

Pioneering work on nitrate in deep soil profiles was presented by Pratt et al. (1972) who investigated nitrate profiles in a Southern California citrus orchard to depths of 100 feet (30 meters); they estimated that it would take between 10 and 50 years for nitrate to leach to that depth. Average nitrate-nitrogen levels

Preferential flow paths, which are responsible for most of the water and solute transport from the root zone to the water table, quickly flush nitrogen to deeper portions of the vadose zone and to the water table, allowing for little or no denitrification.

below the root zone varied from 15 to 35 milligrams per liter (mg/L) under a 50 pounds per acre (lb/ac) treatment and from 35 to 55 mg/L under an excessive 350 lb/ac treatment. Based on gross mass-balance estimates, denitrification at that site was estimated to account for up to 50% of nitrate losses in the thick unsaturated zone profile where application rates were high.

Lund et al. (1974), supported later by Gilliam et al. (1978), Klein and Bradford (1979) and Rees et al. (1995), argued that nitrate losses in the deep vadose zone (due to denitrification) were strongly correlated with the textural properties of the soil. High losses were found in soils with pans or textural discontinuities, while losses were limited in relatively homogeneous, well-draining soils in other areas of Southern California. In contrast, Rolston et al. (1996), using isotope analysis at sites in the southern Sacramento Valley and the Salinas Valley, found little evidence of significant denitrification, even in thick unsaturated zones.

To study deep unsaturated zone hydrology, we established a research site in a former 'Fantasia' nectarine orchard at the UC Kearney Research and Extension Center (KREC) in Fresno County. The objective of our work is to provide a comprehensive assessment of the fate of nitrate in a 52-foot (16-meter) deep alluvial vadose zone that is typical of many agricultural areas in California. The assessment included detailed geologic, hydraulic and geochemical characterization, using nitrate as an example.

Field sampling

A 12-year fertilizer management experiment (from 1982 to 1995) was implemented in a 'Fantasia' nectarine orchard (Johnson et al. 1995). The fertilization experiment consisted of five application treatments in a random block design with triple replicates. Treatments included annual nitrogen application rates ranging from 0 to 325 pounds per acre (0 to 365 kilograms per hectare [kg/ha])(fig. 1). For the vadose zone characterization, three treatment subplots (0, 100 and 325 pounds per acre) were selected in 1997 (2 years after termination of the experiment), which we refer to as the control, standard and high subplot, respectively.

To start, we conducted a conventional root-zone nitrogen (N) mass-balance analysis from application and harvest records for the 12-year experiment in the three subplots. The analysis showed that the annual nitrogen leaching of excess nitrogen fertilizer from the root zone into the deep vadose zone was 51 (± 19), 83 (± 30) and 245 (± 42) pounds per acre. Water losses from the root zone to the deep vadose zone in the flood-irrigated orchard amounted to 1,100 (± 180) millimeters

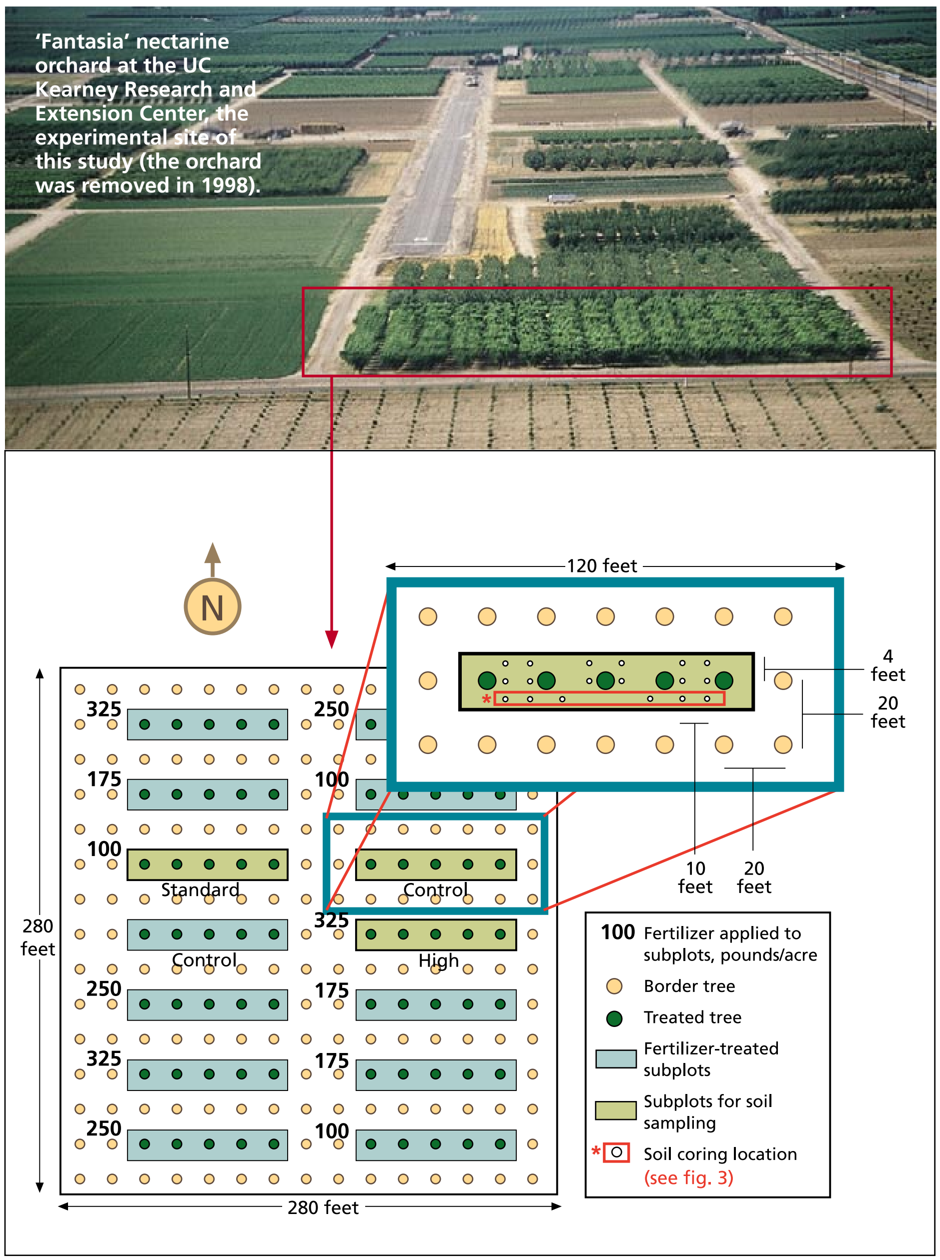


Fig. 1. In 1997, extensive core drilling was conducted, 2 years after the completion of three orchard nitrate-management trials at KREC with annual fertilizer rates of 0, 100 and 325 pounds nitrogen per acre. The complete random block design of the management trial and the three subplots selected for the deep vadose zone drilling are shown.

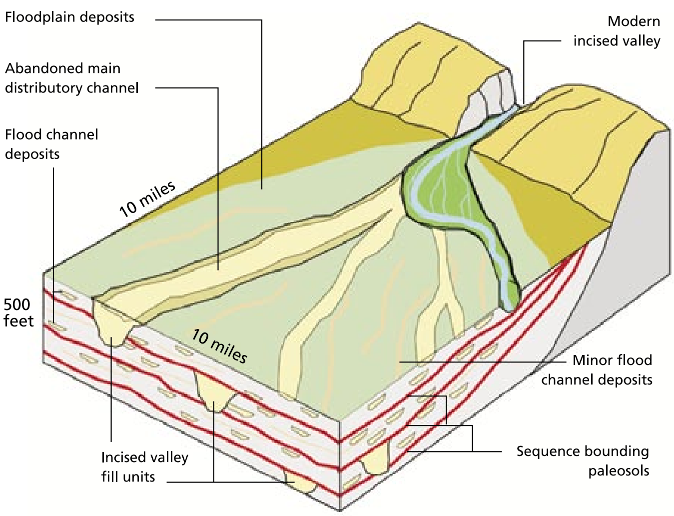


Fig. 2. Schematic diagram of the Kings River alluvial fan and its geologic elements.

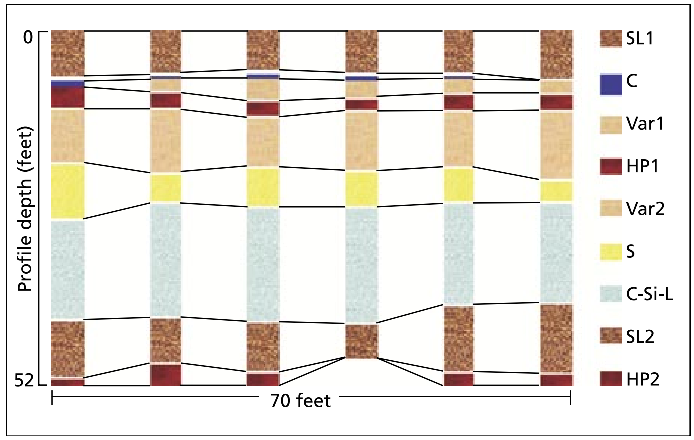


Fig. 3. The 10 major lithofacies identified at the two east-west cross sections, 140 and 144 feet from the southern edge of the orchard. The lithofacies, classified in the field according to color, texture and cementation, exhibit vertically varying thicknesses, yet are laterally continuous over the experimental site. Sandy loam is the most frequent textural unit, while clay is the least.

per year (Onsoy et al. 2005). Assuming uniform flow conditions throughout the deep vadose zone at an average soil moisture content of 25%, the travel time through the deep vadose zone was projected to be 3.2 (± 0.5) years. Based on the leaching rate and travel time, and taking into account that the experiment ended 1 year prior to drilling, we estimate that the deep vadose zone nitrogen storage at the time of drilling would be on the order of 195, 233 and 426 pounds nitrogen per acre in the control, standard and high subplot, respectively.

To confirm this estimate and to determine the applicability of the uniform flow concept, 60 undisturbed sediment cores were obtained in 1997 by drilling to the water table at a depth of 52 feet (16 meters) using a Geoprobe direct-push drilling technique. After geologic characterization of the complete core sections, 1,200 samples were collected (approximately one every 2.5 feet [0.8 meters]). Samples were collected for each sedimentologic stratum or substratum. The soil samples were preserved and stored for later analysis of their texture, hydraulic properties (water content, unsaturated hydraulic conductivity and water retention functions) and biochemical properties (pH, dissolved organic carbon, nitrate-nitrogen, ^{15}N isotope analysis).

Geologic framework

The site is located on the Kings River alluvial fan, approximately 2 miles (3.2 kilometers) west of the current river channel. The quaternary alluvial sediments (that is, sediments deposited by a stream) are derived exclusively from the hard, crystalline Sierran bedrock. Stratigraphically, the quaternary deposits in this part of the valley can be divided into five units (Marchand and Allwardt 1981): the post-Modesto (youngest), Modesto, Riverbank, Upper and Lower Turlock Lake deposits. Except for the post-Modesto, which is less than 10,000 years old (Holocene), these deposits are of Pleistocene age (2 million to 10,000 years old).

Most of the stratigraphic units (sediment facies) found at the site are believed to represent separate alluvial episodes related to several Sierran glaciations. In cores from the study site, these deposits appear as intercalated, thick and thin lenses of clayey silt, silt, sand and gravel from fluvial deposition. Channel sediments consist of moderately to well-sorted, subangular to subrounded sand and gravel. These channel deposits are surrounded by muddy sand and silts of floodplain deposits (fig. 2)(Page and LeBlanc 1969; Huntington 1980; Weissmann et al. 2002). Deposits from the various periods of Sierran glaciations are vertically separated by paleosols. Paleosols are buried soil horizons that were formed on stable upper-fan or terrace surfaces during interglacial periods, when no sediment deposition took place (fig. 3).

The vadose zone sediments are most easily classified by their texture, which ranges from clay to small gravel and includes a wide spectrum of predominantly silty to sandy sediments. The colors of the sediments range from grayish brown to yellowish brown, and more randomly to strong brown (no significant reduction zones). The thickness of individual beds varies from less than 0.4 inch (1 centimeter) for some finely layered clayey floodplain deposits to more than 8 feet (2.5 meters) for sandy streambed deposits. Sharp as well as gradual vertical transitions are present between texturally different units. The relative proportion of the five major textural categories found in the sediment cores was 17.2% sand, 47.8% sandy loam, 13.8% silt loam/loam, 8.3% clay loam/clay and 12.9% paleosol (see sidebars, pages 128 and 129; fig. 4).

KEY (figs. 3, 4): The major lithofacies are:

- **SL1 — recent Hanford sandy loam**
- **C — clay, very thin**
- **Var1 — variable sedimentary structures, predominantly sand**
- **HP1 — shallow paleosol (hardpan), red**
- **Var2 — various textures, sandy loam to clay loam**
- **S — medium sand**
- **C-Si-L — clay/clayey silt/clay loam, fine-textured floodplain deposits**
- **SL2 — sandy loam and**
- **HP2 — deep clayey paleosol (hardpan), red**

Hydraulic properties variability

Hydraulic properties of the unsaturated zone, such as the hydraulic con-

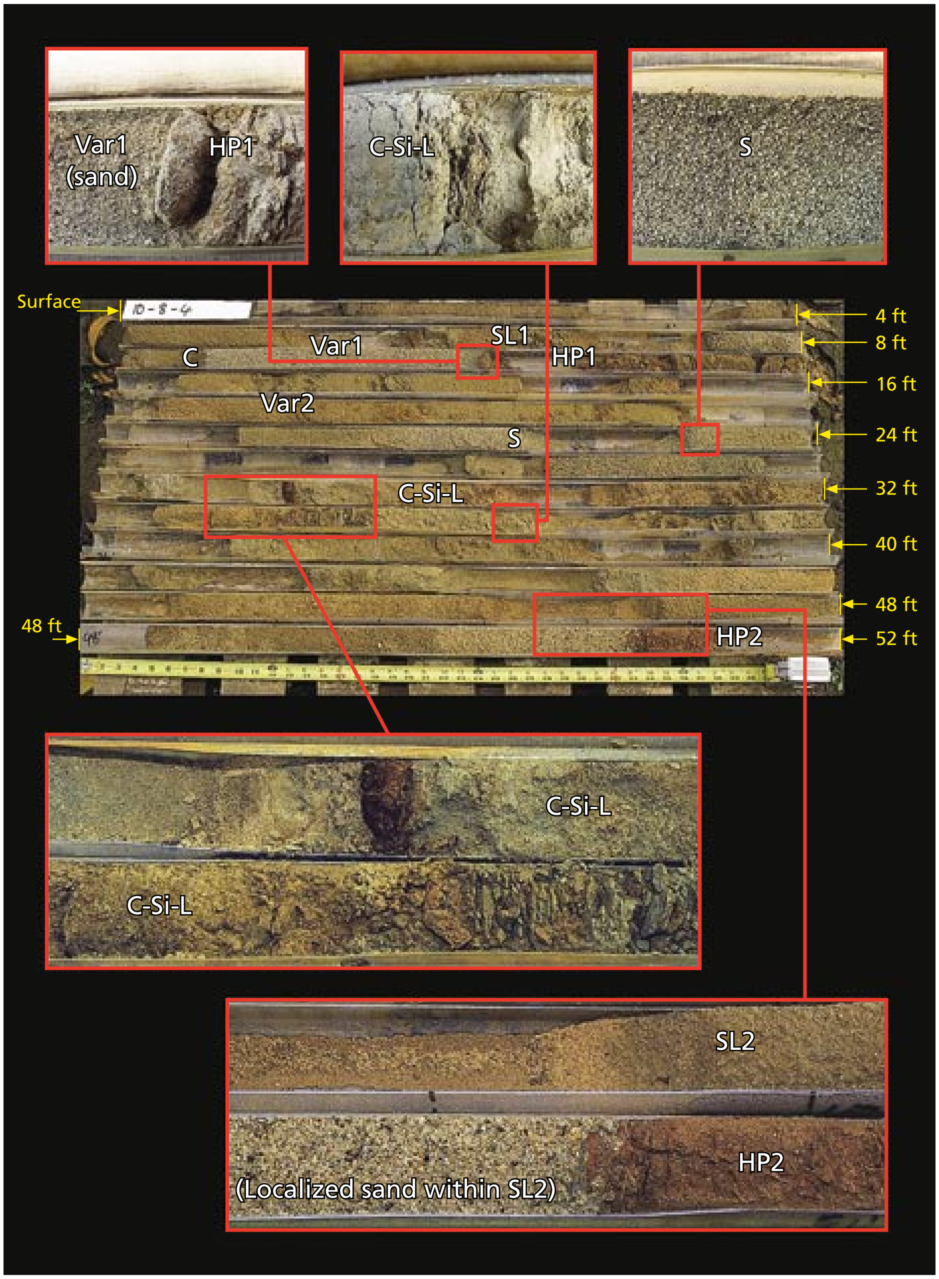


Fig. 4. Individual core sections were collected in 4-foot (1.2 meter) plastic tubes (see fig. 1). This image shows all 13 sections of a 52-foot (15.6-meter) core, lined up from the ground surface (*upper left*) to the bottom of the core (*lower right*). Missing subsections represent soil sampling locations for hydraulic and chemical analysis.

ductivity/moisture curve and the water retention curve — and the spatial distribution of these properties — strongly control the flow of water and the transport of nitrate and other solutes in the deep vadose zone. (Hydraulic conductivity is a measure of how fast water can percolate through the sediments; the higher the moisture and the coarser the sediments, the higher the hydraulic conductivity.) Hydraulic properties were determined in the laboratory on more than 100 undisturbed sediment core samples (3.5 inches [9 centimeters] long by 1.5 inches [3.8 centimeters] diameter) taken from various locations and depths at the orchard site. The laboratory tests involved measuring the water percolation rates in each core at six to 10 different moisture conditions, then determining the hydraulic properties by computer analysis.

Given the large amount of textural variability observed in the cores, it was not surprising that we found the hydraulic properties to also vary significantly, both with depth and laterally across the site (Minasny et al. 2003). The saturated hydraulic conductivity, for example, varied over nearly four orders of magnitude. Within some sedimentary layers (facies) we observed nearly as much hydraulic variability within individual facies as between facies. By far the highest conductivity was observed in sandy facies ("S" and "Var1" in figs. 3 and 4).

Heterogeneity of water flow

Traditionally, water flow between the root zone (at depths of 6.6 feet ([0 to 2 meters]) and the water table (here a depth of 52.8 feet [16 meters]) has been considered essentially a uniform, vertically downward flow process in a more or less homogeneous vadose zone. Within this conceptual framework, water from individual rainfall or irrigation events is thought to be initially stored in the root zone. There, it is available for uptake by the roots. Surplus water then gradually drains into the deeper vadose zone. Individual rainfall or irrigation events create pulses of moisture that penetrate the root zone profile. Through root water uptake and vertical spreading, the moisture pulse dampens out as it travels downward. In the deeper portions of the vadose zone, the downward flow rate has therefore been thought to be equal to the annual recharge rate.

However, the highly heterogeneous geology of the alluvial sediments observed at the orchard site, coupled with the associated heterogeneity of the hydraulic properties, suggest that this traditional conceptual framework is inadequate to describe how water and chemicals are transported through the vadose zone to the water table. Using our field data and computer simulation, we reconstructed two-dimensional cross-sections of the vadose zone that reasonably reflect the spatial variability

Major facies in the study-site vadose zone

The **sand** ("S" and "Var1") is quartz-rich, and contains feldspar, muscovite, biotite, hornblende and lithic fragments consistent with the granitic Sierran source (see figs. 3 and 4). Cross-bedding at the scale of few inches (centimeters) could be observed in some fine-grained sand samples. The dominant color of the sand is a light gray to light brown, the brown hue increasing with increasing loam content. The thickness of the sand beds is as much as 8 feet (2.4 meters), though thickness varies across the study site. Very coarse sand and particles up to pebble grain-size (up to 0.4 inch or 1 centimeter) could occasionally be observed at the bottom of the sand units, but were not present in all the cores. The sand units typically show a subtle fining-upward succession. The basal contact is typically sharp. The texture and distribution of these sandy deposits are consistent with deposition in a fluvial distributary channel on the Kings River fluvial fan. One ancient river channel was observed in cores collected from the orchard site, and it appears to have had a northeast-southwest orientation. The mean thickness of this channel deposit is nearly 6 feet (1.7 meters). The basal coarse sand and pebbles probably represent channel lag deposits that were laid down in deeper parts of the channels.

Sandy loam ("SL1," "SL2") is the most frequent lithofacies within the profile. The color is usually light olive to yellowish brown. Some of the sandy loam sediments are considered to be weakly developed paleosols because of their stronger brownish color, root traces and presence of aggregates. Mean bed thickness is 20 inches (50 centimeters), though individual beds can be as much as 7 feet (2 meters) thick. The sorting is moderate to good. Clay flasers and thin (fractions of an inch, 0.5 to 1 centimeter) clay laminae occur in some sandy loam units. Sandy loam sediments are assumed to have developed at the edge of channels, as levee or as proximal floodplain deposits near the channels.

Silt loam, loam and silty clay loam (portions of "C-Si-L" and "Var2") are usually slight olive brown to brownish gray in color. The bed thickness is within a range of a few inches to a foot (centimeters to decimeters). Fine-grained sediments often show sharp contacts between the units. Changes from one unit to the next exist on small distances. Lamination can more frequently be observed within silty sediments than in fine sands. Root traces and rusty brown–colored mottles are quite common. The depositional environment was presumably the proximal to distal floodplain of the fluvial fan, an area dissected by distributary streams.

The finest sediments are grouped in the fourth category: **silt, clay and clay loam** (portions of "C," "C-Si-L" and "Var2"). These are believed to have been deposited in the distal floodplain and in ponds that developed in abandoned channels. The main color is brownish gray to olive brown. Fine, less than 1-millimeter-diameter root traces and rusty brown mottles are common in the clay sediments. Statistics for the thickness of clay layers in the unit between 27 and 43 feet (8 and 13 meters) depth show a mean thickness of 5 inches (12.8 centimeters), but the mode is about 2.2 inches (3 centimeters). A 20-inch (50-centimeters) thick clay bed was observed at approximately 8 feet (2.5 meters) depth in most of the cores.

Paleosols ("HP1," "HP2") were recognized in different stages of maturity. They show a brown to strong brown, slightly reddish color, exhibit aggregates, ferric nodules and concretions, few calcareous nodules and hard, cemented layers. They also display a sharp upper and a gradual lower boundary as is typical for paleosols (Retallack 1990). Clay content decreases downward in the paleosols. Another feature is fine root traces, though these are typically obliterated in the more mature paleosols. Paleosols formed in periods of stasis marked by nonerosion and nondeposition, during the interglacials (Weissmann et al. 2002). The thickness of the paleosol horizons ranges from 20 inches (50 centimeters) to about 7 feet (2 meters).

of the hydraulic properties observed in the field, then we simulated water flow through this reconstructed vadose zone. Figure 5 illustrates the spatial distribution of the water flux through a hypothetical cross-section at 40 feet, similar to that observed at the orchard site. It captures important features that are characteristic of water flow in heterogeneous vadose zones (Russo et al. 1998; Harter and Yeh 1996). Understanding that flow occurs in this highly irregular pattern is important for interpreting the field data.

In particular, figure 5 shows that even though the simulated water application at the surface was uniform, the heterogeneity of the vadose zone forces water into distinct preferential flow paths (warm colors), separated by large areas of relatively stagnant flow (cooler colors). The preferential flow paths have highly irregular shapes, but are continuous and extend to the water table. The preferential flow paths occupy only a small portion of the vadose zone. In contrast, areas with relatively stagnant water flow occupy most of the vadose zone. Soil moisture differences between these two zones are small. Soil moisture is therefore not a particularly sensitive indicator and may not be useful for identifying the presence and location of these preferential flow paths.

In our study, further field work and computer simulations indicate that the location of these preferential flow paths does not change over time, even though they may partially or completely dry out between infiltration events. A new event will recreate the same set of preferential flow paths.

Preferential flow paths are not only created by the sediment heterogeneity. Other conditions may also trigger and support preferential flow paths: macropores in the root zone; flow instability during infiltration into sand or loamy sand soils (Wang et al. 2003); flow through or above embedded clay or sand lenses ("funneling")(Kung 1990); and "fingering" as a result of a sharp textural boundary within the vadose zone where the finer-textured (silt/clay) layer is located above a coarse-textured (sand) layer (Glass and Yarrington 2003).

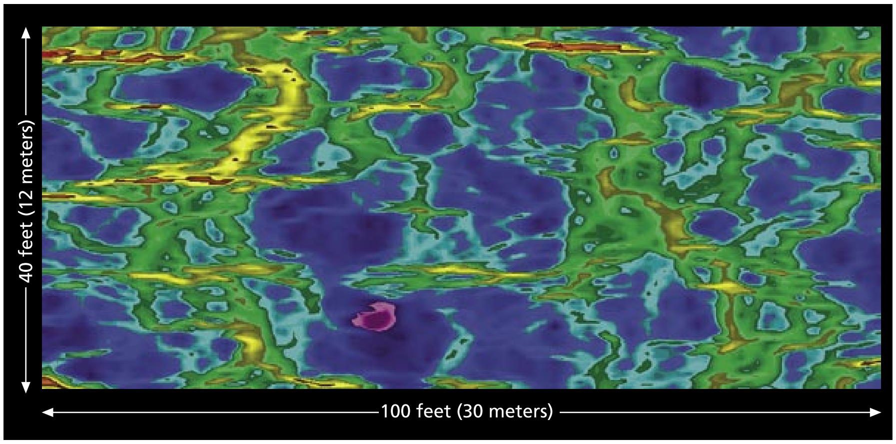


Fig. 5. Hypothetical, computer-simulated, unsaturated water flow rates through a heterogeneous vadose zone, illustrating how heterogeneity in the unsaturated zone generates preferential flow paths: Warmer colors (red, orange, yellow) represent high flow rates, and cooler colors (blue, violet, black) represent lower flow rates. The unsaturated hydraulic properties used for the simulation are similar to those found at the KREC research site.

Since much of the annual recharge occurs through these preferential flow paths, the actual downward flow rate is locally much higher than that estimated when assuming that the entire vadose zone uniformly participated in the downward water flow. Hence, solute travel times through deep vadose zones are likely shorter than if flow were indeed uniform. Because of the shorter travel time, nitrogen storage in the deep vadose zone should be significantly lower than estimated based on the uniform flow concept. On the other hand, under heterogeneous conditions, relatively old water may be trapped in the more stagnant portions of the vadose zone for extended periods. Do the measured nitrate distribution and water chemistry in the deep vadose zone at the Kearney site support this alternative conceptual framework of water and solute flow through the vadose zone?

Nitrogen distribution

To address this question, nitrate-nitrogen (NO_3-N) concentrations were measured in 809 subsamples of our cores. We found that the data were indeed highly variable and log-normally distributed (the logarithms of the data were normally distributed). Nitrate-nitrogen concentrations ranged from less than the detection limit of 0.05 milligram per liter (mg/L)(224 samples or 28% of the sample population) to more than 100 mg/L (two samples). Approximately 10% of the samples exceeded the maximum contamination level for drinking water (10 mg/L), set by the U.S. Environmental Protection Agency under the Safe Drinking Water Act. More than half of those occurred in the subplot with the highest nitrogen application. Mean nitrate-nitrogen concentrations (not including nondetects) in the control, standard and high subplot vadose zone were estimated to be 5.2, 3.3 and 7.4 mg/L, respectively (Onsoy et al. 2005). The nitrate-nitrogen coefficient of variation (CV) ranged from 1.6 to 2.4 within each subplot. The difference between the control and standard subplots was statistically not significant due to the large variability. But the high subplot yielded significantly larger mean nitrate-nitrogen concentrations throughout the profile, consistent with the overapplication of fertilizer.

Within all three subplots, slightly higher nitrate-nitrogen levels were observed in the root zone than in the deep vadose zone below the root zone, possibly due to the last fertilizer application in fall 1996, prior to our drilling. Other than that, we observed no significant vertical nitrate-nitrogen trend in the deep vadose zone.

The highest number of nondetects occurred in the coarse-textured, sandy lithofacies and in the sand lithofacies (above historic water level). There, approximately half of the samples had nondetectable nitrate-nitrogen levels. This is consistent with findings that fingering or preferential flow is particularly dominant in sandy unsaturated sediments. In other words, much of the sand facies does not participate in the flow (stagnant moisture) and would see little or none of the nitrate-nitrogen that is passing through the preferential flow paths.

Study-site geologic profile

A number of distinct sedimentologic units are recognized in the vadose zone profile throughout the orchard and are used to construct a field-scale geologic framework for the research site (see figs. 3 and 4).

The deepest parts of the cores (between 50 and 52 feet [15 and 15.8 meters]) display a strong brownish-colored, clay-rich paleosol. This paleosol marks the top of the upper Turlock Lake deposits (Weissmann 2002). Directly above this paleosol, from depths between 40 and 50 feet (12 to 15 meters) below the surface, the main textural units are sandy loam to fine sandy loam, with some coarse sand and gravel or fine-grained sediments. In the cores with fine sediment at the bottom of this unit, a coarsening-upward succession was observed in this zone; in the other cores a fining-upward cycle was observed.

Between 27 and 40 feet (8 and 12 meters) depth, the sediments are vertically and laterally quite heterogeneous with relatively thin bedding (thickness of a few inches [centimeters] to a couple of feet [few decimeters]), consisting mainly of clayey, silty and loamy material. Another strong brownish paleosol occurs at a depth of 30 to 33 feet (9 to 10 meters). Between 20 and 30 feet (6 and 9 meters) below the surface, a distinct sand layer, representing a former stream channel bed, is found. This unit has laterally varying thickness averaging nearly 6 feet (1.7 meters). A weak, mostly eroded paleosol was developed on top of the sand unit.

From about 10 to 13 feet (3 to 4 meters) to 20 feet (6 meters) below the surface, sandy loam with intercalated sand, clayey and silty material is found. Different trends of upward-fining and upward-coarsening are found on top of each other and laterally next to each other within this unit.

Immediately above the unit, at a depth of about 10 to 13 feet (3 to 4 meters), a nearly foot thick (0.2 meter) to more than 10 feet (1 meter) thick paleosol hardpan occurs. This paleosol marks the top of the Riverbank formation. Recent ground-penetrating radar surveys indicate that this paleosol is laterally extensive across the orchard site.

Sandy loam and subordinated loamy sand and loam are present from the top of the paleosol to the surface, and represent the Modesto deposits at the site. About 8 feet (2.5 meters) below the surface, a laterally continuous clay horizon with a thickness of few inches (centimeters) is found in most of the cores.

Most importantly, the total nitrogen mass estimated directly from the measured nitrate-nitrogen distribution in the deep vadose zone was only 46 (± 9), 37 (± 6) and 83 (± 12) pounds per acre annually for the control, standard and high subplots, respectively. This is less than one-quarter of the total nitrogen mass in the deep vadose zone that was indirectly estimated from the mass balance described above, which is based on the conventional uniform flow concept.

Role of denitrification

Traditionally, such low nitrate-nitrogen mass in the deep vadose zone has been attributed to denitrification (the microbial breakdown process of nitrate by soil microbes). However, the lack of a significant vertical trend in the average nitrate-nitrogen concentration does not support that hypothesis (denitrification in the deep vadose zone would create a nitrate-nitrogen profile that shows decreasing concentration with depth). To further evaluate whether denitrification played a significant role in the deep vadose zone, we measured the amount of soluble organic carbon (a microbial food source) and the amount of $\delta^{15}N$ (a rare nitrogen isotope that increases in relative abundance when denitrification occurs) in the nitrate-nitrogen of samples from four cores (three from the high subplot and one from the standard subplot). (The concentration of isotopes is not reported in absolute values, but rather as a relative concentration, hence the notation "delta" or "δ" ^{15}N. A value of $\delta^{15}N$ = 5‰ indicates that the ^{15}N concentration is 5 permil above normal [1 permil = 0.1 percent].)

Soluble carbon was found to be very low, not favoring high rates of microbial degradation anywhere in the vadose zone profile. The $\delta^{15}N$ values varied from 0‰ to 12‰ and averaged 6‰ (fig. 6). Without denitrification, $\delta^{15}N$ levels are expected to be in the range of –5‰ to 5‰ (Rolston et al. 1996). Denitrification decreases nitrate-nitrogen concentrations, but increases the relative amount of isotopically heavy NO_3– $\delta^{15}N$. Indeed, there was a very weak trend ($R^2 < 0.1$) to support the hypothesis that a limited amount of denitrification may occur in the vadose zone: samples with 2 mg/L to 10 mg/L nitrate-nitrogen had relative $\delta^{15}N$ levels of 5‰ to 12‰, while samples with higher nitrate-nitrogen contained from 0‰ to 6‰ of $\delta^{15}N$. (No $\delta^{15}N$ measurements could be made on samples with less than 2 mg/L nitrate-nitrogen.)

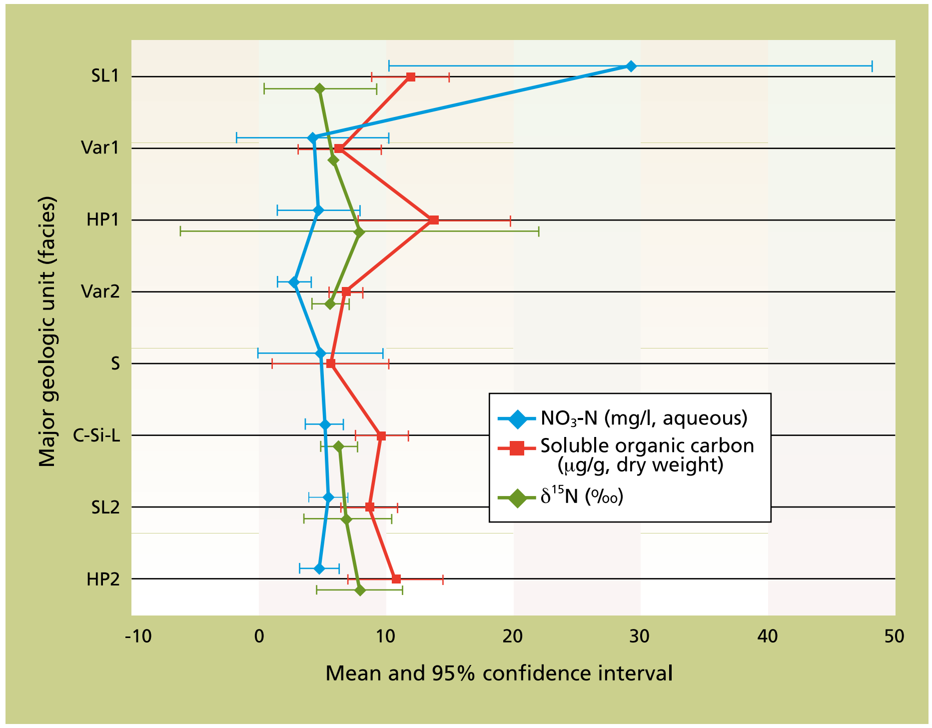


Fig. 6. Composite nitrate-nitrogen, dissolved organic carbon (DOC) and $\delta^{15}N$ profiles from borings at the orchard study site. Higher DOC indicates a higher potential for denitrification. Higher $\delta^{15}N$ levels (above 10) indicate the occurrence of partial denitrification.

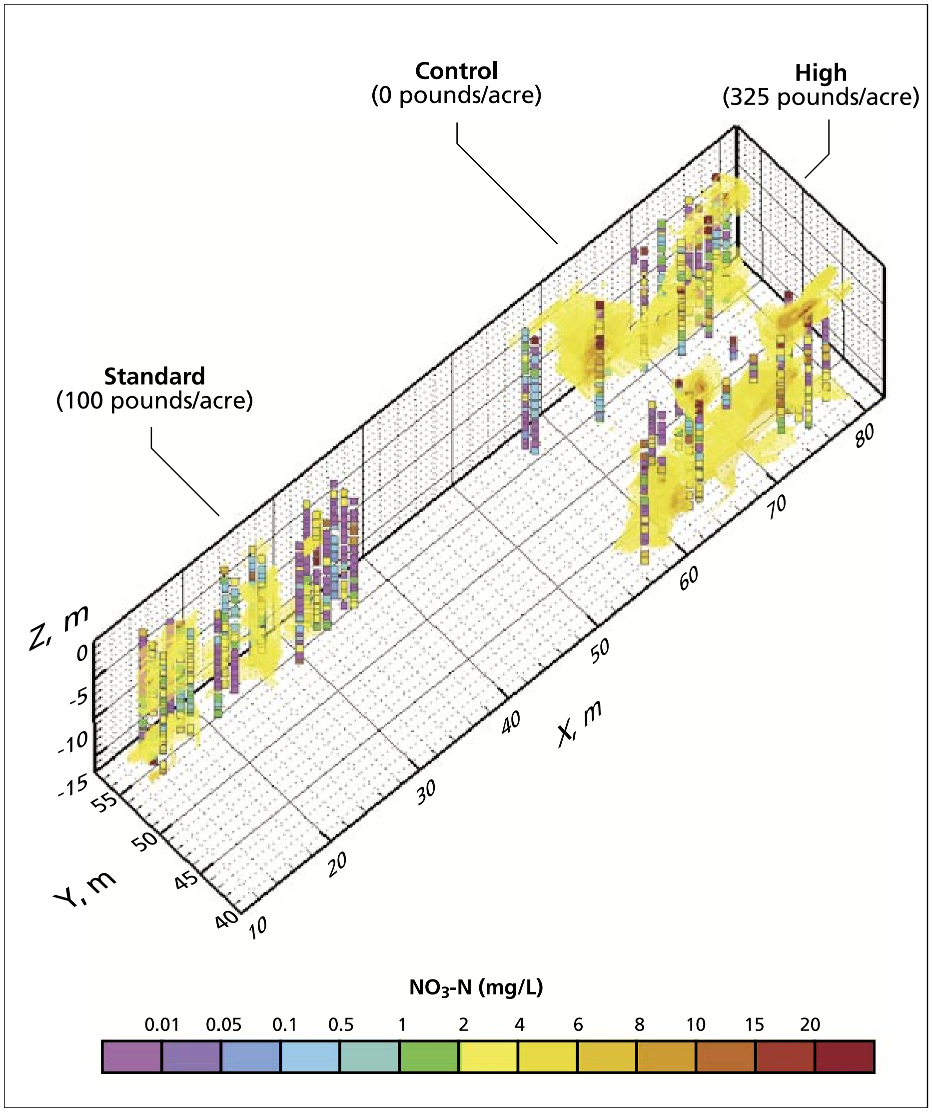
There was significant scatter in these data, corroborating the concept of highly heterogeneous transport. Furthermore, just as there was no significant decrease in nitrate-nitrogen with depth, there was no significant increase in $\delta^{15}N$ with depth, similar to isotopic results at geologically similar Yolo County and Salinas Valley sites (Rolston et al. 1996). Then why was the total nitrogen storage in the deep vadose zone so low?

The nitrate distribution pattern that we found (fig. 7) was similar to that postulated in other experimental studies specifically designed to assess transport in heterogeneous soils as well as that predicted by numerical models of flow and transport in highly heterogeneous vadose zones (Harter and Yeh 1996). Hence, the proposed conceptual framework of preferential flow in the deep vadose zone may provide the answer: preferential flow paths, which are responsible for most of the water and solute transport from the root zone to the water table, quickly flushed nitrate-nitrogen to deeper portions of the vadose zone and to the water table, allowing for little or no denitrification. This would explain the occurrence of high nitrate-nitrogen levels and low $\delta^{15}N$ levels throughout the depth of the vadose zone profile.

Lower nitrate-nitrogen would occur in stagnant water zones outside preferential flow paths. Due to their longer residence time, nitrate-nitrogen in these zones was apparently subject to a small amount of denitrification, which would explain the higher levels of $\delta^{15}N$ that were also found, scattered throughout most of the profile.

The importance of this finding is that while limited denitrification took place in the stagnant water areas of the vadose zone, the majority of the

Fig. 7. Measured core nitrate-nitrogen data (squares) and three-dimensional, kriged (yellow) contours of nitrate-nitrogen data. The kriged isosurfaces (only for NO_3-N > 1 mg/L) are obtained from geostatistical analyses of the water content and nitrate measurements at the sampling locations. The standard subplot yielded the largest areas of negligible nitrate concentrations (NO_3-N < 1 mg/L) among the three subplots. High concentrations are seen in the upper profile and near the water table.



nitrate-nitrogen transport occurred in preferential flow paths, where no significant denitrification appears to have taken place. Hence, the low average nitrate-nitrogen concentration in the vadose zone pore water should not be interpreted as an indicator for high denitrification and low nitrate impact on groundwater. Rather, it may be the result of swift, unattenuated nitrate-nitrogen transport to the water table (the same may apply to the root zone).

Analysis shows variability

Our detailed geologic, hydraulic and geochemical analysis of a typical deep vadose zone in the eastern San Joaquin Valley demonstrated that alluvial vadose zones are subject to significant geologic variability, which in turn causes the hydraulic properties and water flow in the vadose zone to exhibit strong spatial variability. While such variability is expressed to only a limited degree in the variability of the observed moisture content, it leads to highly variable concentrations of chemicals, such as nitrate. Our research presents new evidence indicating that unsaturated water flow and transport of nitrate and other agrochemicals (such as pesticides) in the deep vadose zone below the root zone may be subject to significant preferential flow patterns with significantly faster travel times than would be estimated under uniform flow assumptions. Faster travel times not only decrease the potential for denitrification, but also decrease the potential for natural attenuation of pesticides.

Our work suggests that the traditional interpretation of deep vadose zone measurements should be reconsidered. The assumption of uniform flow is not applicable to many alluvial vadose zone sites. The common practice of compositing soil samples taken from immediately below the root zone provides an estimate of the average nitrate-nitrogen concentration at that depth. However, our work indicates that recharge water may constitute only a minor portion of that vadose zone water and is not effectively represented by composite soil samples. It appears that the average or composite nitrate-nitrogen concentrations are also not appropriate for estimating the amount of denitrification as a closure term to the nitrogen mass balance. We are currently implementing detailed heterogeneous flow and transport simulations to further support these findings and to develop guidelines for sampling the deep vadose zone.

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Before it is pumped to the surface for agricultural or other uses, groundwater percolates through the geologically variable vadose zone. Based on this study, current assumptions about transport of nitrate from fertilizers and other agricultural chemicals need to be reexamined.

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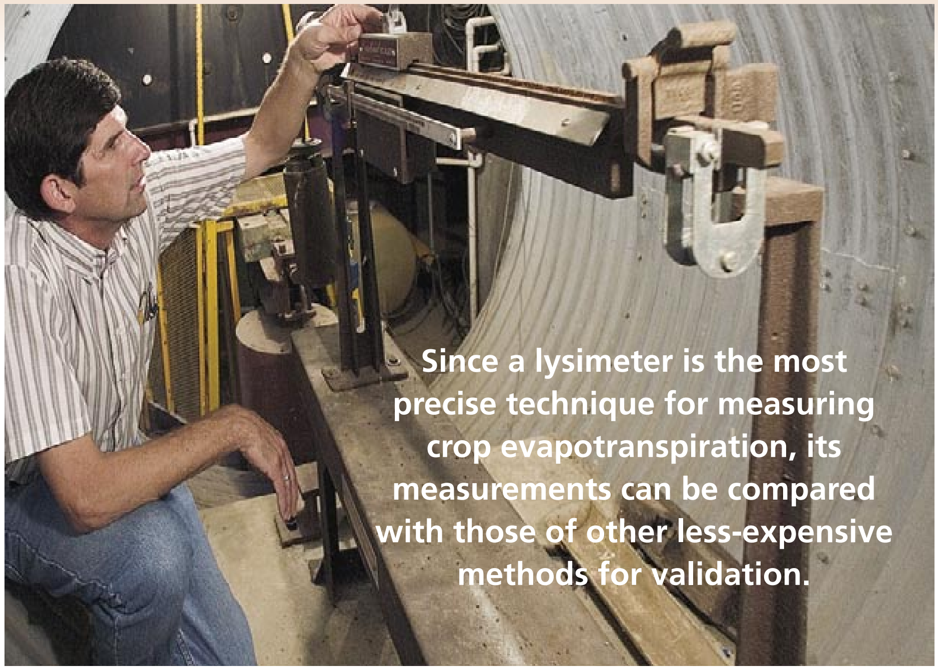
REVIEW ARTICLE

Weighing lysimeters aid study of water relations in tree and vine crops

R. Scott Johnson
Larry E. Williams
James E. Ayars
Tom J. Trout

In 1986, two large weighing lysimeters, — one in a peach orchard and the other in a grape vineyard — were constructed at the UC Kearney Research and Extension Center as a joint effort between UC and the U.S. Department of Agriculture's Water Management Laboratory. Hourly weight changes in the lysimeters have been used to measure the daily and seasonal water use of trees and vines for nearly 20 years. Peaches and grapes exhibit similar seasonal crop-coefficient patterns that start as low as 0.1 in March, increase linearly until early July and then remain constant between 1.1 and 1.2 for the remainder of the season (provided the plants remain disease-, pest- and stress-free). The linear increase phase is proportional to the increase in canopy light-interception and leaf area. These relationships have facilitated modeling to predict crop evapotranspiration under various conditions. The peach lysimeter has also been useful for studying the effects of water stress on tree water use and for evaluating other methods of estimating water use.



Jack Kelly Clark

UC pomology specialist R. Scott Johnson, *above*, adjusts the balance beam in one of two lysimeters constructed at the UC Kearney Research and Extension Center. These rare research tools are large and expensive to maintain, which is why so few of them exist around the world. For 20 years they have been the most precise method of understanding daily and seasonal water use in the San Joaquin Valley. Every hour soil evaporation and plant transpiration — crop "evapotranspiration" — is recorded. When a threshold value is exceeded, the trees or vines growing in the lysimeters are automatically irrigated.

Water is a critical resource in agriculture, and supplying the right amount is essential for healthy plants and optimum productivity. With insufficient water, plants become stressed and unproductive, and eventually die. With an excess, they can suffer from diseases, nutritional disorders and waterlogged soils. The most accurate way to estimate water use by crops is with a weighing lysimeter, which measures water loss from the plants and surrounding soil.

A weighing lysimeter is simply a large "flower pot" resting on a sensitive, underground scale. Short-term weight loss from the system is almost entirely due to water transpired through leaves or evaporated from the soil surface.

While this technique is generally considered one of the most reliable because it is simple and direct (Aboukhaled et al. 1981), weighing lysimeters are expensive to install and maintain, so relatively few have been constructed around the world, especially to study perennial trees and vines. At the UC Kearney Research and Extension Center (KREC), we have had two of these instruments for nearly 20 years. They have been particularly useful for determining patterns of tree and vine crop coefficients, studying water-stress effects on water use, and evaluating other techniques for estimating water use.

Lysimeter and field design

In 1986, two large weighing lysimeters were constructed at KREC as a joint effort between UC and the U.S. Department of Agriculture's Water Management Laboratory. Each lysimeter consists of an underground chamber that houses a balance-beam weighing system constructed by Fred Lourence (Precision Lysimeters, Red Bluff, Calif.) upon which rests a rectangular box measuring 6.5 feet wide by 13 feet long by 6.5 feet deep (Phene et al. 1991; Williams et al. 2003b). In constructing the underground chamber, soil was removed in 6-inch increments so it could be replaced in the box at approximately the same depth as the surrounding soil.

In spring 1987, two peach trees were planted in one lysimeter and two grape vines were planted in the other, and in each case the surrounding 3 acres were planted to the same variety and spacing. The grape variety was 'Thompson Seedless' (clone 2A) with 7-feet-by-11.5-feet spacing. The peach variety was initially 'O'Henry' (late-July harvest) on 'Nemaguard' rootstock, with 6-feet-

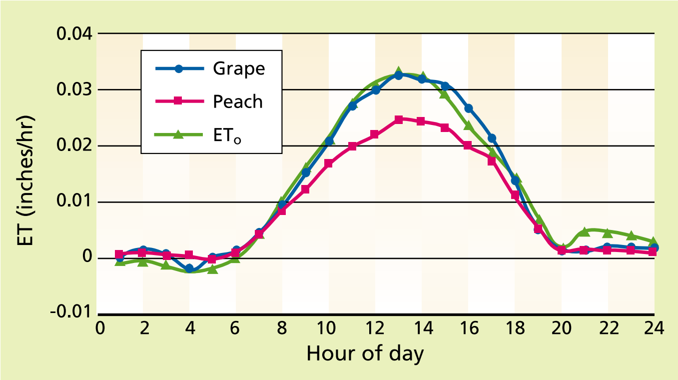


Fig. 1. Hourly crop evapotranspiration (ET) on June 9, 1996, as measured by the Kearney grape and peach lysimeters. Reference ET$_o$ was obtained from a nearby CIMIS weather station.

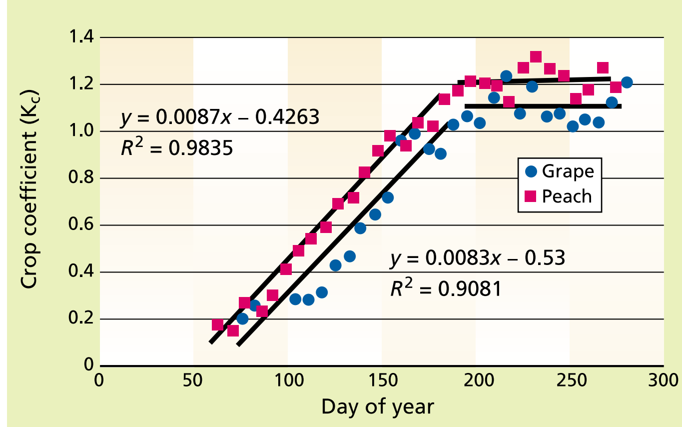


Fig. 2. Seasonal pattern of crop coefficients for mature grapevines (1996) and peach trees (average from 2001 to 2003) as calculated from lysimeters. Each data point is a weekly average. Regression lines are for data collected from bud-break through early July (about day 180).

by-16-feet spacing. In 1997, the mature 'O'Henry' trees were removed from the lysimeter and surrounding orchard and replaced in 1999 with 'Crimson Lady' (late-May harvest) peaches, which were also on 'Nemaguard' rootstock at the same spacing.

Each lysimeter has two separate irrigation systems, one below and the other above the ground. The underground irrigation systems are 12 inches and 24 inches deep in the peach lysimeter, and 16 inches deep in the grape lysimeter. Each underground system has 1-gallon-per-hour (gal/hr) emitters every 12 inches on either side of the plants. The aboveground irrigation systems consist of a single in-row line on or above the soil surface. The grape lysimeter's system is suspended 16 inches aboveground and has 1 gal/hr in-line drip emitters every 12 inches. The peach lysimeter's aboveground system had a 3.5-foot-diameter circle of ten 0.5 gal/hr drip emitters every 12 inches around each tree when planted with 'O'Henry', and a single 26 gal/hr emitter that fills a 4-foot diameter basin around each tree when planted with 'Crimson Lady'. Irrigation water is supplied by two 80-gallon polyethylene tanks suspended from and included in the total mass of the lysimeters.

In addition, the lysimeters can control the low-volume irrigation systems in the surrounding fields. The vineyard is irrigated by a single line of drip tubing suspended 16 inches above the soil with 1 gal/hr in-line emitters every 12 inches. Each tree in the peach orchard has a 6.7 gal/hr spray emitter with about a 10-foot radius.

The lysimeters have been in continuous operation since 1987. Every hour, the lysimeter boxes (including soil, plants and suspended irrigation tanks) are automatically weighed to determine water loss, which includes both soil evaporation and plant transpiration and is often referred to as "crop evapotranspiration," or ET$_c$. The values are recorded with a data logger (Campbell Scientific Instruments, 21 XL Micrologger, Logan, Utah) and the mass change is compared to a threshold value. When this value is exceeded, the trees or vines are automatically irrigated. Generally, low threshold values have been used so that multiple irrigations per day are called for in the summer. This maintains soil moisture content close to field capacity and minimizes any water stress effects. At midnight each day, the water tanks are automatically refilled to a preset level, and the new lysimeter mass is set as the baseline for the next day.

Hourly reference crop evapotranspiration (ET$_o$) values are calculated by a modified Penman equation using weather data collected from a nearby CIMIS (California Irrigation Management Information System) weather station. This equation was developed by scientists to estimate grass ET and is used as a standard around the world. Daily summed ET$_c$ values are divided by daily summed ET$_o$ to provide a crop coefficient (K$_c$) for each day. Once a seasonal pattern of crop coefficients has been established, this information can be used to guide irrigation amounts. The crop coefficient multiplied by ET$_o$ for a given time period gives an ET$_c$ value for that same period of time. Then, after adjusting for irrigation efficiency, the amount of water to apply can be determined.

Tree and vine crop coefficients

During normal midsummer days in central California, with hot temperatures and cloudless skies, the lysimeters generate smooth daily ET$_c$ graphs with minimal noise (fig. 1). During periods of unsettled weather, the lysimeter output is more variable from one hour to the next, but has generally followed the same pattern as ET$_o$, resulting in consistent day-to-day crop-coefficient values.

The typical seasonal crop-coefficient pattern of mature plants for both peaches and grapes starts as low as 0.1 to 0.2 early in the spring and increases steadily until early July (fig. 2)(Ayars et al. 2003; Williams et al. 2003a). Grape is delayed somewhat compared to peach because it is more severely pruned and takes longer to develop its canopy. For the remainder of the season, the crop coefficients for both crops leveled off at values between 1.1 and 1.2. The seasonal pattern of young trees and vines has also been determined (Johnson et al. 2002; Williams et al. 2003b).

The Kearney lysimeter research has elucidated factors affecting the water use of trees and vines, allowing for the better estimation of crop coefficients under conditions different from those in the lysimeter fields. One factor that has clearly been demonstrated is between canopy light interception and tree water use (Johnson et al. 2000), or leaf area and vine water use (Williams et al. 2003a). This relationship holds true for both young

***Left and center*, construction of the two large weighing lysimeters at KREC began in 1986. Each lysimeter consists of an underground chamber that houses a balance-beam weighing system with a rectangular "flower pot" measuring 6.5 feet wide by 13 feet long by 6.5 feet deep. *Right*, researchers enter the completed lysimeter.**

and mature trees and vines. The steadily increasing crop coefficients throughout the spring (fig. 2) are primarily due to the tree or vine's expanding canopy and its increasing interception of light.

The Kearney peach lysimeter yielded a crop-coefficient pattern (Ayars et al. 2003) distinctly different from previously published values for deciduous fruit crops (Snyder et al. 1989). The published values, which were derived primarily from almond trees, start at about 0.5 in the spring and increase to peak values of less than 1.0. Thus, the lysimeter-derived peach crop-coefficient pattern starts much lower initially in the spring, but by midsummer reaches a higher plateau.

These differences can be attributed to differences in the canopy development of peach and almond trees. Almonds are minimally pruned and quickly develop a spur canopy (many short shoots), which has high light-interception in the spring. In contrast, peach trees are more heavily pruned and require extensive shoot growth before they develop a full canopy. These differences indicate that separate crop-coefficient values may be needed for different deciduous fruit-tree species and grapevines, depending on pruning and canopy development parameters.

The maximum midsummer crop-coefficient values of 1.1 to 1.2 are greater than those reported in the past for trees and vines. However, these values are not out of line with recent reports on a wide range of crop plants including beans, corn, cotton, sugar cane and pistachios (Allen et al. 1998). In addition, while other researchers have reported that crop coefficients decrease toward the end of the growing season (Williams et al. 2003a), these decreases were due to insect pest defoliation (Daane and Williams 2003) or irrigation cutoff (Ayars et al. 2003). Such late-season declines in crop coefficients were not observed in either lysimeter as long as the plants were kept healthy, free of pests and well watered. Therefore, even though there may be horticultural or pest management reasons for cutting back irrigation water at the end of the season, there does not appear to be a physiological basis for it. The Kearney lysimeter research has clearly demonstrated that as long as they are kept healthy, peach trees and grapevines are capable of using significant amounts of water throughout the growing season.

However, it is important to emphasize that the lysimeters measure water use under conditions of high soil-water availability, which are not necessarily the best conditions for optimum production, tree health and fruit quality. A study in the grape lysimeter vineyard showed that yields were maximized when moderate water stress was imposed by limiting water applications throughout the season to between 60% and 80% of lysimeter water use (full ET_c)(Williams 2000). Likewise, there are many fruit-tree studies showing the benefits of imposing moderate water stress at different periods of the growing season. Ongoing research is needed to develop deficit-irrigation (less than full ET_c) management strategies that optimize fruit quality, plant health and long-term productivity. To aid in irrigation management, a model to predict peach-tree water use has been developed using lysimeters to quantify the relationships among light interception, soil evaporation, tree dimensions and tree water use (Johnson et al. 2002, 2004).

Water stress and water use

The lysimeters have also been useful for evaluating how water stress affects various parameters, particularly water use. In 1996, the peach lysimeter was subjected to a 3-week drying cycle and during that time frequent measurements were made of soil water content, predawn leaf water-potential and midday stem water-potential (Mata et al. 1999). Water potential is measured with a pressure chamber and basically indicates the tension of water in the leaf. All three parameters showed strong correlations with tree water use.

For soil water content, tree water use started to decline when the available water content decreased by 20% in the top 33 inches of soil, and then declined steadily as the water content continued to decrease. For predawn leaf water-potential and midday stem water-potential there was a continual decline in water use across all values, suggesting that either measurement could be useful in determining how well irrigation is supplying full crop ET_c and in assessing tree water stress. Similar relationships have also been found for grapevines (Williams and Araujo 2002).

A second study of more moderate water stress was conducted in the peach lysimeter in 2002. Three short-term drying cycles of about 1 week were imposed during 3-week periods in early June and again in late July. During each cycle, daily measurements were made of midday stem water-potential. As in the 1996 study, there was a linear decline in tree water use with decreasing midday stem water-potential values (fig. 3). Absolute water use was higher in late July than early June because of greater leaf area. However, the slope of the relationship was similar for both of these periods as well as during the 1996 study, which suggests midday stem

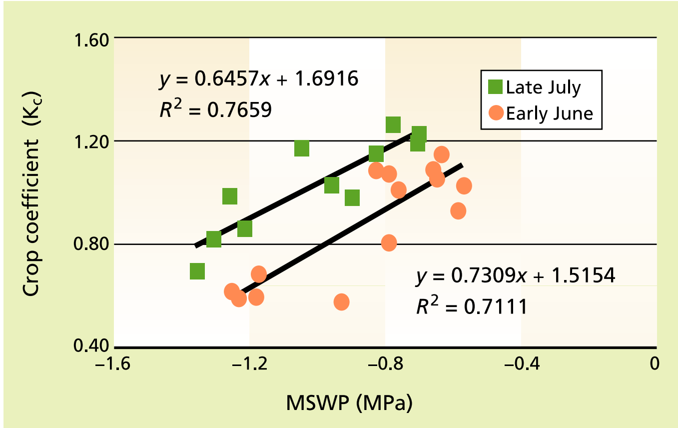


Fig. 3. Relationship between peach tree crop-coefficient (K_c = ET_c/ET_o) and midday stem water-potential (MSWP) for two periods of three dry-down cycles (no irrigation for 5 to 7 days) in 2002. MSWP is expressed in units of mega-pascals (MPa), a measure of water tension in the plant.

Larry Williams

The Kearney lysimeters have been in constant use since 1987. One lysimeter measures water use in peaches, *top*, the other 'Thompson Seedless' grapes, *bottom*. The lysimeters have provided more accurate evapotranspiration values for peach trees and grape vines, information necessary in irrigation management decisions that ultimately affect plant health and fruit quality.

water-potential might be a consistent tool for irrigation management in peach trees. Indeed, this measurement has proven to be useful both for predicting water stress and for helping schedule irrigation for a range of tree and nut species in California (Shackel et al. 1997).

Methods for estimating water use

Since a lysimeter is the most precise technique for measuring ET_c, its output can be compared with that of other less expensive methods for validation. The peach lysimeter has shown that two such methods are inaccurate but that others may be promising. The two inaccurate methods are the heat balance technique for estimating sap flow (Shackel et al. 1992) and the use of leaf-to-air temperature differences, as measured by an infrared sensor to estimate stress (Medawar 1991). Promising methods, such as the measurement of stem water-potential mentioned above, also include the continuous monitoring of diurnal changes in trunk diameter (shrinking and swelling) as an irrigation guide (Fereres et al. 1999; Goldhamer et al. 2003). As more techniques for estimating water use are developed, such as those involving remote sensing or detailed meteorological data, the Kearney lysimeters will be valuable instruments for validation purposes.

R.S. Johnson is Pomology Specialist, Department of Plant Sciences, and L.E. Williams is Professor, Department of Viticulture and Enology, UC Davis, both stationed at the UC Kearney Research and Extension Center; and J.E. Ayars and T.J. Trout are Agricultural Engineers, U.S. Department of Agriculture, Agricultural Research Service, San Joaquin Valley Agricultural Sciences Center, Parlier. *The authors express sincere appreciation for the technical assistance of Pete Biscay, David Clark, Dale Handley, Glenn Hoffman, Kevin Klassen, Richard Mead, Becky Phene, Claude Phene, Richard Soppe and Paul Wiley.*

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Ozone reduces crop yields and alters competition with weeds such as yellow nutsedge

David A. Grantz
Anil Shrestha

In recent decades, air quality has improved near most cities but not in rural areas such as the San Joaquin Valley. Many studies using diverse exposure techniques have shown that ground-level ozone air pollution reduces plant growth and yield, from negligible impacts in some species to over 30% losses in others. We studied the interaction of ozone with weed competition from yellow nutsedge in Pima cotton and tomato in open-top field-exposure chambers at the UC Kearney Research and Extension Center in Fresno County. Ozone impacts on cotton (which is relatively sensitive) were compounded by weed competition, whereas tomato (which is less sensitive) competed well at all ozone concentrations. Our data suggests that crop-loss estimates obtained in single-factor experiments accurately reflect the serious risk of ozone to agriculture, but that more accurate yield predictions will require the consideration of interactions between the components of complex crop production systems, including weed competition.

Photos: Jack Kelly Clark

***Top*, Kearney-based air pollution effects specialist David Grantz (right) and technician Margo Toyota (left) evaluate ozone impacts on cotton in an open-top chamber (OTC) at Kearney. At current ozone concentrations in the San Joaquin Valley, yields can decline up to one third depending on the crop. *Bottom*, Grantz checks cotton plants growing in a closed chamber in Kearney's new state-of-the-art greenhouse.**

The economic viability of crop production in the San Joaquin Valley is threatened in many ways. Chronic threats include reduced crop vigor caused by competition from newly introduced weeds, some of which are increasingly difficult to control, and damage caused by the changing global climate, including increased ground-level ozone (Fuhrer 2003). Ozone can be either "good" or "bad," depending on where it is in the atmosphere. Ozone in the upper atmosphere between 10 to 30 miles (15 to 50 kilometers; the stratosphere) is naturally occurring and "good," in that it absorbs ultraviolet light, protecting against sunburn, skin cancer and damage to vegetation and sensitive aquatic species.

In contrast, ozone produced at ground level and mixed into the air, up to about 6 to 12 miles (10 to 20 kilometers; the troposphere), is mostly attributable to human activity and is considered "bad." It is a strong oxidant in the environment, injuring human lungs, crops and native plants, and materials such as stone, paint and plastics. This ground-level ozone, or smog, inhibits lung development in children, induces asthma attacks and has been linked to increased hospital admissions and deaths.

Ground-level ozone is derived from emissions of oxides of nitrogen (from high-temperature combustion including automobiles, power plants and factory boilers) and emissions of volatile organic compounds (evaporating gasoline, paints and solvents, pesticides

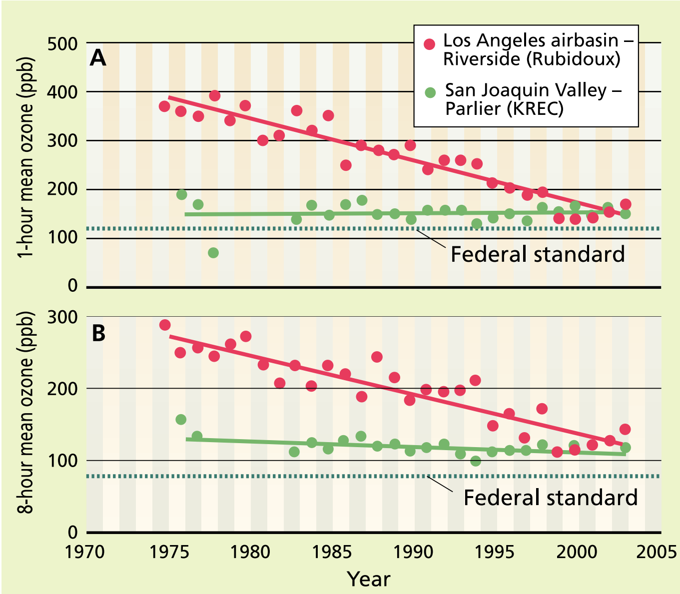

Fig. 1. Trends of ozone air quality in the (A) Los Angeles and (B) San Joaquin Valley air basins. The high concentrations observed in the 1970s in the Los Angeles air basin are no longer observed; the San Joaquin Valley and Los Angeles basins recently traded places as having the worst air in the United States.

TABLE 1. Estimated statewide crop loss (%) in California caused by ground-level ozone, 1993

Crop	Yield loss*
	%
Annual	
Lettuce	0.5
Fresh-market tomato	0.6
Field corn	1.2
Rice	3.9
Wheat	6.7
Processing tomato	6.8
Onion	10.6
Dry bean	17.5
Upland cotton†	23.3
Cantaloupe	32.8
Perennial	
Lemon	8.4
Alfalfa	9.5
Orange	14.0
Wine grape	22.8
Raisin grape	26.2
Table grape	29.9

* Statewide yield-loss data from Mutters and Soret (1998), using 7-hour (27.2 ppb) and 12-hour (25 ppb) mean ozone exposure crop-loss models. Losses are relative to clean background air.

† Data is for upland cotton; comparable data for Pima cotton is not available.

and plant products including fragrant compounds). Natural background concentrations of ground-level ozone are about 20 to 25 parts per billion by volume (ppb). As concentrations increase above this level they become increasingly harmful to human health. The California health-based 1-hour standard is 90 ppb (fig.1A) and the federal standard is 120 ppb (fig.1B), although both standards may be too high to be protective. Crops are damaged above concentrations of 40 to 60 ppb.

Ground-level ozone is a long-standing and worsening problem in many rural areas. Curiously, while rural air quality has not improved rapidly, air quality in Los Angeles and other major metropolitan areas has. This difference is due to rapid population growth in affordable rural areas such as the Central Valley, and the initial abundance in urban areas of easily identifiable air pollution sources such as factories and industrial processes. The steep decline in ozone concentrations at the Rubidoux monitoring site in Riverside County, in the South Coast (Los Angeles) air basin, contrasts dramatically with the nearly flat trend at the Parlier monitoring site at the UC Kearney Research and Extension Center (KREC) in the San Joaquin Valley air basin (fig. 1). Similar trends are observed for the 1-hour average ozone concentration (the basis of the older federal air-quality standard) and for the newly established 8-hour average (the basis of the newer federal standard). However, neither region meets either standard. The San Joaquin Valley and Los Angeles air basins seem to be trading places as the most polluted regions in the United States.

San Joaquin Valley crops are grown in increasingly agroecological systems, with emphasis on integrated pest management. A critical component of these systems is crop competition with other vegetation. Weeds cause considerable crop loss despite the extensive use of control technologies. However, weed management in the San Joaquin Valley may be further threatened by restrictions on herbicide use, due in part to air-quality concerns, and by the establishment of herbicide-resistant weeds.

Ozone and crop loss

Current ambient ozone concentrations impose substantial economic costs on producers and consumers of agricultural products in the United States (Spash 1997). Considering only ozone derived from motor vehicle emissions in the United States, about 60% of all ozone (1993 data from U.S. Environmental Protection Agency, www.epa.gov/ebtpages/air.html), and only eight major crops, the estimated economic damage due to ambient ozone in 1990 ranged from $2.8 billion to $5.8 billion (Murphy et al. 1999).

Despite its "big city" ozone problem, the San Joaquin Valley remains the dominant agricultural area of California. An economic cost-benefit analysis (Kim et al. 1998) suggested that controlling peak ozone concentrations to 150 ppb in Tulare, Kings, Fresno and Madera counties would provide substantial economic benefits, even though 150 ppb is well above the threshold (40 to 60 ppb) for crop damage, and peaks above 150 ppb occur infrequently in the Valley (California Air Resources Board, www.arb.ca.gov/aqd/aqdpage.htm).

Current ambient ozone concentrations in the San Joaquin Valley can cause yield losses from nearly none to as much as a third, depending on the crop (Mutters and Soret 1998). Crop species, and even cultivars within a species, differ in both

Ozone now causes economically significant losses in the yields of most crops, and this will get worse if current trends in rural population density continue.

Photos: California Air Resources Board

Los Angeles used to be the most polluted air basin in the United States. *Left*, a smoggy day in the city's downtown; *right*, a clear day.

sensitivity to ozone and in the ambient ozone environments in which they are grown. The two factors together determine statewide yield losses (table 1).

The equations that allow calculation of these yield losses have been derived mostly using open-top field-exposure chambers (OTCs)(Heagle et al. 1988). While OTCs may subtly alter the crop microenvironment and subsequent plant growth (Manning and Krupa 1992), they did not significantly affect crop yield in 70% of published experiments (Legge et al. 1995). In addition, crop sensitivity to ozone was generally unaffected in the few cases where direct comparisons with alternative exposure methods are available (Heagle et al. 1988; Olszyk et al. 1986).

A consensus has developed among North American scientists that crops are likely to be damaged by ozone when concentrations greater than 60 ppb exceed a total of 20,000 ppb-hours over any 90-day period (Heck and Furiness 2001). A similar consensus in Europe finds that crops are likely to be damaged by ozone when concentrations greater than 40 ppb exceed a total of 3,000 ppb-hours (Karenlampi and Skarby 1996). These conclusions differ in magnitude due to differences in cultivars and growth environments on the two continents. However, they are similar in adopting a threshold concentration (60 ppb or 40 ppb) and an accumulated exposure index (ppb-hours) as determinants of damage. There is little doubt that ozone reduces crop yields at current ambient concentrations.

Yield loss in tomato. In 2001, California produced 93% of U.S. processing tomatoes, mostly in the San Joaquin and Sacramento valleys. California's combined processing and fresh-market tomato crop is valued at approximately $766 million (CDFA 2002). Tomato is only moderately sensitive to ozone (Temple, Surano, et al. 1985). Statewide yield losses due to ozone in 1993 (the last year available) were an estimated 6.8% for processing tomatoes and nearly none for fresh-market tomatoes (table 1).

Yield loss in cotton. In contrast, cotton is relatively sensitive to ozone (Grantz 2003). Yield reductions have been demonstrated for upland cotton cultivars (Olszyk et al. 1993; Temple, Taylor, et al. 1985), with statewide yield losses in 1993 estimated at 23.3% (table 1). The first Pima cotton cultivars introduced into the San Joaquin Valley, including cv. S-6, were affected even more (Olszyk et al. 1993). More recent Pima cultivars — selected under ozone pressure in the San Joaquin Valley — are reportedly more resistant to ozone, but confirming data is unavailable.

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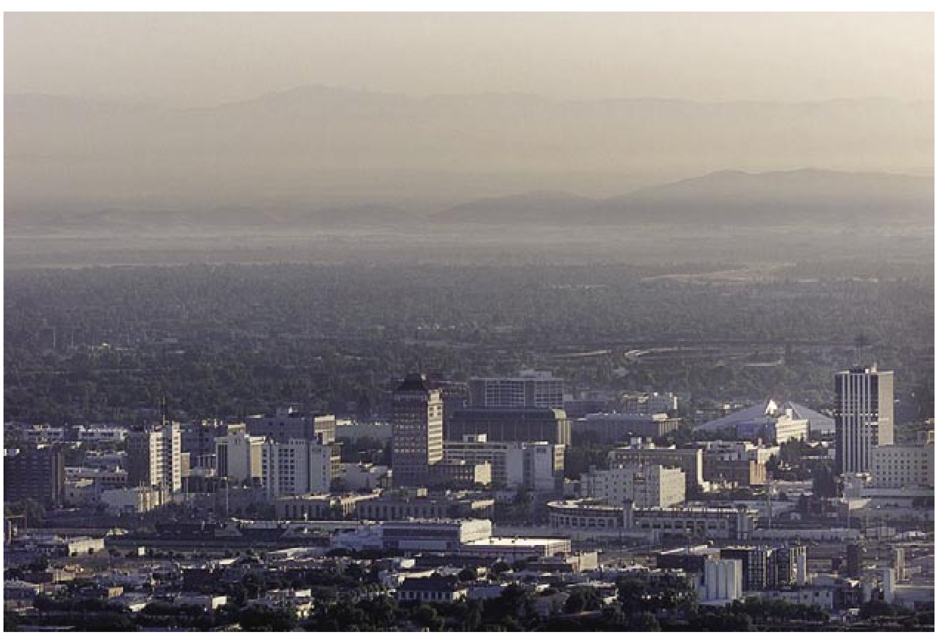

The San Joaquin Valley is now the nation's most polluted air basin. While Southern California air quality has improved remarkably in recent years, the increasing number of automobiles in the Central Valley has led to more days like this one in Fresno.

Weed and crop competition

Herbicides are used on much of the tomatoes (*Lycopersicon esculentum* Mill.) and cotton (both upland [*Gossypium hirsutum* L.] and Pima [*G. barbadense* L.])

Effect of increasing ozone concentration (left to right: about 15, 80 and 150 ppb) on growth of (A) Pima cotton and nutsedge grown in direct competition with one nutsedge per cotton; (B) tomato and nutsedge grown in direct competition with nutsedge (two-to-one); and (C) yellow nutsedge grown in the absence of competition.

grown in California, preventing substantial crop losses (CDPR 2002). At the same time, ozone may profoundly affect these plant communities, altering the growth and fitness of both weedy and crop species as well as their competitive interactions. While ozone impacts on many important crop species have been characterized, there are few reports on the impacts of ozone on the growth and fecundity of weeds (Fuhrer and Booker 2003). Short life cycles and prolific reproduction could accelerate weed adaptation to ozone, and the enhanced competitive advantage of weeds relative to crop species could increase herbicide use. However, the impacts of ozone on such competitive systems cannot be predicted simply from the ozone sensitivities of the individual species (Evans and Ashmore 1992). It is important to consider the mechanisms of plant competition and ozone effects on interactions that may emerge only when weeds and crops are grown together.

Yellow nutsedge (*Cyperus esculentus* L.) has become a particularly difficult and costly weed to control in many California cropping systems. It is a C_4 species, making it water efficient and heat tolerant, and thus well adapted to irrigated agriculture in the San Joaquin Valley. Because yellow nutsedge is predominantly vegetatively propagated underground by tubers, its adaptation to ozone may be slower than that of the more common sexually propagated weeds. Yellow nutsedge is well established in the San Joaquin Valley, but no data is available on this pest's response to ozone. We conducted a series of experiments at KREC on the interactions of nutsedge with tomato and cotton.

Exposure of plants to ozone

Processing tomato (nursery transplants of cultivars HD 8892 and EMP 113), cotton (seeds of cv. Pima S-6) and nutsedge (locally collected juvenile plants that were about 2.5 inches [6 centimeters] tall with two or three leaves) were grown in outdoor OTCs during summer 2003, in 2-gallon (9-liter) pots of sintered clay ("kitty litter," 6-40 mesh), irrigated twice daily and fertilized weekly (Miracle-Gro, 0.17 ounce per gallon [1.3 grams per liter]).

Nutsedge-to-crop plant ratios in each pot were zero-to-one and one-to-zero (single species), and one-to-one, two-to-one and three-to-one (competition within each pot). Three concentrations (12-hour mean exposures) of ozone were imposed: about 15 ppb (low ozone, atmospheric background), 80 ppb (medium ozone, worst-case local ambient conditions) and 150 ppb (high ozone).

Plants were harvested prior to flowering at 1 to 2 months after planting, separated into shoots and roots and dried at 160°F. The root fraction in nutsedge was separated into roots (which included some rhizomes) and tubers, which were weighed separately and counted. In pots containing two species the roots were entangled, so the combined root mass was obtained.

The experiment was performed twice with tomato and once with cotton, each time with four replicate plants per treatment. The experimental design was four population ratios as subtreatments within each of the three ozone

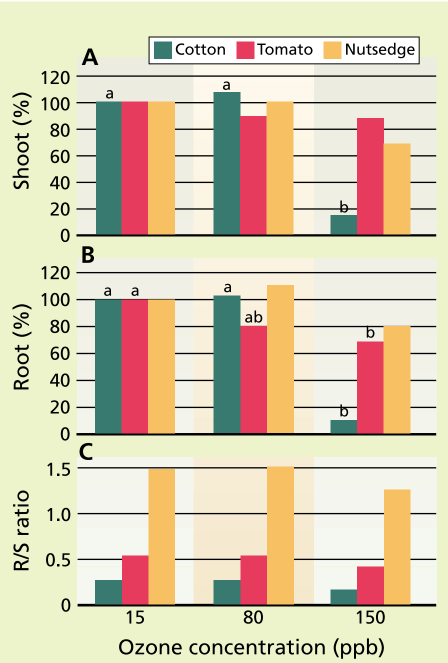

Fig. 2. Effect of increasing ozone exposure on percentage inhibition of shoot and root biomass productivity and on the resulting root-to-shoot biomass ratio (R/S) of tomato, cotton and nutsedge, grown without competition. Shoot biomass of cotton was reduced by ozone at *P* = 0.0007. Root biomass of cotton and tomato were reduced by ozone at *P* = 0.0002 and *P* = 0.0955, respectively. R/S declined in each case but was not significant in any species.

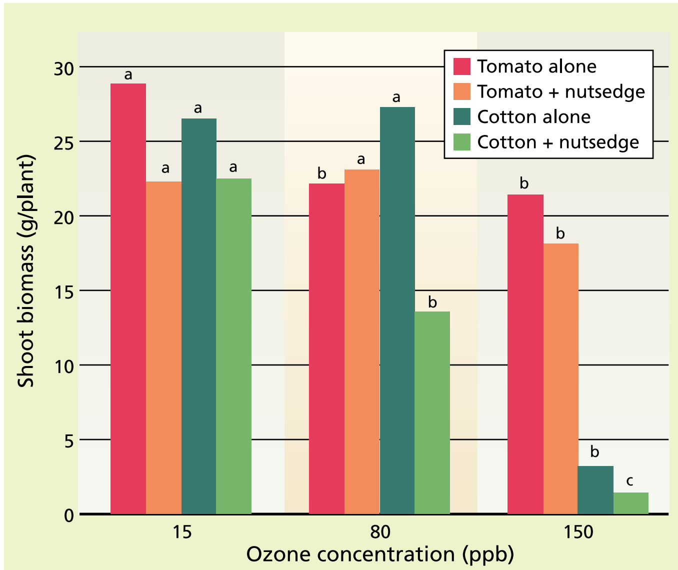

Fig. 3. Effect of ozone exposure and nutsedge competition on shoot biomass production of tomato and cotton grown alone or with nutsedge (averaged over all levels of nutsedge competition). Tomato grown alone and with nutsedge was reduced by ozone at *P* = 0.09 and *P* = 0.08, respectively. Cotton was far more sensitive, and was reduced by ozone at *P* < 0.0001 both in the presence and absence of nutsedge.

concentrations. Species were analyzed separately. Data were transformed as required and analyzed using PROC GLM (General Linear Model; SAS). Mean separation was by Fisher's Protected LSD. Levels of significance are presented in the figure legends, and the bars in figures 2 and 3 are labeled with different letters if differences within a species are significant at $P < 0.10$, a more permissive standard than the more common $P < 0.05$ to accommodate the modest responses in the ozone-tolerant tomato. An additional statistical contrast was conducted between plants grown alone and with competition (averaged over all population ratios).

Effects on individual species

Cotton. As expected from our previous studies (Grantz 2003), elevated ozone negatively affected growth of the cotton plants, which were about 25% shorter and produced 50% fewer leaves. The highest ozone concentration also reduced cotton shoot biomass by about 86% (figs. 2A, 3). In contrast, medium ozone reduced leaf area and plant height only modestly, and in these experiments did not affect shoot biomass production (fig. 3).

The biomass of cotton roots was reduced somewhat more than that of shoots (fig. 2B), particularly at high ozone. These coordinated changes in root and shoot biomass led to a small, nonsignificant decline in the root-to-shoot biomass ratio (R/S; fig. 2C). Significant declines in R/S of cotton have been observed previously at similar ozone concentrations (Grantz 2003).

Tomato. Growth was less sensitive to ozone in tomato than in cotton, particularly at the highest ozone concentration. Shoot biomass was reduced by about 19% at medium ozone with little further decrease at high ozone figs. 2A, 3). Root biomass was reduced more than shoot biomass, by about 30% at high ozone compared with low ozone (fig. 2B). The declines in tomato root and shoot biomass were sufficiently well balanced, as in cotton, that the decline in R/S was not significant (fig. 2C). Ozone has generally been found to inhibit biomass production and reduce R/S in tomato (Varshney and Rout 1998).

Nutsedge. Increasing levels of ozone had no significant effect on either shoot biomass (figs. 2A, 3) or root biomass (fig. 2B) of nutsedge. Plants were more erect at medium than low ozone due to the presence of stiff flowering stalks, which were only occasionally observed at low or high ozone. As the ozone concentration increased further, the nutsedge leaves became more flaccid and plant height declined. Reduced plant stature has obvious implications for light interception by nutsedge in competition with crop plants. As in tomato and cotton, R/S of nutsedge declined as expected but the change was not significant (fig. 2C).

The production and size of nutsedge tubers did not respond consistently to ozone in these experiments, and increased in many plants. Further studies are under way to determine if elevated ozone concentrations stimulate biomass allocation to the reproductive tubers, as predicted from other plant responses to abiotic stress.

Photos: Jack Kelly Clark

A significant but hidden aspect of ozone crop damage is reduced growth belowground, demonstrated here following exposure of plants to elevated ozone levels. *Left*, an intact cotton root system is scanned into a computer for an automated analysis of root length and morphology. *Right*, ozone causes changes in cotton root respiration, measured with a computerized oxygen electrode system.

Weed competition with crops

Cotton and nutsedge. At the low ozone concentration, competition with nutsedge — averaged over all population ratios — reduced the shoot biomass of cotton by 22% (fig. 3). At medium ozone, cotton was slightly more sensitive than nutsedge, particularly belowground, and the loss due to nutsedge competition was closer to 50%. At high ozone, the relative loss due to nutsedge competition was similar to that at medium ozone, although cotton growth was reduced to very low levels even in the absence of competition. This reduction in cotton growth by the presence of nutsedge ($P = 0.005$) reflected the greater weakening of cotton than nutsedge by ozone and the resulting enhanced vigor of nutsedge grown in direct competition (fig. 3). This was particularly true at medium ozone because at high ozone nutsedge was also affected and appeared to be less competitive with cotton. Nutsedge inhibited cotton growth much more at high than at low ozone.

Tomato and nutsedge. At the low ozone concentration, competition — averaged over all population ratios — reduced tomato shoot biomass by about 15% (fig. 3). However, in contrast to cotton, at medium ozone there was no additional impact of nutsedge competition on tomato growth. The reductions of biomass by medium ozone and by competition were similar and not increased by the combination of both stresses. At high ozone there was little further effect on tomato alone but a slight increase in the inhibition of tomato shoot biomass due to nutsedge competition. Because nutsedge was more sensitive to ozone than tomato, the shoot biomass of tomato was most affected by competition with nutsedge at low ozone ($P = 0.055$)(fig. 3).

Tomato root productivity was more sensitive to ozone (30% reduction; $P = 0.096$) than nutsedge root productivity was (19% reduction; not significant) (fig. 2B). At medium ozone, tomato root biomass declined by 20% while nutsedge was unaffected.

The nutsedge shoots in the highest ozone concentration drooped over the side of the pots, further decreasing nutsedge competition for light. As observed previously for the interactions of these two species (Santos et al. 1997), tomato had a competitive advantage over nutsedge in light interception. In our studies, this advantage increased with ozone concentration. Tomato was more sensitive to ozone than nutsedge, particularly near ambient (medium) ozone, but nutsedge was more sensitive to competition than tomato.

Air pollution and agriculture

Ozone air pollution continues to be problematic in rural areas such as the San Joaquin Valley. Single-factor ozone exposure experiments have consistently indicated that ozone now causes economically significant losses in the yields of most crops, and this will get worse if current trends in rural population density continue. This conclusion is unlikely to change with further research. More complex, multifactor experiments are now required to allow more accurate estimates of current losses in specific crops, and to provide a basis for predicting losses in future presumably warmer climates. In particular, this will require consideration of the impact of ozone on the complex interactions that characterize agroecosystems, including the ozone sensitivity of crops, competing vegetation and other pest species, and on the dynamics and mechanisms of specific competitive relationships among these species. So far, this important work has only just begun. The exposure facilities recently completed in the new research greenhouse at KREC will allow us to bring further quantitative techniques to bear, particularly on the belowground competition between these crop and weed species.

In the Pima cotton-nutsedge system, cotton was more strongly affected at high ozone concentrations than nutsedge, was more inhibited by nutsedge competition, and was less able to compete with nutsedge at near ambient (80 ppb) ozone concentrations than in clean (15 ppb) air. In the tomato-nutsedge system, tomato was only moderately sensitive to ozone compared with cotton or nutsedge, competed well with nutsedge at all levels of ozone, and did not lose any competitive advantage with rising ozone concentration. Nutsedge tuber production may have increased at high ozone concentrations. This weed may become more difficult to control, spread more rapidly and require greater use of herbicides or other control strategies, particularly in ozone-sensitive crops such as Pima cot-

Jack Kelly Clark

Yellow nutsedge may become more difficult to control, spreading more rapidly and requiring greater use of herbicides, particularly in ozone-sensitive crops such as Pima cotton.

ton. These results indicate the variety of impacts that climate change, including rising ground-level ozone, may have on important crop production systems.

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COMINGUP

Julie Morrison

Streamflow and tree canopy are important factors determining summer water temperatures in Lassen Creek, which is critical spawning and rearing habitat for Goose Lake redband trout.

Stream temperature monitoring

Under the Clean Water Act, hundreds of miles of California waterways must reduce elevated water temperatures in order to improve cold-water fish habitat. Stream temperatures may be increased due to the diversion of irrigation water for pastures, the return of warm irrigation runoff to streams, or the reduction in canopy cover over streams due to logging and grazing. In the next issue of *California Agriculture*, scientists use a case study from two Modoc County streams to demonstrate how water-temperature monitoring data can be better analyzed and graphically presented, and how relationships between temperature and factors such as flow, canopy cover and air temperature can be identified and quantified. In a related article, a case study near the same streams illustrates how land managers can assess and monitor water-quality impacts related to agricultural discharges from irrigated pasture.

Also:

Using GPS to pinpoint herbicides

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Soil microbial communities

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