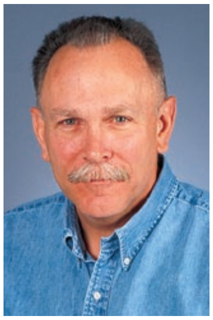
OCTOBER–DECEMBER 2006 • VOLUME 60 NUMBER 4

California Agriculture

Lead toxicity:
Assessing the risk to U.S. children

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



Bob Sams
Director,
ANR Communication Services

Of Mendel, wikis and open source: New models for knowledge creation

IN 1866, Gregor Mendel published his paper "Experiments with Plant Hybridization" and set a foundation for modern genetics and the laws of inheritance. As with many keystone achievements, the importance of his paper was not recognized at the time. Thirty-five years later, long after Mendel's death, rediscovery of his work generated rapid advances in our understanding of genetics and marked a starting point for the research that has improved plant and animal breeding, shown us the structure of DNA, and helped us elucidate the risks and benefits of biotechnology.

However, that is only part of the benefit from Mendel's work and the 140 years of review, replication and analysis that followed. It is not as well known that Mendel's experiments were also studied carefully by Richard Fisher, English statistician and evolutionary biologist. Fisher concluded that Mendel's findings were just too close to expected results — and while the accuracy of Mendel's hypothesis is not challenged today, his work is cited as an example of how smoothing data can lead to confirmation bias. Fisher's later career included work at the famed Rothamstead Experimental Station in England and as visiting faculty at Iowa State University, where he contributed greatly to modern statistical science. Mendel's work and Fisher's analysis are examples of the tradition of open inquiry and scientific dialogue that are the reason for publishing this magazine and for reporting research results openly and accessibly.

As *California Agriculture* marks its 60th anniversary (see page 174), the journal is working hard not only to publish new findings but also to realign production, publication and distribution methods with rapid technological advances in communications. First among these changes is the continuing growth of the Internet. The World Wide Web has become the dominant information retrieval pathway, especially in science, education and business. Two things have fueled this evolution. Digitized content has grown explosively and there is no end in sight. In a recently announced agreement, UC and Google will undertake to digitize and index selected contents of the UC library system, as well as those of other major institutions. Combined with similar initiatives by Yahoo and other search engines, this agreement shows that society has implicitly and collectively agreed that this Herculean task is both possible and desirable. It also demonstrates our confidence that the technology behind today's powerful search engines is capable of storing, indexing and retrieving that information.

Secondly, growing online communities based on "social networking" permit both direct conversations between individuals as well as specialized Web publishing through blogs, Web forums, wikis and virtual communities. Cooperation and collaboration are no longer limited by time or distance, nor are online reviews, online real-time editing or instant publishing. These developments promise to vastly reduce publication costs. The open-source software development community demonstrates that virtual teams can accomplish highly complex tasks and distribute valuable products.

These technical and behavioral changes are disruptive. In fact, Dan Greenstein, university librarian and head of the California Digital Library, has figuratively called them "subversive." New forms of popular and academic publishing will affect scholarly communications much as Web distribution has revolutionized the music industry and newspaper publishing. New kinds of copyright licenses and new definitions of intellectual property rights will be required. One significant effort to define these agreements is the Open Content Alliance. Web archives and aggregators such as UC's own eScholarship Repository and the national Web project eXtension are working to develop open models of content creation, attribution, licensing and ownership.

For *California Agriculture* and all ANR publications, these changes are important, difficult and exciting. Communications and information technology professionals see many tantalizing, confusing and unknown pathways to the open and broad dissemination of peer-reviewed research results. We also see a bewildering array of tools to deliver the benefits of new knowledge to society.

To take full advantage, we must do more than ensure that content exists on the Web and that it is appropriately indexed and recognized by search engines. We must also engineer online peer-review processes that are flexible enough to accommodate the whole range of information and publication methods, from refereed journals to one-page fact sheets. We must explore new forms of community or "salon" review that allow editorial or content changes to Web information in real time. We must also adapt to changing notions of intellectual property and copyright. In a letter to the editor (page 173), Lawrence Pitts, chair of the UC Academic Council Special Committee on Scholarly Communication, reminds us that all of UC shares an obligation to the common good, a value that has always been at the core of ANR's mission. At the same time, we must ensure the quality of our information, protect its identity and source, and deliver it in an effective form to the people of California. We are working to see that *California Agriculture* continues its 60-year tradition of doing just that.

Links to explore

eScholarship Repository
http://repositories.cdlib.org/escholarship/

eXtension
http://about.extension.org

Gregor Mendel
http://en.wikipedia.org/wiki/Gregor_Mendel

Open Content Alliance
www.opencontentalliance.org

Open-source software
www.sourceforge.net

Wikipedia
http://en.wikipedia.org/wiki

Table of Contents

G. DeGrazia/CMSP

COVER: National studies have increasingly linked even low levels of lead exposure to IQ deficiencies and behavioral disorders in young children (page 180). In September, a new study connected attention deficit disorders to lead, among other factors (see www.ehponline.org).

News departments

Research articles

Correction: In the July-September 2006 issue, the credits for two images on page 116 were incorrect. The California wild grape image was taken by wildscaping.com, and the wild radish was taken by Jeff Abbas. *California Agriculture* regrets the error.

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 floor, Oakland, CA 94607. Include your full name and address. Letters may be edited for space and clarity.

More voices: Making the case for open access

Should peer-reviewed research developed at tax-supported institutions such as UC be freely available to the public? A recent *California Agriculture* editorial (January-March 2006; "*California Agriculture* delivers access to peer-reviewed research") explored this issue, noting the impact of soaring journal prices on both libraries and individuals.

Some recent developments:

- In May, U.S. senators introduced legislation requiring agencies with annual research budgets of more than $100 million (e.g., EPA, USDA) to provide public access to research results no more than 6 months after publication. (The National Institutes of Health already encourages posting within 12 months on PubMed.)
- In July, Rice University announced plans to become the first all-digital university press; browsers will be able to read the digital books for free but will pay to download.
- This summer, the journal *Nature* offered authors the opportunity to make their submissions available online immediately as preprints and receive comments from any reader.
- In August, UC libraries joined Google Book Search, the massive book scanning and digitization project, marking the largest expansion of that project to date (UC potentially offers the contents of 100 libraries on 10 campuses).
- By September, UC's eScholarship Repository, the open-access database of the California Digital Library, had posted 3.7 million full-text downloads since opening in April 2002. (*California Agriculture* posted close to 1,900 full-text downloads between May and September, after initial posting of peer-reviewed articles at the site.)

The letters that follow explore these issues.

— Editor

Like others systemwide, UC Irvine students rely on UC library purchases of essential journals and online subscriptions.

Agricultural publications online

The January-March 2006 *California Agriculture* editorial underlined the importance of publishing peer-reviewed agricultural research, the advantages of open-access outlets (including our experiment station and extension service publications) and the advantages of making information available through our institutional repositories.

At my own institution we are currently looking at our languishing experiment station series and discussing what their future should be. As I have looked at other experiment stations, it seems we are not alone in seeing publication in these once-prolific series fall off.

Wouldn't it be a wonderful contribution to the National Digital Library for Agriculture to have access to not only the historical record of agricultural research, but also the current research, readily available to anyone, anytime, anyplace?

Constance J. Britton, Librarian
Ohio State University, Wooster

Editor's note: The National Agricultural Library (NAL) is laying the groundwork to provide comprehensive digital access to agricultural information from partnering institutions and universities.

Digitizing research, improving access

The January-March 2006 editorial addressed a key issue. This is the fact that researchers and members of the public often need access to the results of peer-reviewed research, but it is no longer easily accessible or affordable.

Many agricultural librarians have been confronting this for quite a while. Questions come up routinely, such as a graduate student trying to access information on Pierce's disease findings, or a scientist looking for archival data on soil characteristics. At the extension level, someone may want to know how close to plant a fruit tree to a fence built of pressure-treated lumber, for fear of contamination from toxic chromated copper arsenate. At a recent brainstorming session sponsored by USAIN (United States Agricultural Information Network) and NAL, concerns raised included the need for digital archiving and repositories, the unrestricted availability of publications to a wide audience, and an easy-to-use search interface like Amazon or Google. The development of a digital repository by the USDA modeled on PubMed, as well as an expansion of open-access journals like PLoS (Public Library of Science), are all efforts that need to be supported and encouraged.

Finding "grey" or "ephemeral literature" has always been problematic in many disciplines. Such items are not commercially published, widely distributed or indexed, and not always archived. Many state agricultural documents, especially at the extension level, fall into this category, and there are now plans to digitize such materials. Libraries and land-grant institutions need to explore further collaboration on publishing and disseminating both extension and the more scholarly experiment station research, given the large amount of material that is no longer widely distributed outside of the local area.

Norma Kobzina, Head, Information Services,
Biosciences and Natural Resources Library, UC Berkeley

UC faculty and the right to copyright

I share the conviction that research and scholarship should be broadly accessible and free to the public. The economic dysfunctions cited in the editorial (soaring prices of electronic and print journals, due in part to publisher consolidations) were brought into sharp relief for many UC faculty and administrators during the University's 2003 negotiations with for-profit journal publisher Elsevier, and led to the establishment of the UC Special Committee on Scholarly Communication (SCSC). But while the dysfunctions helped to get our attention, it is the opportunities offered by Internet publishing that have led the faculty at UC and other research institutions to become deeply engaged in these issues and propose solutions.

The Internet reduces to near zero the cost of an additional reader when the content is online instead of in print form. Internet publication can also be used to certify, validate, and ensure accuracy and quality of research results. Online peer-review systems, new measures of impact that include the readership as well as citations of an article, and increased access to original and supplementary data are just a few of the new tools available for ensuring scholarly quality and increasing the usefulness of research.

The SCSC developed a series of white papers for consideration by the UC Academic Council and Assembly, which endorsed them in May 2006. Among other things, these papers recommend that: (1) promotion and tenure processes include appropriate alternative forms of dissemination; (2) researchers manage their copyright to provide greatest access and impact; (3) scholarly societies limit copyright transfer from author to society; and (4) journal publishers accept the right to first publication and routinely permit posting of papers on open-access databases, in some form.

In May, UC's Academic Assembly endorsed a proposal that faculty give UC permission to post their journal articles or conference papers in an open-access repository; final adoption is expected by spring 2007. The SCSC has also proposed open-access archiving of stem-cell research results funded by California's Proposition 71. I am pleased that health sciences have encouraged such policies.

The SCSC does not promote a particular publishing business model or distribution of responsibilities among stakeholders. This is a time for investments that encourage experimentation, such as UC's eScholarship Repository, and for faculty to look outside of their own disciplines to success in other domains.

Lawrence Pitts, Professor of Neurosurgery,
UC San Francisco
Chair, Special Committee on Scholarly Communication

Links to explore

Academic Senate Special Committee on Scholarly Communication
www.universityofcalifornia.edu/senate/committees/scsc/reports.html

Google Book Search
http://books.google.com

National Agricultural Library
http://naldr.nal.usda.gov

Oxford Journals and NAR Open Access Initiative
www.oxfordjournals.org/our_journals/nar/announce_openaccess.html

PLoS (Public Library of Science) and Creative Commons Attribution License
www.plos.org/about/index.html

PubMed (biomedical literature)
www.ncbi.nlm.nih.gov/Literature

SPARC (Scholarly Publishing and Academic Resources Coalition)
www.arl.org/sparc

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Executive editor: Janet White
Managing editor: Janet Byron **Art director:** Davis Krauter

California Agriculture
1111 Franklin St., 6th floor, Oakland, CA 94607-5200
Phone: (510) 987-0044; Fax: (510) 465-2659; calag@ucop.edu
http://CaliforniaAgriculture.ucop.edu

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60 California Agriculture

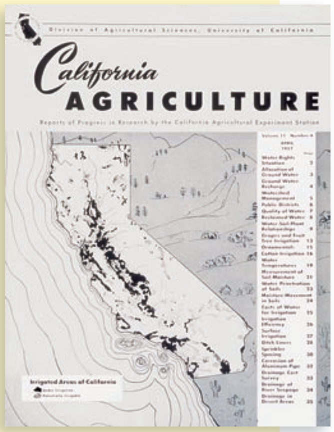
Celebrating a work in progress:

UC journal delivers research to Golden State and beyond

In the last 6 decades *California Agriculture*'s format, length and design changed many times. As California grew and diversified, so did the journal. Today, published findings emanate from a broad band of disciplines, covering topics such as demographics, public policy and climate change.

December 1946

However, our goals of publishing rigorously reviewed research, and translating that science for a diverse — and international — audience, are the same. *California Agriculture* is one of the nation's oldest, continuously published, land-grant university journals, and our presence extends beyond the printed page to our Web site, California Digital Library's eScholarship Repository and numerous scholarly databases. Below, a brief timeline of events:



April 1957

March 1962

December 1946: Publication of the first issue of *California Agriculture*, a four-page tabloid on newsprint.

1950s–1960s: In the early years, scientists report a growing diversity of findings, from the effectiveness of DDT, to attendant residue problems and increasing insect resistance. Other issues include some of the earliest reports on the rural-urban fringe problem (March 1959), integrated control (September 1960) and gamma ray research (March 1962).

April 1957: The first special issue appears, including 24 reports on the water situation.

January 1960: Research Briefs first published; these brief notes about UC research run occasionally through December 1978.

January 1969: The first editorial appears: "Research is People" by C.F. Kelly, then director, UC Agricultural Experiment Station.

September 1970: The first color cover appears, featuring rusty ribs of head lettuce. Color sections become regular in 1978, with the magazine adopting full color on all layouts by 1990.

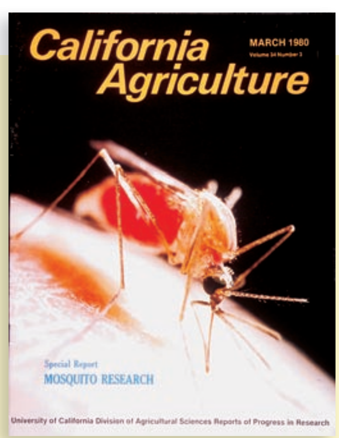
1978: Peer review begins. At first this consists of a single reviewer for each article.

1970s–1980s: Content evolves in breadth and depth, embracing topics such as farmworkers and the wine industry (March-April 1989). The journal explores single subjects in greater depth, such as forestry (May 1979), mosquito research (March 1980) and genetic engineering (August 1982).

California Agriculture adopts desktop publishing soon after it becomes available in 1985.

September 1970

May 1979



March 1980

August 1982

March-April 1989

November-December 1995

May-June 1998

September-October 2000

1981: The journal switches from monthly to bimonthly and now is longer, running 24 to 32 pages.

1990s: More special issues appear, treating controversial subjects from diverse viewpoints. Special collections cover pesticides and food safety (May-June 1994), biodiversity (November-December 1995), hunger (December 1995), aquaculture and fisheries (July-August 1997) and urban encroachment on farmland (May-June 1998).

January 1992: Peer review is further strengthened with the establishment of the Associate Editor panel. The panel includes subject matter experts from within ANR who oversee the process; to be published, manuscripts must be accepted by at least two anonymous reviewers. Increasing requirements for long-term data and statistical analysis lead to lengthier articles and higher rejection rates (currently 25% or more).

The first market research begins in the form of a survey, to which 66% of readers respond.

1994: News sections are established to provide a real-world context for research articles. Front matter is brief and authored by editorial staff. Shortly after, the first Letters column appears.

December 1994: The journal begins listing references for further reading, and in May 1996 extensive use of references and citations begins.

January 1996: *California Agriculture* posts its first Web site, including tables of contents, news stories and research abstracts.

2000 and beyond: Growing emphasis on special collections with public policy implications, including grandparenting (March-April 2001), biotechnology and global warming (May-June 2002). In the Year 2000 series, scientists look at scenarios for the next 25 years in California, in the areas of demographics, natural resources, food production and food security (September-October 2000).

Also in 2000, *California Agriculture* begins posting the entire contents of the journal on the Web site, including full-text PDFs of peer-reviewed research articles.

2002: *California Agriculture* initiates continuous page numbering, a standard practice of peer-reviewed science journals.

January-March 2003: Due to the statewide budget deficit and UC cutbacks, the journal shifts to quarterly issues. Length of magazine increases to between 48 and 96 pages (i.e., Kearney at 40, April-June 2005).

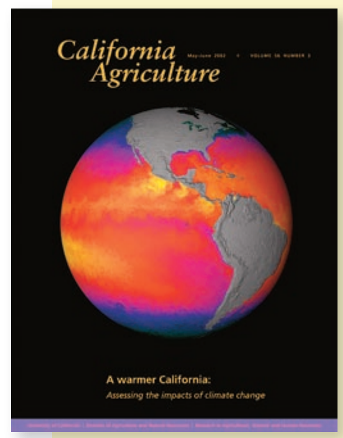
August 2005: Double-blind procedures added to anonymous peer review. The journal begins requesting electronic submission of all new manuscripts.

April 2006: *California Agriculture* implements a new electronic peer-review system using Berkeley Electronic Press software, under contract with the California Digital Library (CDL). Prospective authors use the Repository's secure server to make submissions, upload revisions and check on the status of articles.

May 2006: *California Agriculture* begins posting all published, peer-reviewed articles to the CDL's eScholarship Repository. PDFs continue to be posted in full to the *California Agriculture* Web site.

—Editor

March-April 2001



May-June 2002

April-June 2005

David Morgan

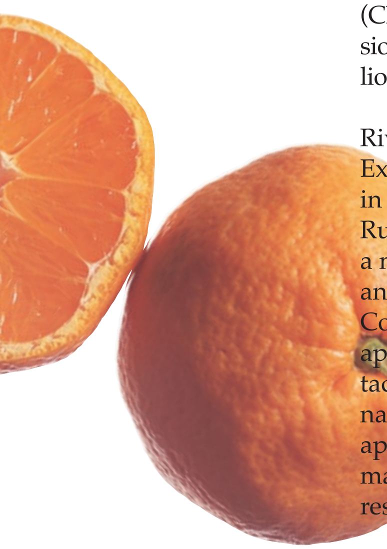
AES Centennial 100

UC Riverside marks a century of agricultural innovation — still thriving in an urban empire

Early in the 20th century, when the citrus belt cut a wide swath from Pasadena to Redlands, an outpost experiment station operated by UC helped to ensure, through science, the prosperity of what was even then a $20 million industry.

Today, sprawling suburban developments, gleaming midrise office towers and crowded shopping malls have replaced all but a few pockets of Southern California's citrus empire. Yet the citrus industry thrives in California, and the experimental outpost known as the Citrus Experiment Station (CES) in Riverside has grown and expanded its mission in support of the state's diverse, nearly $32 billion agricultural industry — still tops in the nation.

This year marks the centennial of UC Riverside's Citrus Research Center-Agricultural Experiment Station (CRC-AES). What began in 1906 with a staff of two at the base of Mt. Rubidoux near downtown Riverside is today a multifaceted enterprise involving 140 faculty and specialists in the experiment station and Cooperative Extension, and an annual budget of approximately $22 million. The CRC-AES now tackles a broad array of agricultural, urban and natural resource problems with fundamental and applied research in plant biology, pest and disease management, and the environment and natural resources. They are supported with advanced facilities, such as a state-of-the-art Insectary and Quarantine Facility and two campus-operated field stations totaling nearly 1,000 acres.



"This campus has a legacy of research in agriculture and natural resources that has strengthened one of this state's most important industries and helped it remain competitive, whether that meant surmounting new insect pests and plant diseases or developing new products for new markets," says Steven R. Angle, dean of the UC Riverside College of Natural and Agriculture Sciences.

The centennial celebration commenced with a barbecue and open house in April, featuring tours of the on-campus field station and ceremonial plantings of the UC Riverside–developed mandarins 'Gold Nugget' and 'Yosemite Gold'. It continues this October with groundbreaking of the $53.9 million Genomics Building on campus and, next February, a banquet and symposium that takes a prospective look at the next century of agricultural sustainability (see box, page 179).

"The contributions of UC Riverside are woven throughout the citrus industry, not only in California, but nationally and internationally," says Ted Batkin, president of the Citrus Research Board in California and chair of the National Citrus Research Council. "What is so impressive is the connection between the Agricultural Experiment Station and Cooperative Extension specialists. It is

Far left, the parasitic wasp *Gonatocerus triguttatus* was evaluated at the Citrus Experiment Station (CES) for biological control of the glassy-winged sharpshooter. *Left and above,* in 1918, CES moved from Mt. Rubidoux near downtown to the site that would become UC Riverside.

Herbert John Webber (seated far right), first CES director, in a 1916 staff photograph.

seamless in providing a continuum of basic discoveries through field application and it is what makes the Riverside campus particularly distinctive."

A "valentine" for Riverside

The official establishment of the Citrus Experiment Station is pegged to the date that the UC Board of Regents formally approved the leases for the Riverside property — Feb. 14, 1907 — though the station had begun operating some months prior. Opening of the station followed a vigorous lobbying effort by leaders of the Riverside Horticultural Club and Southern California Fruit Growers Exchange, a mission that landed Riverside the citrus station and Whittier a pathological laboratory.

When it came time to upgrade and expand the station, an intense political battle was waged between Riverside and the San Fernando Valley, a then-emerging citrus belt with powerful lobbying interests related to development and construction of the aqueduct from the Owens Valley to Los Angeles. Riverside viewed itself as the underdog, so there was wild elation in the streets when, on Dec. 22, 1914, the UC Regents voted to retain the station in Riverside.

In a day now famous in Riverside history, the steam whistle at the electric plant blew for 15 minutes and Mission Inn owner Frank Miller ordered the bells at the hotel be rung continuously. Riverside civic leader and citrus pioneer John Henry Reed called it "the most important day in the history of Riverside" in the *Riverside Daily Press*.


RIVERSIDE DAILY PRESS

Riverside Wins Citrus Station—14-4

CHRISTMAS PRESENT FOR RIVERSIDE THAT LOOKS MIGHTY GOOD TO US

UNIVERSITY DROPS CITRUS STATION IN OUR STOCKING

Good News Was Received Late Yesterday Afternoon and Everybody Went to Bed Happy — James Mills, S.C. Evans, Lyman Brown, E.A. Chase Heroes

New York Citrus Sales

$150,000 IS POMONA GIFT

TO PROTECT CITY LONDON

GERMAN SLAUGHTER IS SAID TO BE APPALLING

The expanded station moved in 1918 to the eastern edge of the city, on a site that would become UC Riverside in 1954, occupying a stately Spanish mission–style headquarters — a building now designated as a Riverside County historical landmark. (Today it houses UC Riverside's A. Gary Anderson Graduate School of Management.)

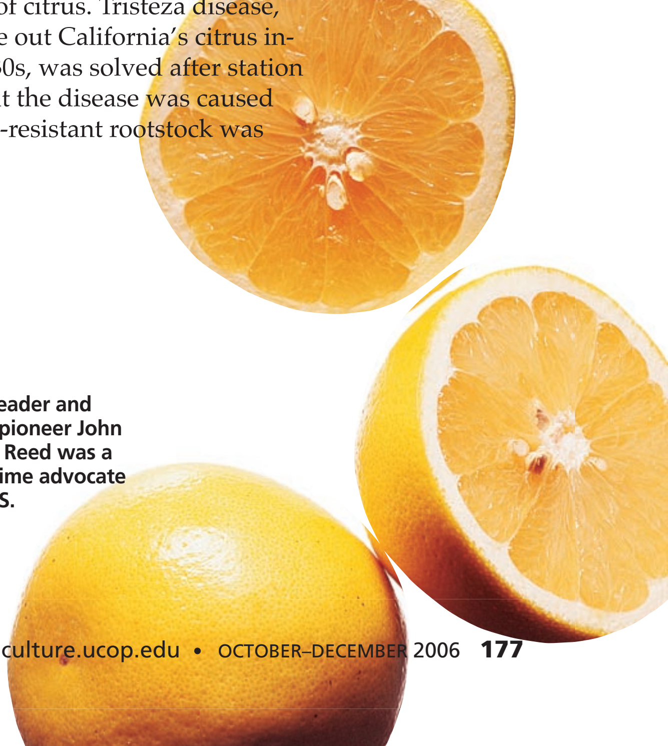
Groundbreaking research

Experiment station scientists conducted groundbreaking research that led to the delivery of new varieties of citrus and other commodities, innovative pest management techniques utilizing advances in biological control and integrated pest management (IPM), and new insights on California's natural resources that would inform both environmental quality and crop production.

Among early accomplishments was the control of the citrophilus mealybug by a natural enemy, one of the station's first ventures in biological control. In the 1940s, Herbert John Webber and Leon D. Batchelor — the station's first and second director, respectively — published *The Citrus Industry,* a comprehensive two-volume work compiling scientific knowledge about the distribution, botany, genetics and reproduction of citrus. Tristeza disease, which threatened to wipe out California's citrus industry starting in the 1930s, was solved after station scientists determined that the disease was caused by a virus; a new disease-resistant rootstock was

Alfred M. Boyce, with pipe, was CES director from 1952 to 1968.

Civic leader and citrus pioneer John Henry Reed was a long-time advocate for CES.



California's population growth, leading to environmental problems associated with the urban-wildland and urban-agriculture interfaces, has prompted a renewed focus on natural resource protection.

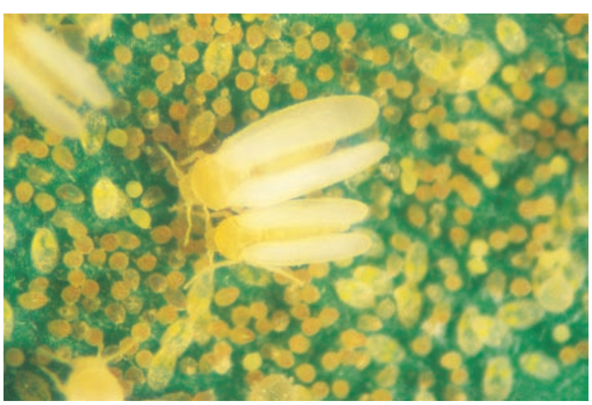
developed by W.P. (Bill) Bitters, who also served as director of the Citrus Variety Collection for 35 years.

Shortly after its formation, the station expanded its mission to include work on many other subtropical crops. The Riverside station gained a strong reputation in the avocado industry, due in large part to the efforts of George Zentmyer — later elected to the prestigious National Academy of Sciences — who would be credited with saving the industry from avocado decline disease with his work on the soilborne fungus *Phytophthora cinnamoni* and his introduction of resistant rootstock.

Following World War II, and under the direction of Alfred M. Boyce, the Citrus Experiment Station enjoyed its greatest growth. When UC Riverside was designated a general campus in 1960, a College of Agriculture was established and new departments in agronomy, agricultural engineering and biostatistics were initiated to augment the station's existing departments.

Experiment station scientists investigated new pesticides and earned a reputation for pioneering studies on insect resistance to pesticides and the measurement of insecticide residues, methods that would become part of the federal evaluation for commercial pesticide approval. The Citrus Clonal Protection Program was founded, today serving as the only approved importation facility in the nation for citrus.

▲ **The UC Riverside College of Natural and Agricultural Sciences developed the Core Instrumentation Facility to support research in genome biology.**



▶ **UC Riverside researchers identified a natural enemy to manage the silverleaf whitefly.**

Also in the 1960s, the first International Citrus Symposium was held at UC Riverside — organized by the late Homer D. Chapman — drawing 800 delegates from more than 50 countries and leading to the formation of the International Society of Citriculture (ISC). ISC, still headquartered at UC Riverside, has convened congresses around the world ever since, with the next one scheduled for 2008 in China.

The second 50 years

When it entered its second half-century, the experiment station carried out a diverse, broad-based research program, but citrus remained an important focus area and scientists retained the strong sense of service to the industry upon which the station was founded. Says plant physiologist Charlie Coggins, who arrived at the station in 1957, "Good, practical research was considered to be what we were all about, and strong fundamental research was expected as an underpinning to that applied research." Coggins' work on growth regulators beginning in the 1960s dramatically extended California's navel orange growing season.

Research at the CRC-AES broadened again in the 1970s under W. Mack Dugger, incorporating such new scientific disciplines and techniques as molecular biology, IPM and genetics. Environmental protection and the challenges associated with agriculture in arid and semiarid regions became new focus areas. New crops were developed, including turfgrass varieties with tolerance to soil salinity and air pollution. The campus also became a leader in plant tissue culture.

At the three-quarter-century mark, the CRC-AES was led by deans Irwin Sherman, now professor emeritus of zoology, then Seymour D. Van Gundy, now professor emeritus of nematology. It was an era during which the still-new discipline of molecular biology was maturing, with IPM and biological control remaining robust areas of research. In one particularly dramatic case, the importation

Far left, **the late George Zentmyer was a world authority on *Phytophtora cinnamomi*, a fungus afflicting avocados and other tropical plants; *inset*, avocado thrips. *Left,* a student researcher at the UC Riverside experiment station. *Above*, an artist's rendering of the $53.9 million Genomics Building, currently under construction.**

Left, **Distinguished Professor Natasha Raikhel, director of the Center for Plant Cell Biology, and students. *Above*, turfgrass research.**

and establishment of a tiny stingless wasp brought the ash whitefly under control. This bothersome pest not only caused millions of dollars in damage to agriculture, but it also despoiled cars parked under landscape trees with sticky excrement. It was a case that brought Citrus Experiment Station research to bear on the urban community, bringing widespread media attention to the UC Riverside campus.

The last quarter-century has also seen the release of several patented new varieties of citrus, starting with the 'Oroblanco' grapefruit in 1981 and continuing with the recent release of the 'Tango' mandarin. Likewise, development of the GeneChip Citrus Genome Array will help scientists quickly examine genetic traits in citrus so they can develop new varieties and tackle disease and postharvest problems. Another breeding program at UC Riverside has yielded cowpea lines that are early-maturing and heat-tolerant, making them particularly well-suited to the drought conditions of West Africa, helping to reduce hunger and poverty there.

Current research initiatives

The College of Natural and Agricultural Sciences has since undertaken a major initiative in genome biology, begun under the leadership of former dean Michael T. Clegg and continuing today. UC Riverside's Institute for Genome Biology and Center for Plant Cell Biology, created to capitalize on the emerging genomics revolution and on expertise in the experiment station, is applying genomics to solve critical health and agriculture-related problems, such as malaria and abiotic stresses to plants. Associated with the institute is the Biotechnology Impacts Center, which serves as an "honest broker" to identify the relevant policy issues related to the potential risks of genomic modification, act as a clearinghouse for credible information and initiate research that addresses its potential benefits and consequences.

California's population growth, leading to environmental problems associated with the urban-wildland and urban-agriculture interfaces, has prompted a renewed focus on natural resource protection. UC Riverside's Center for Conservation Biology generates objective scientific data to inform the development of public policy and restoration plans to preserve endangered species. The experiment station is also expanding its capabilities in environmental and natural resource economics.

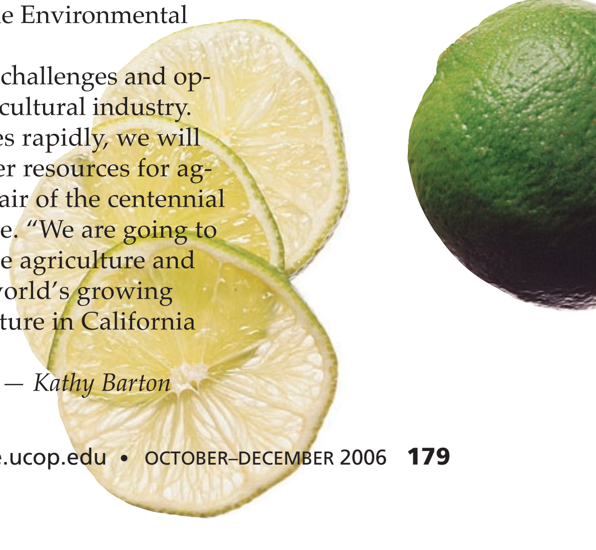
On the occasion of the centennial, the College of Natural and Agricultural Sciences — with guidance from the Chancellor's Agricultural Advisory Council and faculty — is undertaking a strategic planning process to chart its course for the next one. "We have served the agricultural industry well for 100 years," says Executive Associate Dean Donald Cooksey. "Now we need to determine how best to face the next century. Are we well-positioned for the future?"

In the near term, that future is expected to include a continued emphasis on water science with pending formation of a Center for Water Quality Science and Policy to address problems that are projected to become even more acute as demand by urban and agricultural consumers increases. Pest management, especially as it relates to invasive species, is expected to remain among the priorities, as is natural resources, in part through the college's participation in the campuswide Environmental Research Institute.

There will be no shortage of challenges and opportunities for California's agricultural industry.

"As our population increases rapidly, we will lose more of our land and water resources for agriculture," says Van Gundy, chair of the centennial celebration planning committee. "We are going to have to focus on more intensive agriculture and new technologies to feed the world's growing population and to help agriculture in California remain economically viable."

— *Kathy Barton*



Centennial celebration

The UC Riverside Citrus Research Center and Agricultural Experiment Station will celebrate its 100th anniversary with a symposium and banquet on Feb. 14 and 15, 2007. For more information, go to: http://cnas.ucr.edu/news/special_events.htm or contact Carol Lerner, carol.lerner@ucr.edu, (951) 827-5089.

REVIEW ARTICLE

Is lead toxicity still a risk to U.S. children?

by Karrie Heneman *and* Sheri Zidenberg-Cherr

Elevated blood-lead levels put children at risk for neurobehavioral-cognitive deficits, such as IQ deficiency, behavioral disorders and impaired hearing. We examined several factors that contribute to elevated lead levels in U.S. children to help define the extent to which lead toxicity from these sources continues to be a problem. The results of our review suggest that elevated levels of lead in paint, dust, soil, imported pottery and ceramic ware, ethnic remedies, and some imported candies continue to be areas of concern, while typical levels in food products appear to be acceptable. It is important to continue monitoring lead levels in children as well as in environmental and food sources.

California Childhood Lead Poisoning Prevention Branch

Chewing and sucking on things is normal in young children, but it can increase the risk of lead poisoning if lead is present. Lead was removed from paint in 1978, but dust from older paint can easily be ingested by children via their hands or toys.

The U.S. Environmental Protection Agency (EPA) estimates that 430,000 American children between 1 and 5 years old have blood-lead levels at or above 10 micrograms per deciliter (μg/dl) (EPA 2004b), costing the United States an estimated $43.4 billion dollars annually (Landrigan et al. 2002). Elevated blood-lead levels put children at risk for deficits in neurobehavioral-cognitive performance that manifest later in childhood (Needleman et al. 1990). These deficits include IQ deficiency, behavioral disorders and impaired hearing. In addition, 400,000 more children may be yet undiagnosed (GAO 1999).

Furthermore, these deficits may persist even 20 years after exposure (Bernard and McGeehin 2003), since lead is sequestered in bone. While the body can remove it, some amount remains behind and with chronic exposure can accumulate. There may be no safe level of lead. For example, IQ has been shown to be adversely affected at levels below 10 μg/dl, by as much as 7.4 points (Canfield et al. 2003), suggesting that any exposure to lead can put a child at risk. What is most disconcerting is the fact that sustained, low-level lead exposure can go unchecked because such neurological abnormalities may have no apparent symptoms (Koplan 2002).

Young children are at the greatest risk of lead toxicity, as their body burden (the total amount of lead in the body at a given time) is influenced by weight. Children between 1 and 4 years old face additional risks because of pica (ingestion of nonfood substances) and hand-to-mouth activity (Mielke and Reagan 1998). These factors are of particular concern because lead can damage a child's rapidly developing nervous system, making the threat of permanent neurological damage greatest during the first 6 years of life (CDC 1991).Research has shown that the negative effects of lead on the cognitive function of children are persistent across cultures, racial and ethnic groups, and social and economic classes (Nordin et al. 1994).

Other known risk factors for lead toxicity among children include: (1) living in housing built before 1978, when the federal government banned the use of lead-based paint for houses; (2) recent or ongoing renovation in pre-1978 housing; (3) peeling paint in pre-1978 housing; (4) urban residence; (5) low-socioeconomic status; (6) the use of imported pottery and ceramic ware; and (7) the use of traditional ethnic medicines (CDC 1991).

In the past, lead in the ambient air and in food contributed much more to overall exposure of the general U.S. population than it does now. Because lead from these sources has been drastically reduced, blood-lead levels in U.S. children and the general population are lower than they were 1 or 2 decades ago (EPA 2004b). However, despite the decreased use of lead in food canning, gasoline and paint, lead will remain in our environment for many years. While it is critical that recognized sources of lead be minimized in a child's environment, eradicating all sources of excessive lead exposure would be difficult and expensive, making continual surveillance for lead toxicity imperative.

In an effort to detect and treat cases of lead toxicity, government agencies such as the U.S. Centers for Disease Control and Prevention (CDC), and organizations such as the American Academy of Pediatrics, have recommended universal screening for all children aged 6 months to 6 years participating in low-income programs. This concept has been met with mixed responses from the medical community. Proponents suggest that the plan meets all the cost-benefit criteria for suggested population-based screening and that it would be cost effective if the prevalence of lead poisoning in the population was even as low as 0.1%. Opponents argue that the prevalence of elevated blood-lead levels is low, and that there is no effective therapy for children with low lead levels. Indeed, except in cases of extreme, acute exposure, therapy for children with elevated blood-lead levels consists of education and efforts to remove sources of lead from the child's environment (DHS 2003a).

Current surveillance systems may not provide accurate estimates of lead toxicity among children. Despite national recommendations to screen all children participating in low-income programs, screening rates vary and remain low; an estimated 400,000 U.S. children with elevated blood-lead levels are undiagnosed (GAO 1999). While the national childhood blood-lead surveillance program collects state data, reporting is not consistent. In California, for example, only cases where blood-lead levels exceeded 25 μg/dl were reported prior to Jan. 1, 2003.

Nationally representative surveys and local prevalence data is also collected, but these report blood-lead levels at or above 10 μg/dl. Recent estimates from the National Health and Nutrition Examination Survey (NHANES) IV showed that the prevalence of blood-lead levels greater than or equal to 10 μg/dl among American children 1 to 5 years old is 2.2% (Meyer et al. 2003). Similarly, CDC 2003 surveillance data indicates 2.04% prevalence of elevated blood-lead levels in children under 6 (CDC 2003).

Although this information is useful, the prevalence of low-level lead toxicity (less than or equal to 10 μg/dl) across populations has not been documented. Our research group collected lead toxicity data in 1996 from children in four California counties, representing both low- and high-risk environments (where high risk was defined as being of low-income and living in houses built before 1950). We found that approximately 13% of the children had blood-lead levels greater than 5 μg/dl. This is of concern given that other researchers have found detrimental effects on IQ (Canfield et al. 2003) and reading and math scores at blood-lead levels from 5 to 10 μg/dl (Lanphear et al. 2000).

We review several factors that contribute to elevated lead levels in children living in the United States, to help define the extent to which lead toxicity from environmental and food sources continues to be a problem. It is anticipated that these results will help revise existing education programs so that the Healthy People 2010 objective (a set of national health goals) to eliminate all elevated blood-lead levels in children can be met (DHHS 2000).

Sustained, low-level lead exposure may result in neurological abnormalities without any apparent symptoms.

Lead in the environment

The U.S. Department of Health and Human Services has referred to lead poisoning as the most common environmental pediatric problem for young children (CDC 1991). Major environmental sources of lead poisoning in children are lead-contaminated water, lead-based paint, and soil and dust. Lead exists in the environment as a result of geological activity and human actions, and occurs naturally in soil and dust (natural lead). Through a global assessment of atmospheric trace metals, Nriagu and Pacyna (1988) concluded that lead as an environmental pollutant is essentially caused by human action. Human activities include the mining and smelting of ores, the combustion of fossil fuels and the dissemination of lead through industrial processes; the most pervasive is tetra ethyl lead, which was used as an antiknock additive in gasoline prior to its ban in the United States in 1996.

In 1999, the EPA estimated that 8% of American children were served by lead-contaminated water systems, possibly contributing up to 20% of a child's lead exposure. The Safe Drinking Water Act of 1974, created to improve U.S. drinking water by establishing tolerable levels of a variety of contaminants (including chemicals), recommended that no amount of lead in tap water is safe. However, this was solely a recommendation and was not enforced (EPA 2005).

Contamination of water by lead generally occurs during the last phases of water delivery, making it difficult to regulate. Upon entering the plumbing system of a house or building, the corrosiveness of water causes lead to leach from the pipes (plumbing may have lead pipes, solder or other materials) (EPA 2005). The Lead and Copper Rule, published by EPA in 1991, aimed to reduce the corrosivity of water through treatment. EPA reviews of water systems in 2004 found that the Lead and Copper Rule was 96% effective for systems serving 3,300 people or more (Millett 2005). In response to these findings, EPA recently issued the Drinking Water Lead Reduction Plan to help further reduce lead levels (Millett 2005), and preliminary monitoring results released by EPA in March 2005 reported that national lead levels in water were no longer elevated (Davis 2005).

Single paint chips may contain between 6.45 and 32.25 milligrams lead per square inch (1 and 5 milligrams per square centimeter) (CDC 1991), and analysis of NHANES III data shows that children living in housing built prior to 1946 are 5.1 times as likely to have elevated blood-lead levels (Bernard and McGeehin 2003). Estimates from 1998 show that 40% of homes in the United States still contain lead-based paint, 16% of homes have hazardous levels of lead in dust, and 7% of homes have hazardous soil lead levels (EPA 2004b). EPA estimates that between 5.9 million and 11.7 million children are exposed to lead in dust and soil annually (EPA 2004a).

Photos: California Childhood Lead Poisoning Prevention Branch

Imported ceramic cookware may contain high levels of lead in the decoration. Lead leaches into food during cooking and storage, especially with acidic foods.

Soil becomes contaminated with lead through three methods: the weathering and chipping of lead-based paint, industrial pollution or deposition from the use of leaded gasoline. EPA regulations have greatly reduced the risk of lead exposure from industrial pollution or the use of leaded gasoline, but exposure to lead-based paint continues to be a problem.

Other sources of lead

Imported ceramic cookware. Another potential source of lead contamination is imported ceramic cookware. One case study reported that a child who regularly consumed fruit punch stored in a lead-glazed urn had an increase in blood-lead levels from 22.79 μg/dl to 95.32 μg/dl during a 4-week period. Consumption of fruit punch from the same container by others resulted in a 20% increase in blood-lead concentrations (Matte et al. 1994). Glazes used on traditional pots imported from both South American and Asian countries may contain lead. Lead can leach into food when these contaminated pots are used for cooking or storage. Cooking with acidic foods (such as tomatoes, vinegar, alcohol or soy sauce) in these pots is of special concern because their low pH enhances the leaching process (DHS 2003b).

TABLE 1. FDA analysis of lead concentrations in food products

Food group	Mean lead concentration	Standard deviation
	······· μg/g ·······	
Dairy	0.002	0.005
Meat, fish, poultry	0.003	0.006
Grain, cereal products	0.003	0.006
Vegetables	0.004	0.006
Fruit, fruit juices	0.004	0.006
Oils, fats, shortening	0.003	0.007
Sugar, desserts	0.002	0.007
Beverages	0.007	0.007
Mixed dishes	0.002	0.003
Infant food	0.003	0.005

Source: FDA 2004b.

Ethnic remedies. The use of folk medicine by ethnic groups has also been associated with lead toxicity (CDC 1993). A recent analysis of 70 ayurvedic products (those based on traditional medicine in India) from stores in the Boston area showed that almost 20% contained lead, ranging from 5 μg/g to 37,000 μg/g per sample (Saper et al. 2004). Surma, also know as kohl, kajal or al-kahl, is an ethnic remedy that is applied to the eyes of children in some Asian communities. This powder primarily consists of lead sulphide, and use may result in elevated blood-lead levels, possibly increasing blood lead in children by as much as 8.5 μg/dl (Sprinkle 1995).

In Latino communities, the use of azarcon and greta, two herbal remedies used to treat intestinal and stomach ailments, may result in elevated blood-lead levels. Samples of azarcon, an orange powder, contained large amounts of lead tetroxide, while greta, a bright yellow or orange powder, also contained high lead levels. Other folk medicines associated with lead poisoning include ghasard, an Indian remedy; litargirio, a Hispanic folk remedy; and paylooah, a medicine used in the Hmong culture (Sprinkle 1995; CDC 1993). In light of these findings, culturally sensitive warnings about these products are warranted.

Lead in food

Data from 1990 suggests that children up to 16 years old consume between 3.8 μg and 8.5 μg of lead per day from food, water and beverages, meaning that approximately 16% of a 2-year-old child's daily intake of lead may come from food (Abadin and Llados 1999) (table 1).

Candy. Recent warnings issued by the U.S. Food and Drug Administration (FDA) and state health departments have raised concern about lead contamination in candy imported from Mexico (FDA 2004a; DHS 2005). The CDC reported that, based on routine blood-lead screenings, six California children suffered from lead toxicity after eating tamarind- and chili-flavored candy imported from Mexico. The FDA then found between 0.3 μg to 0.4 μg of lead per gram of candy. The California Department of Health Services independently found elevated lead levels in candy as well (> 0.5 μg of lead per gram) (DHS 2005). It is believed that lead contamination may be introduced from ingredients or occur during candy processing such as drying, storing and grinding (CDC 2005), or that lead may leach into the candy from tainted wrappers (Fuortes and Bauer 2000).

Currently, there is no regulatory limit for lead in food, but the FDA has established a Provisional Daily Total Tolerable Intake of 6 μg of lead per 30-gram food serving (0.2 μg/g) (Lynch et al. 2000). The candies described above each weighed 30 grams or more per piece, so consumption of a single candy could deliver lead in an amount greater than the Provisional Daily Total Tolerable Intake (August and Brooks 2004); however, factors such as nutritional status, age and gender influence the amount of lead absorbed after consumption.

As a result, it is difficult to accurately determine the true risk posed by consumption of these products.

Chocolate. The issue of chocolate as a source of lead exposure among children has also recently surfaced in the media, although warnings issued by state departments of health only pertain to imported candy. Contamination of chocolate by lead is thought to occur because the majority of beans are grown in locations that still use leaded gasoline. Despite high per-capita consumption of chocolate in the United States, there is a paucity of data on lead concentrations in chocolate products.

The American Environmental Safety Institute, an environmental advocacy group based in California, tested a variety of chocolate products and reported that they contained between 0.00157 μg and 0.105 μg lead per gram chocolate. The USDA Total Diet Study (FDA 2004b) found between 0.0 and 0.110 μg lead per gram chocolate. Analysis of chocolate samples by our research group yielded similar results. Mean lead levels ranged from 0.0010 to 0.0965 μg lead per gram chocolate (table 2).

The Codex Alimentarius, global food standards developed by the Food and Agriculture Organization (FAO) and World Health Organization (WHO), limits the lead content of cocoa powder or beans to 1 μg of lead per gram product (FAO/WHO 1981). Analysis of a variety of chocolate products from various global locations, completed by a Swiss research group in 2002, found that the lead contents of these items ranged from 0.011 μg to 0.769 μg per gram, below the international standards (Mounicou et al. 2003).

TABLE 2. Lead concentrations in chocolate*

Food	No. samples	Mean lead concentration	Standard deviation
		········· μg/g ·········	
Dark chocolate pieces	8	0.0965	0.0892
Milk chocolate bar	12	0.0418	0.0705
Premium milk chocolate bar	12	0.0949	0.1160
Candy-coated chocolate	8	0.0010	0.0020

* Food products were collected from Albertson's, The Nugget and Safeway in Davis, CA. Methods available upon request from authors.

This, coupled with research suggesting that only 5% to 10% of lead contained in cocoa is bioavailable to the body (Mounicou et al. 2002), suggests that there is limited risk of lead toxicity to regular consumers of chocolate products.

Calcium supplements. Historically, calcium supplements have also been found to contain lead. Deposits of calcium that are mined for supplements may contain lead. Recent lab analysis of 21 different over-the-counter products completed in 2000 demonstrated that 11 had detectable lead levels, between 1 and 3 μg per dose (Ross et al. 2000). In California, analyses of 136 products demonstrated that approximately 67% exceeded 1.5 μg of lead per dose, the tolerable level set by Proposition 65 regulations (Scelfo and Flegal 2000). (Prop. 65 was enacted to protect and inform Californians about exposure from harmful chemicals.) Although intestinal absorption of lead is reduced in the presence of calcium, it is not completely inhibited. Considering that many Americans consume calcium supplements on a daily basis per recommendations from their physicians, the potential for lead contamination from these products should not be ignored. However, consumption of calcium supplements effectively reduces the risk of osteoporosis, and until further research is completed, it should be maintained that the benefits of supplement usage outweigh the risks.

Ongoing surveillance needed

Ongoing surveillance of lead levels in environmental and food sources is imperative to ensure that appropriate actions can be taken in a timely fashion. Our review suggests that elevated levels of lead occur in paint, dust, soil, imported pottery and ceramic ware, ethnic remedies, and some imported candies. Furthermore, although the monitoring of lead levels in candy should continue, current data suggests that in the United States the risk of lead toxicity from these items is relatively low. If future analysis shows lead contamination of such food products, methods should be developed to reduce their lead content.

Photos: California Childhood Lead Poisoning Prevention Branch

Large amounts of lead have been found in certain ethnic remedies. *Top*, surma or kohl is applied to children's eyes in some Asian communities. *Center and bottom*, azarcon and greta are used to treat intestinal and stomach ailments in some Latino communities.

Due to drastic reductions in lead in the ambient air and food, blood-lead levels in children and the general U.S. population are now lower than they were 1 or 2 decades ago (EPA 2004b); however, NHANES and CDC data suggests that between 2% and 3% of American children still exhibit elevated levels of blood lead (Meyer et al. 2003). At the present time, therapy for children with blood-lead levels between 10 μg/dL and 20 μg/dL is limited to education and efforts to remove sources of lead in the child's environment, and no action is taken for children with blood levels less than 10 μg/dL.

Studies show that the education and counseling of parents and children is effective in reducing blood-lead levels, in concert with the careful removal of

RECENTEVENTS

Photos: Center for Environmental Health

In recent years, lead has been detected in children's jewelry and soft vinyl (PVC) lunchboxes. In 2005, the Center for Environmental Health, a nonprofit based in Oakland, initiated lawsuits against retailers and manufacturers of these products, resulting in widespread reformulation to reduce lead content. In July 2006, the U.S. Food and Drug Administration warned lunchbox manufacturers to stop marketing vinyl lunchboxes containing any level of lead that may leach into children's food.

For more information, go to www.cehca.org.

hot spots such as peeling paint on window sills and porch banisters (Rooney et al. 1994). Most importantly, studies have demonstrated that cognitive function improved when moderate blood-lead levels in children were reduced (Kimbrough et al. 1994). Perhaps the parents of children with levels between 5 μg/dL and 10 μg/dL should also be included in these education programs to ensure that they are adequately educated on the risk factors associated with lead exposure. In the future, sustained efforts to reduce the lead exposure of American children will be necessary to achieve the Healthy People 2010 goal of eliminating all elevated blood-lead levels in children.

K. Heneman is Postdoctoral Researcher, and S. Zidenberg-Cherr is Cooperative Extension Specialist, Department of Nutrition, UC Davis.

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RESEARCH ARTICLE

Cost-benefit analysis conducted for nutrition education in California

by Amy Block Joy, Vijay Pradhan
and George Goldman

Documenting the cost-effectiveness of nutrition education programs is important to justify and determine expenditures and ensure continued funding. A cost-benefit analysis was conducted using the program demographics and food-related dietary behavior of participants enrolled in California's Expanded Food and Nutrition Education Program (EFNEP), based on methodology developed by Virginia Cooperative Extension. The initial benefit-cost ratio for nutrition education in California was 14.67 to 1.00. Several sensitivity analyses were done to estimate the effect of changes in key variables. The resulting benefit-cost ratios ranged from 3.67 to 1.00, to 8.34 to 1.00, meaning that for every $1.00 spent on nutrition education in California, between $3.67 and $8.34 is saved in health care costs. These results bolster the argument that nutrition education programs are a good investment and funding them is sound public policy.

USDA/Ken Hammond

ANR Communication Services/Suzanne Paisley

The impact of nutrition education on health care spending has not been extensively studied; the authors utilize a new cost-benefit analysis methodology, developed by Virginia researchers, to quantify nutrition education impacts in California. *Top,* a mother receives health counseling at a WIC clinic in Virginia. *Above,* California EFNEP participants learn healthy cooking choices.

Successful nutrition education programs should be effective in both improving dietary health and ensuring a positive economic impact. Evaluations of the Expanded Food and Nutrition Education Program (EFNEP), federally funded nutrition education for low-income families, have demonstrated many positive behavior changes over the last 35 years. These include improvements in diet (increasing intakes of fruits, vegetables and fiber, and decreasing fat and soda consumption); food shopping and preparation (saving money, reading labels, food safety); and nutrition knowledge and attitudes (Contento et al. 1995; Del Tredici et al. 1988). Although the positive improvements in dietary health due to nutrition education are well documented, its value in health care savings has not been extensively studied.

Documenting cost-effectiveness is critical if community nutrition programs are to survive under current economic conditions. Cost-benefit analysis is one of the standard ways to document economic benefits. Used primarily by economists for policy- and decision-makers, cost-benefit analysis offers an analytic procedure that is widely applicable to most government, public, private and nonprofit programs (Sassone and Schaeffer 1978).

In 1999, Virginia Cooperative Extension (VCE) designed, implemented and published the first cost-benefit analysis to evaluate the economic value of EFNEP (Rajgopal et al. 2002; Lambur et al. 1999). The Virginia researchers developed a methodology to measure the economic impact of nutrition education by using behavior changes among EFNEP participants. They developed criteria associated with a number of chronic diseases / conditions and deter-

Glossary

Benefits (direct, indirect): Direct benefits are estimated monetary amounts for delaying treatment or preventing a chronic disease; indirect benefits include increased productivity, longer life span and reductions in lost workdays.

Cost-benefit analysis:

$$\frac{\text{Benefits (direct + indirect)}}{\text{Costs}}$$

Costs (direct, indirect): Actual expenditures for program implementation. Direct costs include personnel, benefits, travel, supplies and equipment. Indirect costs include the value of time lost from work by participants.

Costs (in-kind): Total estimated costs for office space and maintenance (donated by county budgets) and utilities (not paid for directly). In California these were calculated using estimated proportions of Virginia's costs.

Costs (tangible, intangible): Tangible costs are easily monetized (direct and indirect benefits); intangible costs are not (e.g., increased self-esteem, improved quality of life). For example, a doctor's visit is considered tangible, while "not feeling well" is intangible.

Equipment costs: The total amount paid for equipment (e.g., computers, teaching supplies).

Salaries and benefits: Total funds spent on all personnel, including program delivery staff, program supervisors, clerical and administrative staff and state office staff for fiscal year 1998-1999 (Oct. 1, 1998, to Sept. 30, 1999). Staff merits awarded in July 1999 for work done in 1998 were also included.

Supplies and expenses: Total amount paid for state/county programs to deliver the nutrition education, including the cost of materials, phone, copying, fax, demonstration supplies, teaching materials and utilities.

Travel costs: Total travel costs for county-based program staff and state staff (e.g., teaching, training, meetings, conferences).

For every dollar spent on nutrition education, at least $3.67 is saved on delayed medical treatment costs.

mined the associated medical costs, and implemented sensitivity analyses on the data to adjust for certain assumptions.

The VCE calculated a benefit-cost ratio ranging from 2.16 to 1.00, to 17.04 to 1.00, meaning that between $2.16 and $17.04 was saved in health care costs for every $1.00 that was spent in Virginia on nutrition education programs for low-income residents. We calculated similar benefit-cost ratios for California using program demographics and food-related dietary behaviors from participants enrolled in the state's EFNEP program, utilizing VCE's methodology. In California, the EFNEP program is administered through the UC Division of Agriculture and Natural Resources (ANR).

Virginia methodology

The VCE studies provided detailed background on two important factors used in their methodology: the relationship between diet and chronic disease, and the assigning of monetary values to nutrition outcomes. Cost-benefit analysis was used to measure economic value by comparing "benefits" (monetized in terms of decreased medical treatment costs) with "costs" (actual nutrition education expenses over a set time). The Virginia researchers decided to compute the monetary benefits of EFNEP using the future savings in health care costs accrued by the potential avoidance of certain diseases and conditions among the participants who received nutrition education lessons (Rajgopal et al. 2002).

Both the Virginia and California studies used computer software called ERS-3.01 (Evaluation and Reporting System, version 3.01, National EFNEP Program, USDA; Merrill et al. 1993) to enter the demographic and dietary behavior data of EFNEP participants. The monetized benefits were direct and indirect: The direct benefits were the dollars of postponed health care costs due to the delay of these chronic diseases and conditions, and the indirect benefits were those that increased productivity due to a healthy lifestyle (e.g., fewer sick days) (Rajgopal et al. 2002).

EFNEP for low-income families

The EFNEP program (in both Virginia and in California) teaches low-income families how to purchase, safely prepare and serve a balanced, highly nutritious diet. The program emphasizes the increased consumption of fruits and vegetables, decreased consumption of fat, and improved skills in food safety, preparation and shopping, with the long-range goal of improved health and risk reduction for chronic diseases. The 1990 Dietary Guidelines for Americans were the basis for instruction during the time of this study (USDA/DHHS 1995), although the recently updated version is currently used. Participants receive intensive nutrition education from

ANR Communication Services/Suzanne Paisley

EFNEP provides 4 to 6 weeks of classes in a small-group setting to more than 13,000 low-income California families each year. The program is administered by UC nutrition scientists and educators.

USDA/Ken Hammond

The link between diet and chronic diseases/conditions, such as heart disease, diabetes and obesity, has been established by scientific research. EFNEP uses a food behavior checklist to evaluate changes in nutrition behavior among participants, such as increases in fruit and vegetable consumption.

trained paraprofessional staff for approximately 6 to 8 hours per week over a period of 4 to 6 weeks. Entry and exit dietary-assessment data is collected on every participant enrolled in and graduated from EFNEP.

The study in California was done using EFNEP data from 1998, following the methodology developed by the VCE (using their 1996 results). Virginia used health and labor statistics from 1996 in their assessments of monetary values, utilizing national averages.

During the time period that we studied (1998), California EFNEP served 13,430 enrolled families in 17 counties. County locations varied from urban (Los Angeles, Orange, San Francisco) to rural (Tulare, Stanislaus, Butte). Enrolled participants were ethnically diverse (62% Hispanic, 9% black, 15% white, 12% Asian and 1% Native American) and primarily female (92%). The median age was 25 to 30 years old, and 10% of the women were pregnant. Most participants had at least two children (65%), while 35% of the families had one child and 8% had five or more. Approximately 41% were enrolled in the Special Supplemental Nutrition Program for Women, Infants, and Children Program (WIC), 34% in the Food Stamp Program, 19% in Head Start and 35% in the Child Nutrition Program; all are federal support programs for low-income families. The majority of individuals (98%) met the federal income level for eligibility (at or below 150% poverty level) with 75% of them at or below the 100% poverty level.

All enrolled families completed two records: the EFNEP family record for demographic information and the California food behavior checklist for pre- and post-evaluation data. The California food behavior checklist contained 14 of the same questions used in the Virginia study, plus an additional seven questions. Of the 21 questions, seven had been validated in terms of predicting increased fruit and vegetable consumption (Murphy et al. 2001; Blackburn et al. 2006).

Trained program-delivery staff collected the family record and checklist (both were self-reported, unless the individual was unable to complete the form). The data was collected and entered into the ERS-3.01 computer program, and the results were aggregated.

The nutrition education lessons were taught weekly in a group setting (four to 10 individuals) over a period of 4 to 6 weeks, which has been documented as effective in promoting positive dietary changes and meeting program goals and objectives (Del Tredici et al. 1988; Joy 2004). Eighty-six percent of the families completed the nutrition-education program lessons and the pre- and post-tests, and were continuing in the program. Of the 14% that did not complete the program, the reasons given included: moved without a contact address (19%), family concerns (12%), took a job/returned to school (12%) and other (47%).

Determining benefits and costs

The VCE methodology included a list of program benefits and costs associated with EFNEP (see glossary), as well as the following three major assumptions.

(1) Diet and chronic disease link. The link between diet and disease has been established by research. For their analysis, the Virginia researchers included heart disease, stroke, hypertension, colorectal cancer, osteoporosis, type 2 diabetes, obesity and foodborne illness. These were studied because they have a known dietary association, and the EFNEP program teaches participants how to reduce their risk and delay or prevent their onset. For California, additional nutrition behavior indicators were included: one question on increasing fiber consumption; two separate questions on increasing fruit and vegetable consumption; three questions on decreasing fat consumption; and one question on decreasing the number of visits to fast food restaurants.

(2) Estimation of diet-related risk. The Virginia study relied on the fact that there is a relationship between diet and chronic disease, which it discussed in detail. Likewise, in the literature there is evidence of this relationship, but it is imprecise. In order to justify this assumption, the Virginia researchers created a formula to quantify this relationship. For example, how much of a role does diet play in the development of colorectal cancer? We can estimate that the link is not 100%, nor is it 0%. Other factors are involved — genetics, lifestyle, age, ethnicity and environmental toxins, as well as factors that have not yet been identified. The Virginia researchers estimated that 35% of the incidence of colorectal cancer is diet-related. For each condition, this estimation was computed based on published reports from sources cited in

▶ To establish a cost-benefit relationship, the amount of money saved by delaying a disease or condition for 5 years was estimated. Blood pressure monitoring can help to detect heart disease, hypertension and stroke risks.

ANR Communication Services

TABLE 1. Nutritional behavior and scores of EFNEP participants, filtered pre- and post-test for optimal nutritional change for eight chronic diseases/conditions

Nutritional behavior taught in EFNEP	Optimal behavior score
Colorectal cancer	
Increase fruit and vegetable consumption	≥ 4
Decrease fat consumption	≥ 4
Increase fiber consumption	≥ 4
Use food labels to select healthy foods	≥ 4
Satisfy all above criteria simultaneously	(150; 7.65%)*
Foodborne illness	
Thaw foods safely	1, 2
Store foods safely	1, 2
Satisfy all above criteria simultaneously	(2,011; 27.95%)
Heart disease	
Increase fruit and vegetable consumption	≥ 4
Decrease fat consumption	≥ 4
Increase fiber consumption	≥ 4
Use food labels to select healthy foods	≥ 4
Satisfy all above criteria simultaneously	(150; 7.65%)
Obesity	
Increase fruit and vegetable consumption	≥ 4
Increase fiber consumption	≥ 4
Decrease fat consumption	≥ 4
Decrease eating in fast food restaurants	≤ 2
Use food labels to select healthy foods	≥ 4
Satisfy all above criteria simultaneously	(122; 6.77%)
Osteoporosis	
Drink milk	≥ 4
Improve food selection and preparation	= 4
Satisfy all above criteria simultaneously	(2,769; 20.12%)
Stroke/Hypertension	
Reduce sodium in diet	≥ 4
Use food labels to select healthy foods	≥ 4
Increase fruit and vegetable consumption	≥ 4
Increase fiber consumption	≥ 4
Satisfy all above criteria simultaneously	(42; 2.57%)
Type 2 diabetes	
Increase fruit and vegetable consumption	≥ 4
Increase fiber consumption	≥ 4
Decrease fat consumption	≥ 4
Decrease sugar consumption	≥ 4
Use food labels to select healthy foods	≥ 4
Satisfy all above criteria simultaneously	(87; 5.21%)

* No. filtered out of 9,528; % practicing optimal nutritional behavior based on number of program graduates (not shown).

Healthy People 2000, a publication of objectives aimed at reducing chronic disease by changing lifestyle factors, including diet (DHHS 1990).

(3) Behavior changes for 5 years. Studies have shown that some EFNEP families who attain optimal nutritional behaviors maintain them for 5 years following the nutrition education (Nierman 1986). Documentation for more than 5 years has not been published. Therefore, the Virginia researchers did a sensitivity analysis to modify this assumption.

Monetizing educational benefits

For the California study, benefits were constructed and calculated in the same way as in Virginia. Both states use the same nutrition-education delivery approaches and teach enrolled low-income participants how to choose and prepare a healthy diet (Lambur et al. 1999). Both programs have similar behavioral results and associated costs.

The VCE monetized direct, tangible benefits (Lambur et al. 1999) using costs compiled from Healthy People 2000 (USDA/DHHS 1995). National figures computed by the Virginia researchers were used for treatment costs. Although California medical costs would likely be much higher than the national average, we used the same kind of cost-benefit data as the VCE in order to provide a more conservative benefits estimation. Similarly, the intangible benefits were calculated using the VCE methods reported in their protocol. The VCE used a lost-workdays approach for the indirect cost-benefits, based on worker productivity (e.g., health care savings as well as the value of the work lost due to illness).

The tangible benefits of nutrition education were the costs saved by preventing or delaying the onset of a disease or condition. The reason that the delay is of value is because a given amount today is worth more in the future. We used 5% for the discount rate, as Virginia did. Virginia developed a formula for calculating both the direct and indirect benefits, which we utilized in our study (see box).

Nutritional behaviors as benefits

Nutrition behaviors taught in EFNEP (Rajgopal et al. 2002) to prevent or delay diseases/conditions were used retrospectively to calculate the benefits for each of the eight conditions/diseases studied (table 1). The California results were similar to the Virginia results except for the following: (1) the Virginia researchers collected data on infant mortality, but we did not use this information in our analysis because California EFNEP does not collect any medical data on participants; and (2) the California food behavior checklist included all the questions used in Virginia, plus seven additional ones.

In order for participants to be included in the California analysis, they had to be practicing "optimal nutritional behaviors," and stringent conditions were applied. The rigor of the analysis was increased with both

TABLE 2. Diet-related diseases/conditions and factors used in cost-benefit analysis of direct, tangible benefits*

Disease/condition	Avg. age of onset	EFNEP graduates studied [A]	Incidence rate in population [B]	Diet-related portion [C]	Graduates practicing optimal nutr. behaviors† [D]	Graduates to accrue benefits (calculated) [E]	Present value of behavior [F]	Total direct benefit
	years	*no.*	. . . .	%		*no.*	. . . .	$ . . . .
Colorectal cancer	36	9,528	15.0	35.0	7.65	38.26683	16,424.75	628,583.11
Foodborne illness	23	9,528	2.8	100.0	27.95	74.566128	18,866.83	1,406,826.40
Heart disease	55	9,528	31.2	26.0	7.65	59.127719	691.76	40,902.19
Hypertension	30	9,528	37.4	45.0	2.57	41.211553	697.87	28,760.31
Obesity	23	9,528	37.0	50.0	6.77	119.33343	11,686.59	1,394,600.80
Osteoporosis	45	9,528	28.0	N/A	20.12	536.7694	65,468.86	35,141,719.00
Stroke	45	9,528	1.7	N/A	2.57	4.1627832	13,143.81	54,714.83
Type 2 diabetes	40	9,528	14.5	45.0	5.21	32.390674	45,898.13	1,486,671.30
Total								40,182,766.94

* Factors as discussed in Rajgopal et al. (2002).*
† Calculated based on number of program graduates (not shown).

filtering of the Virginia questions as well as the seven additional questions from the California food behavior checklist. Only EFNEP graduates who achieved the greatest benefit (a score of 4 or more) in all the dietary practices criteria were considered as practicing optimal nutritional behaviors. All other graduates were eliminated from the analysis (including those who practiced the optimal behaviors at pre-test).

Responses were filtered by satisfying all the criteria simultaneously. For example, the original sample size for California was 20,999. After removing participants who did not complete either the pre- or post-survey, the sample size was 9,528. For example, with heart disease, of the 9,528 who completed the pre- and post-tests, only 150 answered all eight questions with a score of 4 or more. This was 7.65% of the California population who received EFNEP lessons (table 1). The only participants used in the calculations were those whose behaviors could reasonably be attributed to the nutrition education. Causally connected participants who improved in their behaviors (e.g., moved from not practicing to sometimes practicing) but did not achieve the highest score were screened out of the analysis.

Cost-benefit calculations

We used the same values as Virginia for the cost-benefit analysis formula because our data was collected at about the same time as theirs, and for the purposes of this study represented national averages.

We calculated the benefits as follows: For direct, tangible benefits, if the disease/condition could be prevented or delayed for 5 years, then the benefit was the amount of money saved by the delay in treatment costs for 5 years (using a 5% discount rate) (table 2). For indirect, tangible benefits, calculations were done only for those diseases/conditions where data was available (table 3).

Calculation of direct benefits

Formula: A x B x C x D = E; E x F = benefits*

A = Number of EFNEP graduates studied per year
B = Incidence rate (%) of disease/condition in general population (estimation)
C = Incidence rate of disease related to dietary change (estimation)
D = Percentage of graduates practicing optimal nutrition behaviors (calculated/filtered)
E = Estimated number of graduates to accrue benefits (calculated: A × B × C × D = E)
F = Present value of "benefit" for disease/condition (estimation)

* Formulas corrected by author postpublication, 10/6/06.

(Virginia used Bureau of Labor Statistics data from 1995 for these analyses.)

In general, the population served by EFNEP is less likely to be employed than the general population represented by this data. One of the sensitivity analyses was done to correct for this generalization. The benefits of postponing pain and suffering were not included in the analysis, though this would be a very large number.

To select participants practicing optimal nutrition behaviors, a cost-benefit method was used. SPSS (Statistical Package for Social Sciences) was used to analyze results for each of the diseases/conditions studied. All participants who met the optimal behavior at the pre-test were eliminated from the study to increase the likelihood that the improved behavior was a result of the nutrition education.

California EFNEP costs, benefits

The cost of delivering nutrition education to California participants was derived from the California EFNEP budget, using all tangible costs. The estimated total direct costs for fiscal year 1998-1999 were $2,543,667, and the estimated indirect costs were $236,883 (cost definitions and calculations available from authors).

The initial benefit-cost ratio for California was 14.67 to 1.00, meaning that for every $1.00 spent on EFNEP, $14.67 was saved in future medical costs (initial cost calculations available from author). Even though this result seems high, the researchers used stringent conditions to apply both the benefit calculations and the cost estimates. In addition, our initial result was similar to that calculated by the Virginia researchers.

A number of different values for the critical variables were used for these analyses; economists call this sensitivity analysis. Therefore, the cost-benefit results would change as values for these variables change. We used sensitivity analyses to quantify how the cost-benefit calculation changed, using VCE's protocol. The following four sensiti vity analyses were done to be conservative and to prevent overstating results (table 4).

Low-income populations. The Virginia study reported that the incidence rates used for diseases/conditions were for the general population, and there was reason to believe that the incidence rate in low-income populations such as EFNEP families would be higher. In Healthy People 2000, "low income" is noted as a special risk factor for chronic diseases. Although the Virginia researchers recalculated their cost-benefit to correct for this possible disparity, we decided to leave the initial incidence rate unadjusted. The incidence rate used in our analysis is likely to be conservative for low-income individuals.

Diet for stroke and osteoporosis. The Virginia benefit calculations were based on the assumption that there was a 100% relationship between diet and disease for stroke and osteoporosis. The initial analysis used 100% (e.g., everyone will get this condition at some time) for the incidence rate, since there was no actual data available. However, 100% is inaccurate for both of these diseases. The first sensitivity analysis done on the Virginia and California data used a 50% incidence rate for both stroke and osteoporosis, then an additional incidence rate using 25% as an estimation. For California, the revised benefit-cost ratio using 50% was 8.34 to 1.00, and using 25% it was 5.17 to 1.00 (table 4).

Osteoporosis benefits. The California and Virginia studies both had the largest tangible benefit in their osteoporosis calculations. Dietary factors play a role in delaying osteoporosis for 5 years. The EFNEP population is mostly female (92%) and younger (25 to 30 years old), which would justify the assumption that dietary changes could reduce the risk of osteoporosis later in life. However, there are a number of other risk factors for osteoporosis that are not related to nutrition (e.g., genetics, hormones and smoking), and the age at which risk prevention is reduced may be much younger. The EFNEP intervention, however, would provide a positive benefit for reducing the risk of osteoporosis. Since the sensitivity analysis for diet and osteoporosis (previous paragraph) reduced the incidence to 25%, an additional reduction did not seem warranted.

Long-term benefits. The long-term benefits of EFNEP have been studied for at least 5 years following program participation, but there are no studies to date showing that the benefits are life-long. The Virginia study did two sensitivity analyses to correct for this: they assumed that 50% of the population that showed optimal improvements would maintain them over 5 years, and that 25% of the population would maintain them for 5 years. In California, the same two analyses were done: for 50% the benefit-cost ratio was 7.33 to 1.00, and for 25% the ratio was 3.67 to 1.00 (table 4).

As in all studies using data that is self-reported, and due to data collection procedures in the field, the potential for bias from confounding variables can never be completely eliminated.

Good public policy

Our initial benefit-cost ratio for California was 14.67 to 1.00, and our ad-

TABLE 3. Diet-related diseases/conditions and factors used in cost-benefit analysis to calculate indirect benefits

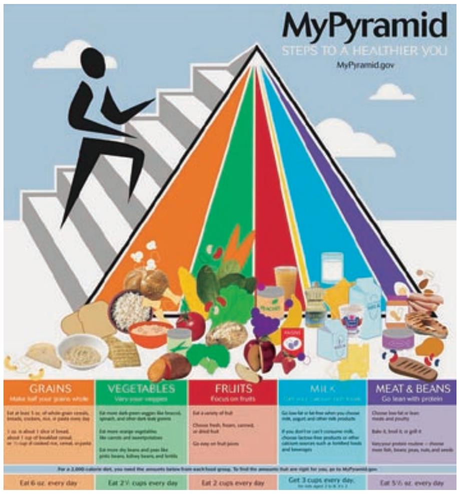
Disease/condition*	Avg. age of onset†	Avg. delayed onset due to nutrition education†	Avg. annual lost workdays†‡	Graduates to accrue benefits (calculated)	Present value of lost earnings†	Total indirect benefit of delaying condition
	years	years	no.	no.	$	$
Foodborne illness	23	65	1.5	74.566	1,600.19	119,326.16
Heart disease	55	60	58.0	59.128	693.53	41,008.43
Hypertension	30	35	41.0	41.212	4,779.67	196,970.20
Obesity	23	65	1.83	119.333	1,952.23	232,959.60
Stroke	45	50	60.0	4.163	2,084.54	8,671.69
Type 2 diabetes	40	65	0.6	32.391	228.80	7,410.83
Total						606,346.91

* Indirect benefits were not calculated for colorectal cancer and osteoporosis.
† Source: Lambur et al. 1999.
‡ Rate of $7.60 per hour, discounted 5%.

TABLE 4. Sensitivity analyses on reducing the number of participants practicing optimal behavior to 50% and 25% for direct and indirect benefits

Disease/condition*	Direct value 100%	Direct value 50%	Direct value 25%	Indirect value 100%	Indirect value 50%	Indirect value 25%
	$	$	$	$	$	$
Colorectal cancer	628,583.11	314,291.55	157,145.77	—	—	—
Foodborne illness	1,406,826.40	703,413.20	351,706.60	119,326.16	59,663.08	29,831.54
Heart disease	40,902.19	20,451.10	10,225.55	41,008.43	20,504.22	10,252.11
Hypertension	28,760.31	14,380.16	7,190.08	196,970.20	98,485.10	49,242.55
Obesity	1,394,600.80	697,300.40	348,650.20	232,959.60	116,478.30	58,239.15
Osteoporosis	35,141,719.00	17,570,859.50	8,785,429.70	—	—	—
Stroke	54,714.83	27,357.42	13,678.71	8,671.69	4,335.85	2,167.92
Type 2 diabetes	1,486,671.30	793,335.65	371,667.82	7,410.83	3,705.42	1,852.71
Totals	40,182,766.94	20,091,388.98	10,045,694.49	606,346.91	303,171.97	151,595.98

* Benefit-cost ratios for sensitivity analyses: incidence rate of 50% for osteoporosis/stroke (8.34/1.00); incidence rate of 25% for osteoporosis/stroke (5.17/1.00); long-term benefit for 50% of population (all diseases) (7.33/1.00); long-term benefit for 25% of population (all diseases) (3.67/1.00).



In addition to publishing nutrition guidelines such as the Food Guide Pyramid (updated in 2005), USDA spends $255 million annually on direct nutrition education for low-income consumers. The study provides evidence that this spending is cost-effective.

ditional sensitivity analyses provided a range of results from 8.34 to 1.00, to 3.67 to 1.00. The bottom line is that for every dollar spent on nutrition education in California, at least $3.67 is saved on medical treatment costs.

We believe that the benefit-cost ratios presented in our study are low. Several decisions ensured that our estimates were conservative, including: (1) using stringent criteria to determine the optimal nutrition behaviors associated with the delayed onset of several chronic diseases; (2) reducing the incidence rate for osteoporosis and stroke; (3) using national averages for treatment costs instead of California's higher costs; (4) reducing the population that practiced the optimal behaviors to 25%, to adjust for the 5-year time frame of treatment delay; and (5) reporting benefit results for individuals only when these benefits would be expected to extend to other family members as well.

Nutrition education is now widely acknowledged as an important component of the U.S. Department of Agriculture (USDA) budget. The current EFNEP budget is larger than it was in 1998, more than $65 million nationally. At the same time, the Food Stamp Nutrition Education (FSNE) program also targets food stamp–eligible clients with a budget of more than $190 million, for a total national USDA nutrition education budget of about $255 million.

Based on our findings and those of the Virginia researchers, nutrition education appears to be a good economic investment for the country, especially with an underserved population likely to have poor eating habits and higher risk for numerous chronic diseases and conditions. We believe this data provides strong evidence that nutrition education programs are cost-effective and that continuing to fund them is a sound investment and good public policy.

A. Block Joy is Specialist and Director of the UC Food Stamp Nutrition Education program in California, Department of Nutrition, UC Davis; and V. Pradhan (deceased) was Senior Statistician and G. Goldman is Economist, Emeritus, Department of Agricultural and Resource Economics, UC Berkeley. *The authors thank Ruby Cox, Specialist, Virginia Cooperative Extension, who consulted on the methodology of the analysis, and whose insight, enthusiastic support and guidance were invaluable. We also acknowledge Barbara Sutherland, EFNEP Director, and the EFNEP Advisors who managed adult EFNEP in their respective counties and collected the data used in this study: Mary Blackburn (Alameda), Gloria Brown (San Francisco/San Mateo), Ann Cotter (Orange), Susan Donahue (Butte), Nancy Feldman (Stanislaus), Mary Fujii (Contra Costa), Chutima Gavanthor (Riverside), Margaret Johns (Kern), Cathi Lamp (Tulare), Connie Lexion (San Bernardino), Anna Martin (San Joaquin), Yvonne Nicholson (Sacramento), Gwendolyn Stanford (San Diego), Jeanette Sutherlin (Fresno), Barbara Turner (Los Angeles) and Estella West (Santa Clara). In addition, we thank William Benford, Chris Hanson, Karrie Heneman and Karl Schroeder. This study was funded by a competitive grant from the UC Division of Agriculture and Natural Resources.*

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Tribute: Vijay Pradhan

Two of the authors would like to recognize the outstanding contributions made by Vijay Pradhan, who passed away after the study was completed. He implemented the statistical analyses for this study, looking at all the possible criteria and meticulously working with multiple variables. Pradhan spent 2 years on the design, development and implementation of the analyses for California, and he met with the other authors regularly to discuss the results. His dedication to the completion of the study was a reflection of his character; he was a devoted, concerned, caring and committed researcher. He was a self-motivated professional who took pride in his achievements. Vijay Pradhan was a man of great integrity and a valuable friend.

REVIEW ARTICLE

Radiofrequency power disinfects and disinfests food, soils and wastewater

by Manuel C. Lagunas-Solar, Nolan X. Zeng, Timothy K. Essert, Tin D. Truong *and* Cecilia Piña U.

Radiofrequency (RF) is an advanced telecommunication technology first invented in the early 1900s, which is in use today for wireless communication worldwide. Because of its ability to penetrate and heat various materials, RF has the potential to disinfect and/or disinfest food, agricultural and environmental materials. However, research to validate this approach has been restricted by limited understanding of how RF photons interact with materials, and by limited access to and the high cost of its source electronics. Since the early 1990s, we have conducted research at UC Davis on continuous RF power applications using nonconventional RF systems and new operational concepts. Laboratory tests have successfully demonstrated the effectiveness of RF power to disinfect and/or disinfest fresh produce, rice, soils, agricultural wastewater, and other foods and materials. Likewise, rapid pulses of RF are lethal to arthropod pests and may provide a nonthermal disinfestation process for fresh, temperature-sensitive commodities, as well as a promising alternative to the fumigant methyl bromide.

UC Davis researchers have developed a prototype for automatic, computer-controlled batch and conveyorized applications of radiofrequency power. The system can disinfect and/or disinfest fresh produce, ready-to-eat foods, milk and juices, as well as agricultural products such as rice and wastewater.

A major challenge in producing and distributing disease- and insect-free foods is the need to maintain their sensory and nutritional attributes while minimizing the adverse impacts of treatment. This challenge emerged because of consumer attitudes and market expectations concerning the safety, quality and condition of foods; the adverse environmental impacts of agricultural practices; and expanding global markets, which impose logistical demands on regional, national and international trade.

To a large extent, food safety depends on the use of adequate disinfection and disinfestation techniques, while quality is maintained by integrating multiple handling, packaging, and storage and distribution practices. Disinfection is aimed at eliminating spoilage and pathogenic organisms to reduce storage losses and prevent food-related illnesses. The disinfection of nonfood agricultural commodities such as soils, feeds and waste materials is also needed, either because they are recycled or used in food production, or to protect the environment. Disinfestation (control of insect pests) is needed mostly to comply with trade barriers aimed at preventing the spread of nonnative arthropod pests. Pesticides, refrigeration, packaging and modified atmosphere storage are the technologies most often used today for disinfection and disinfestation. New, noninvasive, user-friendly and economically viable processing technologies are needed to meet evolving consumer expectations and trade standards.

A research project was established at UC Davis to study, evaluate and demonstrate new radiofrequency (RF) processing applications for food, agricultural and environmental materials. We review laboratory-scale results for several RF processes with potential commercial applications, and provide preliminary economic estimates for their installation and operation. Our experimental methods are described briefly and generally; the scientific and technical details of many of these results have been or are being reported elsewhere.

How radiofrequency power works

RF is an advanced telecommunication technology first invented in the

Unprocessed (left) and processed (right) apple juice; the photo shows no microbial growth on the RF-processed sample, even after both samples were stored for 19 months at room temperature.

An Angoumois grain moth larva emerges from a rice kernel. In laboratory experiments, RF processing achieved 100% disinfestation of the moth with no effects on rice quality.

RF thermal power formula

The thermal power induced by RF is given by the following formula:

$$P = 55.61 \times 10\text{-}14 \; E2 \; \nu \; \varepsilon'' \qquad (1)$$

where P is the thermal power generated (W/cm^3); E is the electric field strength in (V/cm); ν is the RF frequency in (Hz); and ε'' is the dielectric loss factor of the material (intrinsic property). The dielectric loss factor (ε'') largely depends on the material's chemical composition and is essentially the ease by which molecules can be heated by an RF field.

early 1900s, which is in use today for wireless communication worldwide. Traditionally, RF energy refers to nonionizing electromagnetic radiation with frequencies ranging from approximately 30 megahertz (MHz) (wavelength = 11 yards [10 meters]) to 300 MHz (wavelength = 1.1 yards [1 meter]). However, the U.S. Federal Communications Commission (FCC) allows other frequencies to be utilized for industrial, scientific and medical applications (e.g., 13.56 and 27.12 MHz) (Kasevich 1998). Our studies focused on the use of lower frequencies outside the FCC domain, ranging from 300 kilohertz (kHz) (wavelength = 1,094 yards [1,000 meters]) to 10 MHz (wavelength = 36.1 yards [33 meters]). Early tests demonstrated the potential advantages of lower frequencies, in terms of the type and efficiency of RF interactions with different materials. Within the lower frequency range, very high (> 80%) overall energy-use efficiencies are achievable with modern design and engineering systems. These novel RF systems can be manufactured and operated with significant savings, and increased ruggedness and reliability as compared with conventional RF systems.

RF power is produced when electricity is applied to an RF generator whose signal is amplified and delivered to a parallel electrode system (RF cavity), in which a selected material is placed (fig. 1). Within the RF cavity, an oscillating electric field is created, and energy is transferred to the treated material through electronic-field interactions with dipole or induced dipole molecules (those formed by the polarization of neutral molecules). These dipole molecules are forced to reorient within the changing electronic field, which results in movement or drifting that causes internal friction and creates thermal energy (heat). The process is known as "RF thermal processing" or simply "RF heating."

At certain frequencies or frequency bands, some foods and nonfood materials can be heated preferentially and faster, creating rapid thermal effects on pests but minimal interactions with the host material. This is due to the difference in electrical conductivity between arthropod pests (high) and the host commodity (low). This process is called "selective or differential RF heating" and could provide an alternative disinfestation process for thermally sensitive fruit and vegetable products. In general, complex organisms such as arthropod pests are more severely and easily affected by heat. The higher response of pests and lesser sensitivity of host commodities offer a window of opportunity for disinfestation with minimal or no impact on the commodity (fig. 2).

The differential effect is generally less effective with microbial contaminants, since microbes are significantly smaller in mass and are usually well attached to a much larger volume (and mass) host, thus being rapidly and effectively cooled. For disinfection to occur, the microbe must reach lethal temperatures, which are usually also deleterious to the host commodity. However, RF heating induces the thermal inactivation of biological organisms (such as fungi, bacteria, protozoa, parasites and nematodes), viruses and enzymes, as well as arthropod pests present in heat-tolerant commodities (such as dried fruits, grains, nuts, seeds, wastewater and soils).

Unlike traditional surface heating, RF penetrates deeply into foods and agricultural materials (see formula 1). The surfaces of the treated materials are slightly colder because of radiation losses, and the insides are heated homo-

Definitions

Dielectrics: material (isolator) that does not conduct electricity
Dipole: material having two equal but opposite charges or magnetic poles
Gram-negative: not forming a color precipitate when treated with alcohol (Gram's staining method for bacteria identification)
Gram-positive: forming color when treated with Gram's method

Abbreviations

cfu: colony-forming units
Hz: hertz
kV: kilovolts
kW: kilowatts
kWh: kilowatt hour
MAP: *Mycobacterium avium* subsp. *paratuberculosis*
MHz: megahertz
RF: radiofrequency
W: watts

geneously and at controllable rates. In general, RF heating eliminates surface overheating, reducing thermal loads and allowing a food's quality and nutritional attributes to be maintained.

Types of RF treatments

Capacitive heating. Common materials such as water (a major component of most foods), and most cellulose-based and plastic materials used in packaging, are generally inactive or transparent to RF. Other materials such as soils, wood, dried foods, grains, and nut products absorb RF readily and can be heated rapidly. RF photons easily penetrate these commodities, allowing them to be processed in large masses while heating the material thoroughly. This process is known as "capacitive heating."

Conductive heating. Conductive heating is utilized for moist materials such as foods (fresh fruit, vegetables, juices), and agricultural (animal feeds, fishmeal) and environmental (soil, wastewater) materials. The electrical conductivity of these materials is high, promoting the interaction of electrical current in the material to generate heat. Conductive heating can be optimized over a low-frequency band (e.g., 150 kHz to 5 MHz), with high energy absorption and energy-use efficiencies (> 90%). When complex mixtures of materials having different RF properties are processed, each component can be heated directly at different rates and a threshold temperature reached to assure efficacy (Lagunas-Solar et al. 2003).

Ultra-short pulses. RF energy can also be delivered in ultra-short pulses (micro to milliseconds) (μs to ms), creating very high peak (instant) RF power levels. When energy is delivered in ultra-short time pulses, biological targets such as insects and mites are subjected to instantaneous high thermal levels without compromising the host material. Pulsed RF generates mostly nonthermal effects in the host. During the pulse, intense electrical fields induce molecular polarization, which forms dipoles; realignment of dipoles with the RF field becomes the major mechanism for energy transfer. These polarization effects can disinfect some biological materials, because it causes cellular changes including modifications in membrane potential, permeability and structural properties (electroporation).

In the laboratory, pulsed RF has induced lethal biological effects on arthropod pests without thermal effects on the host (Lagunas-Solar and Essert 2004). However, for pulsed RF systems to operate reliably with high pulse-repetition rates (pulses per second), further system design and engineering is needed. The potential for nonthermal disinfestation of fresh produce in conveyorized operations, with high energy-use efficiency, promises a nonchemical alternative to pesticides that merits further investigation.

Fresh fruits and vegetables

Selective RF heating effects were suggested as a potential insect control for grains several decades ago (Nelson and Charity 1972), but no demonstrations with fresh produce have been reported.

We exposed fresh fruits and vegetables individually and identically in a RF research cavity (840 watts [W] input power, 6 kilovolts per centimeter [kV/cm], 1 MHz, 4 minutes) and the results were normalized for comparison purposes. Because RF heating effects are mostly determined by the material's

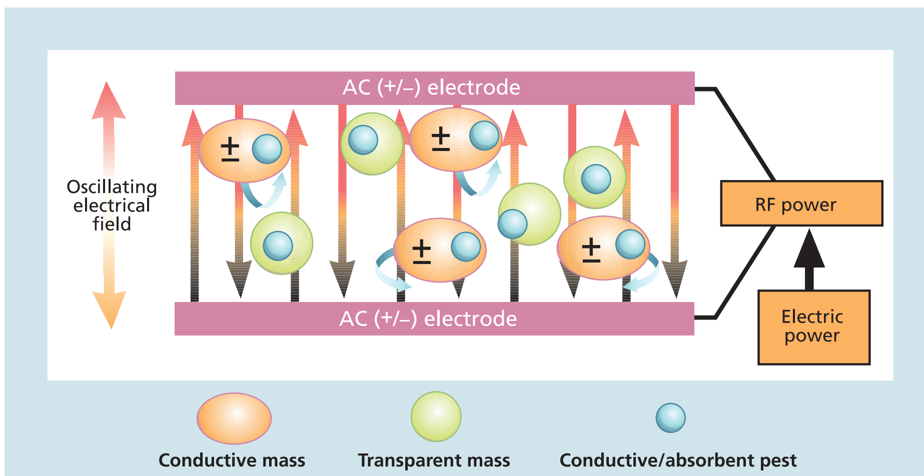


Fig. 1. Components of an RF cavity. Permanent and induced dipoles within the cavity are forced to realign to the changing electronic field, creating friction that generates thermal energy (heat). Molecules that are not permanent dipoles (transparent mass) and cannot be polarized are inactive or transparent within the RF cavity. Insect pests (conductive/absorbent mass) absorb RF, rapidly heating up and dying (disinfestation).

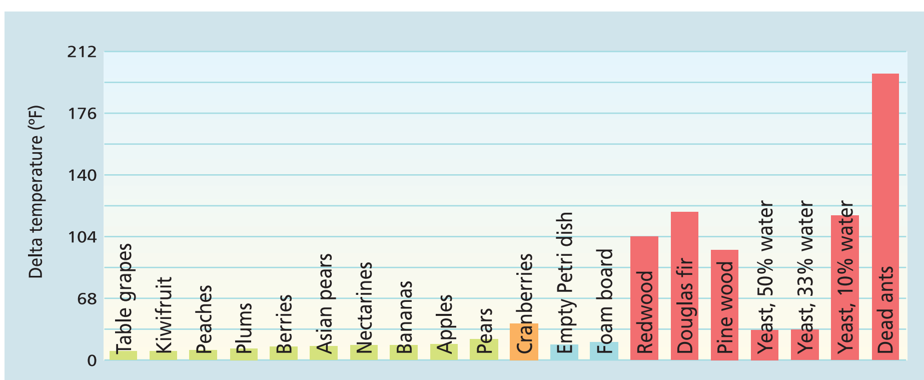


Fig. 2. Differential (selective) heating effects for samples individually treated with 840 W at 1 MHz for 4 minutes, with an electric field of 6 kV/cm. Temperatures were measured with nonmetallic (alcohol) thermometers during RF processing; the change in temperature is shown. Similar results were obtained with fresh vegetables (asparagus, carrot, cucumber, eggplant, garlic, onion, pepper, potato) (data not shown).

chemical composition (see formula, page 193), powdered yeast was used to represent microbes (e.g., fungi, bacteria, protozoa) while ants (*Pogonomyrmex subdentatus*) were chosen as surrogates for insect and mite pests. We also studied materials commonly used to package fresh produce, such as foam board, wood (Douglas fir, pine and redwood) and polyethylene.

Significantly different heating rates and temperatures were observed between the commodities (lowest heating rates), packaging materials (medium) and particularly model pest contaminants (highest) (fig. 2). Minor heating (~ 54°F [~ 12°C] maximum for cranberries) was observed in fresh commodities with a range of 39°F to 46°F (4°C to 8°C) for all others, indicating that a low thermal load (temperature × time) was well tolerated by fresh commodities. Increased temperatures were rapidly lowered by heat losses reaching ambient temperature (~ 72°F [~ 22°C]) in a few minutes. Insects reached a level lethal to all arthropod pests (> 194°F [90°C]). Yeasts heated faster with lower levels of moisture (e.g., dried commodities), suggesting that microbial disinfection in moist products is unlikely. All plastic packaging materials heated at levels similar to the fruits, while wood materials heated faster, suggesting the potential use of RF processing for disinfestation.

Hot water immersion is currently a common practice to disinfest fresh commodities. Selective RF heating for dry thermal disinfestation appears possible and may provide an easily adapted alternative for conveyorized operations with single fruits or fruit packages. If developed, it would be especially useful for organic products. Challenges to developing this process include measuring the RF properties of fresh produce over a frequency band useful to optimize process efficiencies and minimize uneven heating due to the often-irregular shapes of fruits and vegetables. Our operational cost estimates appear to be competitive at $0.0024 per pound ($0.0054 per kg) and comparable to other RF processes. Prototyping for small-scale field demonstrations will be needed to evaluate the efficacy of RF processing and confirm its economics and logistics.

TABLE 1. RF thermal disinfection of foods and nonfoods inoculated with human pathogens*

Sample material	Temperature	Reduction levels		
		E. coli O157:H7	*S. thyphimurium*	*M. paratuberculosis*
	°F (°C)	%		
Ready-to-eat foods/ Japanese bento box				
Cooked rice	201.2 (94)	> 99.998	> 99.9993	n/a
Salmon	158.0 (70)	> 99.999	> 99.9993	n/a
Shrimp	179.6 (82)	> 99.9993	> 99.9995	n/a
Kamaboko†	161.6 (72)	> 99.993	> 99.9993	n/a
Konnyaku‡	165.2 (74)	> 99.999	> 99.998	n/a
Potato salad	188.6 (87)	> 99.999	> 99.998	n/a
Orange juice	129.2 (54)	> 99.999	> 99.994	> 9.8
	145.4 (63)	> 99.9996	> 99.9993	> 99.9995
	161.6 (72)	> 99.9996	> 99.9995	> 99.9994
Wastewater	113.0 (45)	~ 2	~ 2	Not detectable
	129.2 (54)	~ 9	~ 99	~ 2
	145.4 (63)	> 99.9999	> 99.99999	> 99.9999
	161.6 (72)	> 99.9999	> 99.99999	> 99.9999
Fishmeal	140.0 (60)	99.97	99.93	n/a
	149.0 (65)	99.998	99.992	n/a
	158.0 (70)	> 99.9995	> 99.99993	n/a
	176.0 (80)	> 99.9995	> 99.99993	n/a
	194.0 (90)	> 99.9995	> 99.99993	n/a

* Reduction levels expressed as percentages were obtained from measured $\log^{10}$ reduction levels.
† Kamaboko is a food made from fish paste.
‡ Konnyaku is a gelatinous, noncaloric food derived from a bulbous perennial herb.

Ready-to-eat foods

Processed or partially processed foods often contain pathogens from natural or humanmade sources (IFT 2002). For effective disinfection, a threshold temperature must be reached in all of the food's components. With conventional surface heating, the food surface must be overheated, since heat must be conducted throughout its entire volume. We tested RF thermal disinfection in two types of freshly prepared Japanese bento boxes (n = 30 each). Samples of each component were inoculated with *Escherichia coli* O157:H7 and/or *Salmonella thyphimurium*, both important food pathogens.

Closed plastic packages were treated with the goal of reaching a minimum temperature of 158°F (70°C) in every component. After processing, the treated and control samples were assayed using standard microbiology procedures at the UC Davis Dairy Food Safety Laboratory in the School of Veterinary Medicine. Treated samples in standard Petri dishes were also incubated using selective media for about 21 days and showed no colony formation. Overall, the RF treatments caused no sensory changes, and only minor cosmetic damage occurred to fresh lettuce used in some boxes as a decorative item (table 1).

A panel of Japanese scientists and visitors (Ishida Ltd. Co., Kyoto, Japan) conducted sensory tests and concluded that there were no detectable differences in marketing quality between the RF-treated and untreated boxes. Clearly, RF processing through the package is possible for many foods, reaching disinfection levels without the deterioration of sensory and nutritional properties.

A conveyorized RF process could disinfect ready-to-eat foods quickly, in less than 1 minute. With proper design of the RF cavity, multiple packages could be processed continuously. Based on operational costs (mostly electric power) and without capital cost amortization, the costs would be an estimated $0.0034 per pound ($0.0074 per kg) or approximately $0.0037 per box. This RF process would be applicable to similar packaged products for disinfection in a production line, such as grains, dried foods, nut products, cereals, animal feeds and fishmeal. Furthermore, disinfecting or disinfesting food products in the package would help prevent recontamination.

Fresh fruit juices and liquid milk

Fresh, unprocessed fruit juices are potential sources of human pathogens, particularly those containing several different natural, unprocessed (including organic) ingredients. Contamination can result from field conditions and handling as well as poor hygienic practices during manufacturing. This is why juices, and particularly liquid milk, are heat-pasteurized, but the process can lower nutritional and sensory properties, mostly due to surface overheating. (Nonpasteurized fruit juices are available in some segments of the market.) A homogeneous and less energy-intense thermal process would improve and preserve quality.

Samples (100 milliliters [mL]) of fresh orange juice (Sunkist Growers), apple juice and cider (Martinelli, Apple-a-Day), were innoculated with *E. coli* O157:H7 and *S. typhimurium* at about 106 colony-forming-units per milliliter [cfu/mL] and treated with RF (200 W, 13.3 MHz, 1 kV/cm, 1 minute). Samples of liquid milk inoculated with *Mycobacterium avium* subsp. *paratuberculosis* (MAP), a bacterium believed to be resistant to conventional heat pasteurization, were also RF processed. In addition, nearly a dozen freshly made unpasteurized fruit smoothies were prepared from raw fruits, processed with RF and tested for differences in sensory properties.

Because of their mixed composition (including apple, berries, carrots and oranges), these smoothies and fruit juices heated rapidly and homogeneously in less than 1 minute (table 1). RF processing was reproducible and achieved total destruction of the pathogens, as shown by the absence of colonies after thermal incubation (~ 7 days, 98.6°F [37°C]). Panels of industry experts determined that RF processing did not affect the sensory properties of either smoothies or fruit juices.

A conveyorized RF system for fresh juices, smoothies and milk could provide processing capabilities in the production line (on-line), and achieve disinfection in-the-package in less than 1 minute, while meeting design and engineering challenges similar to those of ready-to-eat foods. Operational costs, mostly for electric power, were an estimated $0.0031 per pound, or $0.0016 per gallon ($0.0060 per liter). RF systems for disinfecting fruit juices could be built with a range of processing capacities, allowing its use by small operators or those demanding larger throughput.

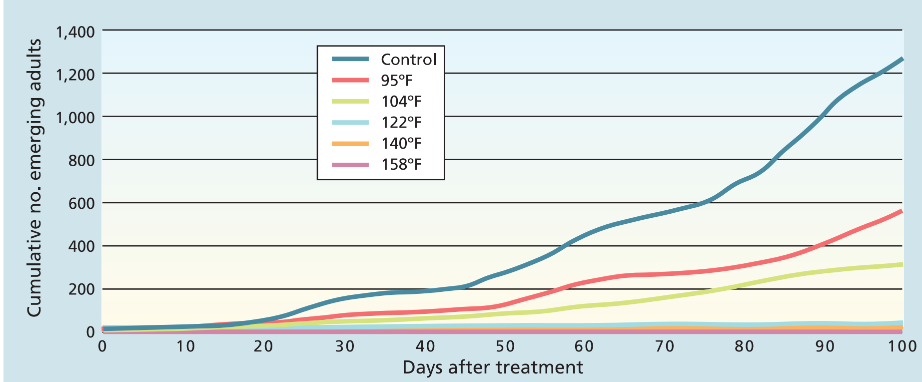


Fig. 3. RF thermal disinfestation effects on naturally infested (Angoumois grain moth) paddy rice. Triplicate samples (155 grams each; 465 grams total) were treated at 95°F to 158°F (35°C to 70°C) using 100 W of 385 kHz RF photons, for 5 minutes. Emerging adults were observed for up to 100 days to include overall emergence (survival) from eggs, larva and pupa stages, and compared to controls (not treated). Emergence was controlled at 122°F to 158°F (50°C to 70°C).

Disinfestation of paddy rice

We tested commercial samples of paddy rice naturally infested with Angoumois grain moth (*Sitotroga cerealella*), whose larvae and pupae live entirely inside the grain. Chemical fumigation with pesticides such as methyl bromide and phosphine is inefficient because the dispensed gases cannot break through naturally occurring air locks, preventing the fumigant from penetrating or diffusing inside the hollowed grain.

A well-insulated paddy-rice sample holder (polyethylene and foam board) was designed and constructed to contain up to 170 grams of paddy rice and maintain a homogeneous temperature (± 1.8°F; ± 1°C) during processing. After treatment, all samples (in triplicate) were transferred to plastic containers with secure lids containing small mesh screens, which maintained moisture and oxygen supply and allowed the surviving insects to grow. Samples were incubated at 82.4°F to 86°F (28°C to 30°C) and 35% to 43% relative humidity for up to 100 days (approximately three to four complete insect life cycles). Every 2 to 3 days, the surviving or emerging adult moth populations were determined and compared to the controls. After each observation, all live adults were removed to allow other life cycles (from eggs, larvae, pupae) to emerge and be assayed. In addition, the quality attributes of all treated and control samples were analyzed by the California rice industry using standard analysis methods.

Disinfestation levels reached 100% control of all Angoumois grain moth life cycles (fig. 3), and the milling and quality of the rice were not affected

TABLE 2. Quality attributes of RF-processed paddy rice*

Quality attributes	Controls	Test 1 (122°F [50°C])	Test 2 (140°F [60°C])	Test 3 (158°F [70°C])
	%			
Moisture	13.5 ± 0.1	13.5 ± 0.1	13.5 ± 0.1	13.5 ± 0.1
Whole kernel	79.3 ± 1.1	81.1 ± 7.9	78.3 ± 0.5	77.9 ± 0.8
Total rice	68.1 ± 0.3	68.3 ± 0.1	68.2 ± 0.1	68.0 ± 0.1
Dockage	16.9 ± 4.8	11.7 ± 1.0	12.4 ± 1.6	13.2 ± 1.7
Brown rice	81.1 ± 0.4	81.4 ± 0.2	81.3 ± 0.2	81.3 ± 0.1
Whiteness	44.2 ± 0.2	44.1 ± 0.2	44.2 ± 0.2	44.3 ± 0.3

* Mean values and standard deviation for triplicate measurements each with 2.2 lbs (1 kg) samples.

Researchers are investigating the application of RF power to disinfest and disinfect carpets. Specific frequencies were used to rapidly heat insects; ants were killed in a few seconds.

(table 2). RF processing appears to be a promising alternative to fumigation for rice and similar dried commodities such as seeds, nuts and dried fruits. Further research to optimize this process and evaluate sublethal effects on infesting insects is under way with beetles and moths.

An RF conveyorized system could operate commercially with large processing capacity, because rice and other grains are handled at rates of many tons per hour. The logistics of such operations must be further evaluated, but they could offer an effective nonchemical alternative to fumigants at operational costs of $2.20 per ton.

Plant seed treatment

RF processing can disinfect, disinfest and induce favorable biological activation effects (such as increased rate, vigor, and synchronization of germination) in plant seeds without affecting their ability to germinate. We demonstrated RF disinfection with various seeds including tomato, carrot, pepper, cantaloupe, peas and cauliflower. In contrast to hot-water treatments (~ 131°F [55°C] for 15 minutes), RF processing allows higher temperatures because heat distribution is better and occurs quickly, in less than 1 minute.

We demonstrated and validated the kinetics of activation in the germination of various types of seed, in collaboration with private industry (Campbell Soup Research Institute, Davis, Calif.). The preliminary data indicates that overall germination is not affected, but its rate (vigor) and timing (synchronization) are greatly improved at thermal loads (temperature and time) capable of simultaneous disinfection and disinfestation. The application of RF to process plant seeds would decrease the risk of recontamination in packaged seed products. Batch or conveyorized operations are also feasible. The operational cost of this treatment is estimated at $2.20 per ton. Because seeds are not a high-volume commodity, less-expensive RF systems with relatively low power capacity can be used.

Treating agricultural wastewater

We investigated the disinfection of agricultural wastes using wastewater from dairy and animal farms in Tulare County. Wastewater samples (100 mL) were inoculated with *S. thyphimurium*, *E. coli* O157:H7 and MAP, then treated with temperatures between 113°F and 194°F (45°C to 90°C). Standard biological procedures (diluting, plating, incubating and counting) with appropriate selective media were used to assay in duplicate all treated and control samples.

Measured disinfection effects (percentage reduction) included corrections for the assay's detection limit (400 cfu/mL), while the extrapolated values were calculated from the initial inoculum levels since no colony growth was detected after 21 days of incubation (table 1). In addition, microorganisms present in the original wastewater samples — including gram-positive (data not shown) and other gram-negative bacteria — were reduced by about 99%. RF processing also effectively controlled MAP bacteria, which appears to resist conventional heat pasteurization at similar thermal levels.

RF processing could be technically and economically competitive with chemical (chlorination, ozonation) and UV processing to disinfect wastewater in concentrated animal feeding operations (Lagunas-Solar et al. 2005). The operational costs for wastewater disinfection at a rate of 1 ton per hour would be about $6 per ton. Lacking in chemical residues, treated wastewater could be recycled as animal feed or for soil fertilization without having detrimental

TABLE 3. Economic estimates for RF processing at 2,205 pounds/hr (1,000 kg/hr)*

	Economic cost factors	
Commodity: objectives	**RF power**	**Cost per pound (kg)**
	kW	*$*
Fresh produce: disinfection and disinfestation	48.1	0.0024 (0.0054)
Processed foods: disinfection	66.7	0.0034 (0.0074)
Fruit juices: disinfection	61.7	0.0031 (0.0069)
Liquid milk: disinfection	60.2	0.0030 (0.0067)
Paddy rice: disinfection and disinfestation	22.2	0.0011 (0.0025)
Plant seeds: disinfection and disinfestation (activation of germination)	22.7	0.0011 (0.0025)
Wastewater: disinfection	60.2	0.0030 (0.0067)
Fishmeal: disinfection	32.4	0.0016 (0.0036)

* Electricity at $0.10/kWh; overall energy-use efficiency of 81%.

effects on soil chemistry or transferring known plant and human pathogens (Lagunas-Solar et al. 2005).

Fishmeal disinfection

Fishmeal is used worldwide as a high-protein feed ingredient in aquaculture and animal/poultry production. However, it must be disinfected because contamination with microbial pathogens can occur during storage, transportation and distribution. The market demands Salmonella-free fishmeal to avoid recontamination in the animal-human food cycle.

We investigated RF disinfection at temperatures ranging from 122°F to 194°F (50°C to 90°C) with commercial fishmeal samples (Corpesca, Santiago, Chile) inoculated with *Salmonella* sp. and *E. coli* O157:H7. Between 158°F and 194°F (70°C to 90°C), no colonies were detected in plated samples after 21 days of observation (table 1), with greater than 99.999% reduction in microbial pathogens compared to the controls. Simultaneously, the natural flora present was reduced by more than 99.9%, adding further quality assurances to the treated product.

By industry standards, the fishmeal maintained its quality (e.g., protein and lipid contents, moisture) and in vivo digestibility (Lagunas-Solar et al. 2005a) (fig. 4). In addition, due to improved thermal energy distribution and volume heating properties, RF allows a lower thermal load (~ 662°F per minute [350°C per minute]) than conventional [surface] heating (~ 2,462°F to 3,272°F per minute [1,350°C to 1,800°C per minute]). The process has been licensed to private industry, which is evaluating its commercial deployment. Operational costs are estimated at about $3.20 per ton (table 3), much lower than chemical alternatives (about $15 to $20 per ton) or conventional heating (about $25 per ton).

Agricultural soils and pests

If implemented successfully, RF techniques could provide a rapid, residue-free and cost-effective alternative to soil fumigation with methyl bromide, which is being phased out globally due to its contribution to ozone depletion. Research on soil disinfection with RF has focused on containerized and nursery soils (Lagunas-Solar et al. 2005b). Microwaves, hot water and steam applications are also being investigated as alternatives to methyl bromide to disinfest and sterilize soils.

Because soils are good dielectrics and RF can easily penetrate them, RF power offers many advantages; but the use of conventional, continuous RF power systems for soils is currently limited due to high startup (capitalization), logistical barriers and somewhat higher operational costs than methyl bromide. To improve commercial applicability, newly designed and constructed pulsed RF systems are being tested for disinfestation and soil processing (Lagunas-Solar and Essert 2004).

Nematode control. We demonstrated nematode (*Panagrellus* and *Cephalobus* sp.) control in agricultural soils in the laboratory using continuous and pulsed RF power applied with high energy-use efficiency (> 90%). Previously, the lethal temperature for nematodes was experimentally determined as greater than 131°F (55°C), requiring that soils be heated to increase their ambient temperature by 86°F to 104°F (30°C to 40°C). Control of *Fusarium* sp. was also demonstrated during the same experimentation.

A newly designed, pulsed RF system was also tested. The system is capable of generating about 200 MW pulses with kHz-level repetition rates using 10 kW of electric power. Nematode-infested soil samples were treated for 5 to 15 minutes using 400 pulses per second. The soil temperature increased from 73.4°F to 113°F (23°C to 45°C), indicating that part of the pulsed RF energy was converted to heat. After the treatment, nematodes in treated soil samples were extracted into water overnight and then collected using the Tyler standard screen filter. Nematode mortality was more than 90% compared with the control. However, 90% control can also be reached with continuous RF power when heating reaches more than 131°F (55°C). Further studies are under way.

Other research. Pulsed (nonthermal) RF experiments with adult fruit flies (*Drosophila melanogaster*) and all life cycles of mites (*Amblyseius cucumeris*, *Tyrophagus putrescientae*) in fresh table grapes showed 100% mortality in less than 10 seconds, while inducing negligible temperature changes in the grape (< 1.8°F; < 1°C) (unpublished results). This is due to the high electrical conductivity of arthropods, which allows enhanced, pulsed, RF-induced electric effects at the expense of thermal effects.

Finally, applications of continuous RF power are being developed for the home, particularly to disinfest carpet and garden pests. This application

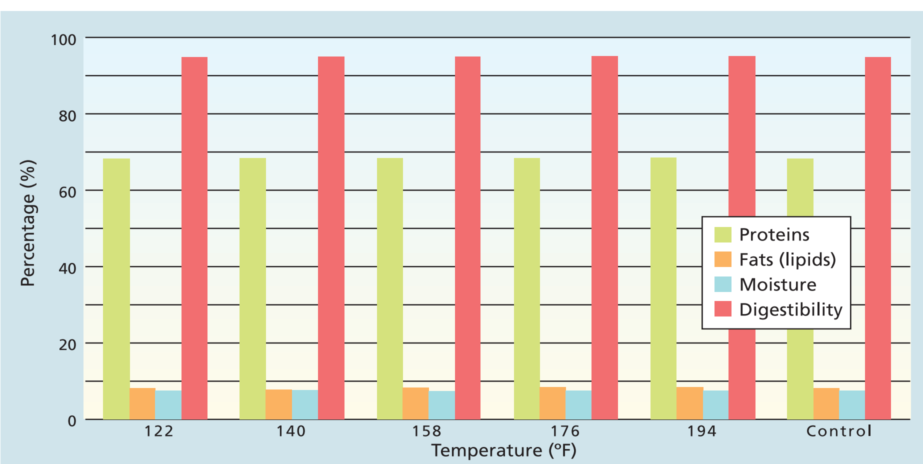
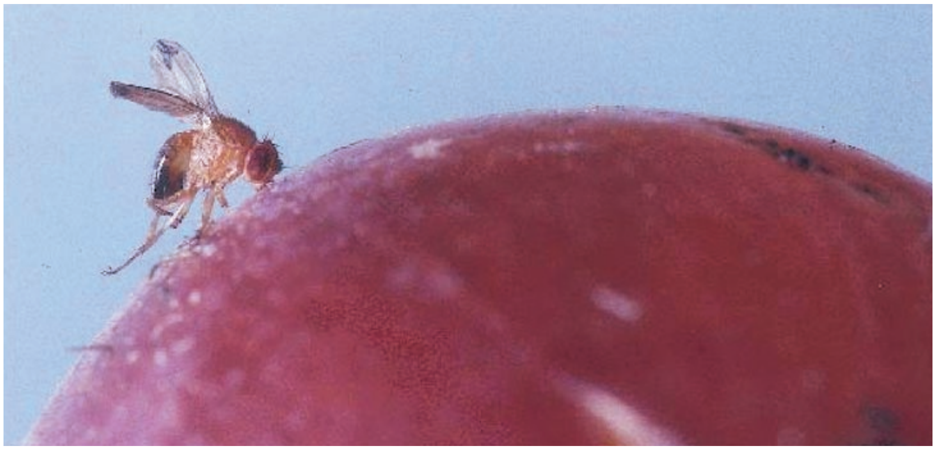


Fig. 4. Percentage of commercially packaged fishmeal samples that retained quality attributes (protein and lipid content, moisture, and protein digestibility) following thermal disinfection at different processing temperatures. Disinfection reached 99.9% at 140°F (60°C) and 100% at 158°F (70°C) and above. Animal feeding studies were conducted at the Norwegian Institute of Fisheries and Aquaculture Research, Fyllingsdalen, Norway.



Ultra-short pulses of RF power were used to treat adult flies on the surface of a 'Red Flame' seedless grape berry. No heating effects were detected in the grape, but microscopic observations indicated acute dryness and charring of the fly's integument, wing ruptures and deformed abdomens, all effects related to rapid heating.

utilizes specific frequencies or narrow bands to induce the rapid heating of insects and mites in RF-transparent (nonabsorbing) materials such as carpets or other home materials, thus providing rapid, nonchemical pest control.

Economics of RF processing

Our preliminary cost estimates for RF processing included the specific heat of materials; the thermal load requirements to achieve effects, the cost of electricity ($0.10/kWh) and process efficiencies (table 3). They did not include the cost of designing and purchasing RF equipment for specific applications. These estimates are based on the operation of UC Davis laboratory prototype systems, which achieve high energy-use efficiencies (electric-to-RF > 90% and RF-to-thermal > 90%).

Although commercial systems currently cost from $1,500 to $2,500 per kW, we were unable to obtain estimates for newly designed, lower-frequency RF systems. However, we anticipate considerable cost reductions (10 to 20 times) to about $100 to $200 per kW for manufacturing systems using solid-state electronics and lower single or narrow non-FCC-approved frequency bands (< 10 MHz). These new systems are currently being designed and tested by our laboratory.

Pulsed RF systems offer the potential for even larger energy savings, since intermittent pulses only demand about 10% of energy consumption. If high energy efficiency and reduced consumption are achieved, RF processing is competitive with conventional heat processing (10% to 15% energy-use efficiencies). No regulatory intervention is expected because RF processes are based on either thermal inactivation (continuous RF), or a combination of thermal inactivation with electronic-field effects (pulsed RF). While RF processes would operate outside the allowed FCC frequencies, their operation is fully shielded to prevent RF emissions to personnel and the environment.

Despite experimental demonstrations of its effectiveness and low operational costs, there is no evidence that RF is currently being used commercially to disinfect or disinfest foods or nonfood products in the United States or globally, nor have any such uses been published in the scientific literature. This is believed to be due to the lack of understanding on the mechanisms of interaction between RF photons with foods and nonfood materials, especially in the low-frequency range (< 100 MHz), coupled with the challenges associated with designing and operating RF research prototype systems. Nevertheless, a few commercial food (baking and drying) and nonfood (wood drying and disinfestation) applications are known, and medical research is being conducted for thermal tumor ablation treatments. However, these applications have limited impact and have not reached wide acceptance, despite the absence of regulatory barriers.

While RF has tremendous potential, commercial input from the targeted industries is needed to focus and prioritize research and development into problems, as defined by industry interests, regulatory demands, and marketing conditions and opportunities.

M.C. Lagunas-Solar is Research Chemist, N.X. Zeng is Research Physicist, T.K. Essert is Principal Electronic Technician, T.D. Truong is Research Assistant, and C. Piña U. is Staff Research Associate, all at Crocker Nuclear Laboratory, UC Davis. (Truong is also Graduate Student, Department of Chemical Engineering and Material Sciences, UC Davis.) *The authors thank the following UC Davis professionals for their expert guidance and assistance during collaborative experimentation in their respective fields: James S. Cullor and Wayne L. Smith, School of Veterinary Medicine; James D. MacDonald and Linda Bolkan, Department of Plant Pathology; Edward P. Caswell-Chen and Steven A. Nadler, Department of Nematology; and Zhongli Pan, Department of Biological and Agricultural Engineering. This work summarizes research conducted under the sponsorship of Hortifrut S.A. (Santiago, Chile), the California Dairy Research Foundation and the California Rice Research Board.*

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Impact of environmental factors on fish distribution assessed in rangeland streams

by Lisa C. Thompson, Larry Forero, Yukako Sado *and* Kenneth W. Tate

We sampled fish in pools located on tributaries of Cow Creek in the northern Sacramento Valley, and related fish distribution and habitat use to environmental factors across the 2003 agricultural growing season. This rangeland watershed experiences extensive livestock use, and many landowners divert stream water for pasture irrigation. Our goal was to provide landowners and managers with current baseline information about the conditions in which fish were found. Our results provide a basis for the development and comparison of irrigation best management practices that may improve conditions for native fish in rangeland streams.

Habitat and land-use factors were studied in a northern Sacramento Valley rangeland, in order to better understand the life cycle needs of salmon and other fish. *Above*, Lisa Thompson, UC Davis assistant specialist in Cooperative Extension, holds a water sample collected from a pool in Old Cow Creek. *Left,* a temperature logger is inserted into protective PVC case with tethering cable.

Fish population declines and habitat alteration across Northern California watersheds have resulted in the listing of numerous species under both the state and federal Endangered Species Acts, and instigated the implementation of total maximum daily load (TMDL) water-quality strategies for impaired water bodies. These events have highlighted the importance of species recovery and habitat restoration efforts, while increasing scrutiny of the potential impacts of agricultural practices on cold-water fisheries. Agricultural practices of concern in Northern California watersheds include irrigation diversions, irrigation return flows, riparian grazing and roads.

Restoration and regulatory efforts often adopt a single-variable approach to species recovery. For example, a sediment TMDL is being developed to aid the recovery of coho salmon (*Oncorhynchus kisutch*) in the Garcia River. To meet the same goal on the south fork of the Trinity River, a stream-temperature TMDL is being developed. Sediment and stream temperature are both important habitat variables, but a more holistic approach using a suite of interacting habitat and land-use factors would provide listed fish species with a greater chance of recovery. However, few studies have concurrently examined habitat, water quality, fish and agricultural practices. This study of Cow Creek in the northern Sacramento Valley is the first step in such a project for Northern California watersheds. Research on how these factors interact will provide vital information for agricultural management, stream habitat restoration and fisheries recovery planning.

Past land use can be related to the fish communities currently seen in streams (Harding at al. 1998). There is a tendency in some agricultural streams for fish species that depend on streambeds for spawning or foraging to be replaced by species that occupy the water column or are able to clean sediments from their nests. Alternatively, exotic species — such as the bottom-foragers common carp, fathead minnows and catfishes — may invade degraded streams. There is little specific information on the responses of fish in California rangeland streams to land-use practices.

Thermal refugia

The temperature requirements of salmonids vary with life history stage and by species (Mihursky and Kennedy 1967). Different species have different optimal temperatures for migration, spawning, egg incubation and juvenile growth, and also different lethal-temperature criteria (Beschta et al. 1987; Thompson and Larsen 2004). Since fish are poikilothermic (cold-blooded), their metabolic rate and food needs increase with higher water temperatures. If adequate food is not available, fish will lose weight and eventually die, even if temperatures do not reach lethal levels.

A more holistic approach using a suite of interacting habitat and land-use factors would provide listed fish species with a greater chance of recovery.

Fish in some Northern California streams are known to use thermally stratified pools as cold-water refugia during hot weather (Nielsen at al. 1994). However, fish may face a tradeoff between temperature and dissolved oxygen in their use of pools. Stratified pools may have cooler temperatures at the bottom, but also lower dissolved-oxygen concentrations with increased depth (Elliott 2000). In addition to pools, fish may seek groundwater-fed locations in order to experience cooler temperatures (Ebersole et al. 2003), but since groundwater may be lower in dissolved oxygen than stream water, fish may still experience stress.

Alternatively, levels of dissolved oxygen in groundwater may be higher than those of stream water depending on how much dissolved oxygen was in the groundwater when it first entered the ground, since dissolved oxygen tends to change little once water goes underground. In their search for appropriate temperature and dissolved-oxygen levels, fish may locate farther from optimal feeding sites, or away from refuges such as large woody debris, overhanging banks or rocks. This may result in increased mortality, due to low growth rates and increased vulnerability to size-selective predation, or due to increased predation as fish spend less time in refuges in order to feed (Walters and Juanes 1993). The distribution of fish relative to thermal refugia, and the timing of this use are undocumented for most California rangeland streams, which hampers management efforts to improve fish habitat.

The upper lethal temperature limit for rainbow trout (*O. mykiss*) is generally thought to be about 75.4°F (Beschta et al. 1987). However, Zoellick (1999) found that redband rainbow trout (*O. mykiss gairdneri*) in southwestern Idaho occupied stream reaches with maximum daily water temperatures of 80.1°F to 84.2°F, and tolerated temperatures above 78.8°F for up to 4.4 hours. Flows decreased to 0 cubic feet per second (cfs) in some streams, and some of the streams subsided underground. Despite the low or nonexistent flows, Zoellick observed that pools at the lower ends of the occupied reaches did not show temperature stratification, so trout were assumed to be experiencing the observed maximum temperatures.

In some cases the downstream limit of trout distribution in these Idaho streams appeared to be limited by unsuitable habitat (e.g., no water or very shallow braided stream channel), but in one case flows and channel conditions appeared to be suitable, so trout may have been limited by temperatures in excess of 84.2°F. It is not known whether California native fish such as rainbow trout are able to tolerate similar conditions in Central Valley streams. Little is known about the specific temperature tolerances of rainbow trout/steelhead and salmon in the Central Valley. (Rainbow trout and steelhead are the same species, *O. mykiss;* however, steelhead migrate to the ocean, while rainbow trout spend their entire life cycle in freshwater.)

Myrick and Cech (2004) did a comprehensive review of the published information available for the effects of temperature on juvenile Central Valley Chinook salmon (*O. tshawytcha*) and steelhead. They looked at survival of eggs, alevin and juveniles, as well as juvenile growth rates, and reported that the number of published studies was "surprisingly low." They reported that survival of eggs declined above 54°F for Chinook salmon, but they found no published, peer-reviewed studies on the effects of temperature on Central Valley steelhead eggs and alevins. The thermal tolerance of juvenile Chinook to chronic elevated temperatures is believed to be approximately 75°F, but no studies of this sort have been conducted on Central Valley steelhead.

Furthermore, no published data was available regarding the thermal tolerance of Central Valley Chinook to acute temperature elevation, which is dependent on the temperature to which a fish is first acclimatized, and such peer-reviewed data was also unavailable for Central Valley steelhead. The growth rate of juvenile Chinook salmon in the studies reviewed was optimal from 63°F to 68°F, with slower growth outside of this range. Myrick and Cech (2005) studied the growth rates of juvenile steelhead obtained from Nimbus State Fish Hatchery at 52°F, 59°F and 66°F. They found that the steelhead growth rates were highest at 66°F, but

Glossary

Alevin: A fish that has just hatched from the egg. In the case of salmon and trout, the alevin lives in the gravel at the bottom of the stream until it absorbs its yolk sac and is ready to emerge and begin foraging.

Assemblage: A group of species commonly found together in the same habitat area, such as a stream, lake or estuary. Species within an assemblage may share some habitat preferences, such as water temperature or velocity.

Julian day: The day of the year, from 1 to 365 (366 in a leap year).

Rainbow trout/steelhead: Fish of the species *Oncorhynchus mykiss*. Rainbow trout live their entire life cycle in freshwater. Steelhead are the anadromous form; they migrate to the ocean to feed and grow, then return to freshwater to spawn.

Refuge: Location (e.g., under a log, rock or undercut bank) where fish can escape from the risk of mortality due to predators such as birds, otters or larger fish.

Refugia: Isolated location in which fish are able to survive during times when most of the surrounding habitat has become unsuitable (e.g., due to high water temperatures).

Thermal stratification: A gradation of temperature, warm to cool, from top to bottom in a pool or lake, that occurs during summer months. Increases in flow or wind may mix the water to an even temperature throughout, disrupting the stratification.

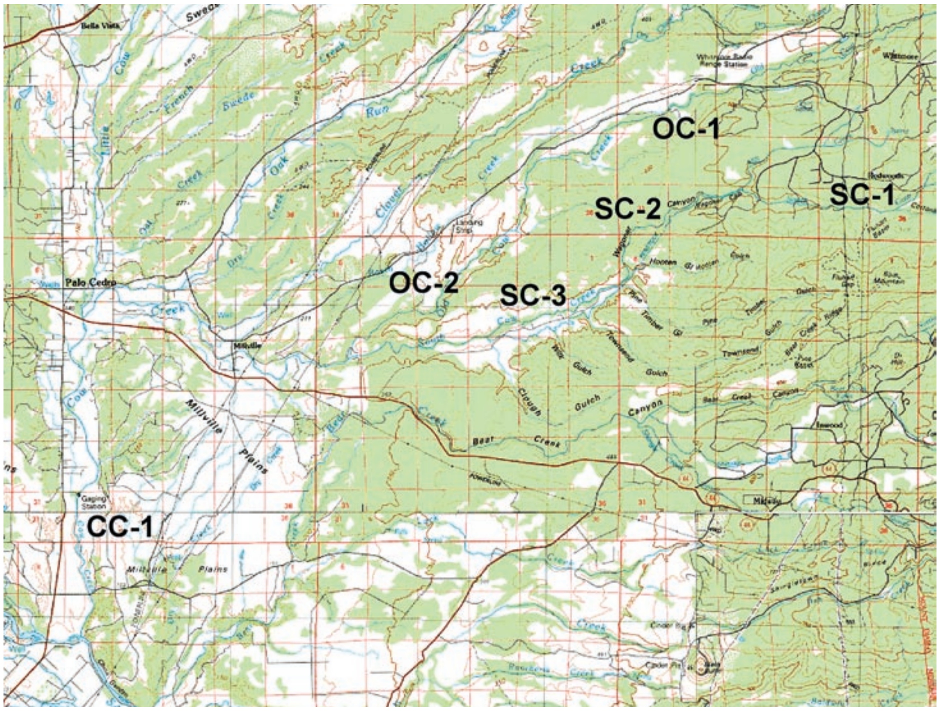
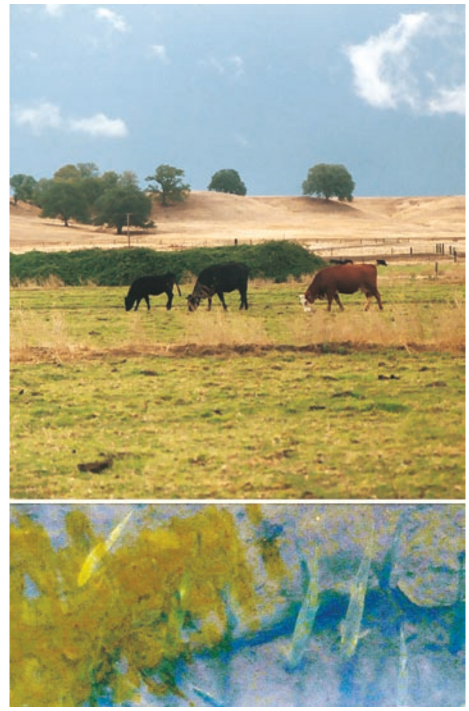


Fig. 1. Sampling sites on Old Cow Creek (OC-1, OC-2), South Cow Creek (SC-1, SC-2, SC-3) and the mainstem of Cow Creek (CC-1).



***Top*, cows graze near Cow Creek; *above*, trout in a pool in Old Cow Creek in midsummer.**

noted that the study did not test higher temperatures.

Stream biodiversity and exotics

Historically, native fish in Central Valley streams were distributed in a series of assemblages according to elevation (Moyle et al. 1998). Cold-water fish such as rainbow trout, riffle sculpin (*Cottus gulosus*) and speckled dace (*Rhinichthys osculus*) were found at mountain elevations (above approximately 1,800 feet) (Moyle 2002), and down into the upper foothills (approximately 1,200 feet). Fish such as California roach (*Lavinia symmetricus*) and hardhead minnow (*Mylopharadon conocephalus*) lived at foothill elevations (approximately 300 to 1,800 feet). Fish such as Sacramento suckers (*Catostomus occidentalis*) and Sacramento pikeminnow (*Ptychocheilus grandis*) appeared in the foothills, and were also present on the valley floor (approximately 0 to 300 feet). Species tolerant of warmer water, such as Sacramento perch (*Archoplites interruptus*) and splittail (*Pogonichthys macrolepidotus*) were present on the valley floor.

The introduction of nonnative fish species is a widespread phenomenon across the United States (Rahel 2000), including California streams. Introduced fish species in California tend to prey upon or compete with native species, frequently to the detriment of native populations, particularly in environments that have been modified to be warmer, slower flowing and more nutrient-rich than normal (Moyle 2002). The modification of stream water flow and habitat may affect the interaction between native and nonnative fish species. Moyle et al. (2003) assessed fish assemblages in the Cosumnes River and found that most nonnative species were in low-elevation, agricultural sections of the river, whereas native rainbow trout were mainly at higher elevation, higher gradient segments of the river. Apparently, nonnative species were intolerant of cooler waters with faster flows. Moyle et al. (2003) suggested that the management of water to provide increased flows and cooler water would benefit native species.

Developing stream-specific data

The development and implementation of successful best management practices (BMPs) to alleviate rangeland and irrigated pasture impacts on native fish and their habitat must be based upon a clear understanding of: (1) current habitat and fish assemblage conditions; (2) how environmental factors such as temperature determine fish distribution and habitat use; and (3) how management is modifying environmental factors. With this information, stakeholders can methodically assess streams of concern, identify priority stream reaches, examine current management practices potentially affecting priority reaches, and develop first approximations of BMPs to reduce impacts.

We utilized Cow Creek in Shasta County as an example of methodologies to develop region-specific information. We attempted to determine how different fish species were distributed along the length of the creeks from higher to lower elevation; whether preferred native species such as rainbow trout use pools; whether fish distribution and the use of pools change across the summer; whether pools stratify in terms of temperature and/or dissolved-oxygen concentrations; and how fish distribution relates to environmental factors such as temperature, flow, elevation and pool characteristics.

Location and data collection. We chose six pools in the Cow Creek drainage, at a range of elevations representative of rangeland habitat in this part of the Sacramento Valley (fig. 1). We sampled temperatures at each pool continuously from May through November, by placing two temperature loggers (Onset Optic Stowaway) near the bottom of each pool, and one temperature logger in the air (e.g., attached to a tree near the pool). We measured maximum depths to estimate the cover fish would find in a given pool, and length and width to allow estimates of pool area and fish density per pool. (Structures such as overhanging banks, boulders, logs and overhanging branches may also provide cover, but the measurement of these stream features was outside the scope of this study.)

We defined the upstream boundary of a pool as the point at which water cascaded in from a higher point, or where ripples ceased and the water became flat. The downstream end of the pool was defined as the point at which riffles started again. We sampled water flow, temperature and fish, monthly from June to October. Flow was measured at the downstream end of the pool, using a handheld flowmeter (Global Water FP101). During each monthly visit we used a handheld temperature and dissolved-oxygen probe (YSI 550A) to measure these variables at the surface, middepth and bottom of the pools. We did snorkel counts to estimate fish species present, density and age class. One snorkeler moved slowly through the pool, first working upstream along one bank, then floating down the middle, then upstream along the other bank and again down the middle. Fish observed during the second pass down the middle were assumed to be repeat counts, so they were only counted if a fish of a given species and size had not been seen in the pool up to that point.

Data analysis. We analyzed our data graphically and with regression-based linear mixed-effects analysis (S-Plus version 6.1 software; Pinheiro and Bates 2000), in order to relate fish distribution and habitat use to environmental factors. Seven individual linear mixed-effects analyses were conducted to determine if there were statistically significant ($P < 0.05$) differences for the water temperature, pool depth and area, flow, and elevation of pools occupied by trout compared to pools not occupied by trout, between June and October. Linear mixed-effects analysis has distinct advantages for repeated-measures field studies such as this one, and has been used successfully to analyze other California stream data sets (Tate, Lile et al. 2005). Because we repeatedly sampled each site over the course of several months, there is a potential for codependence between observations made at each site at different times. The codependence introduced by repeated measurements of a single site through time can be efficiently addressed using a linear mixed-effects analysis.

Pool characteristics

The Cow Creek pools we studied ranged in elevation from 400 to 1,718 feet (table 1), and in surface area from 165 to 854 square yards. Maximum pool depth ranged from 3 to 7 feet, and usually occurred at the upstream end of the pool. Flows varied between pools and across the season, with lower elevation pools tending to have higher flows. None of the pools were stratified during our visits. Temperatures at the top and bottom of given pools showed differences of 0.10°F or less. Dissolved-oxygen concentrations were also similar at the top and bottom of each pool, giving further evidence that the pools were well mixed.

Dissolved-oxygen levels observed across the season ranged from 7.52 to 10.79 parts per million (ppm), well within the preferred ranged for sensitive fish such as salmonids (Bjornn and Reiser 1991); but this was expected, since we took our measurements at midday when aquatic plants produce oxygen. It is probable that dissolved-oxygen levels declined overnight, and were lowest just before dawn. An adequate supply of dissolved oxygen is important to fish, especially salmonids such as salmon and trout, during all stages of life (Bjornn and Reiser 1991; Brown 1985). The swimming ability of adult salmonids has been shown to decline at dissolved-oxygen levels less than 6.5 to 7.0 ppm. For spawning fish, dissolved-oxygen levels should reach at least 80% saturation with temporary levels no lower than 5.0 ppm. The growth rate of juvenile salmonids declines when dissolved-oxygen levels are below 5.0 ppm, and death occurs at less than 1.0 to 2.0 ppm of dissolved oxygen.

Fish distribution in Cow Creek

We observed fish in all pools from June to October 2003 (fig. 2a). The native fish species observed between the months of June and October were: California roach, Chinook salmon, rainbow trout/steelhead, Sacramento

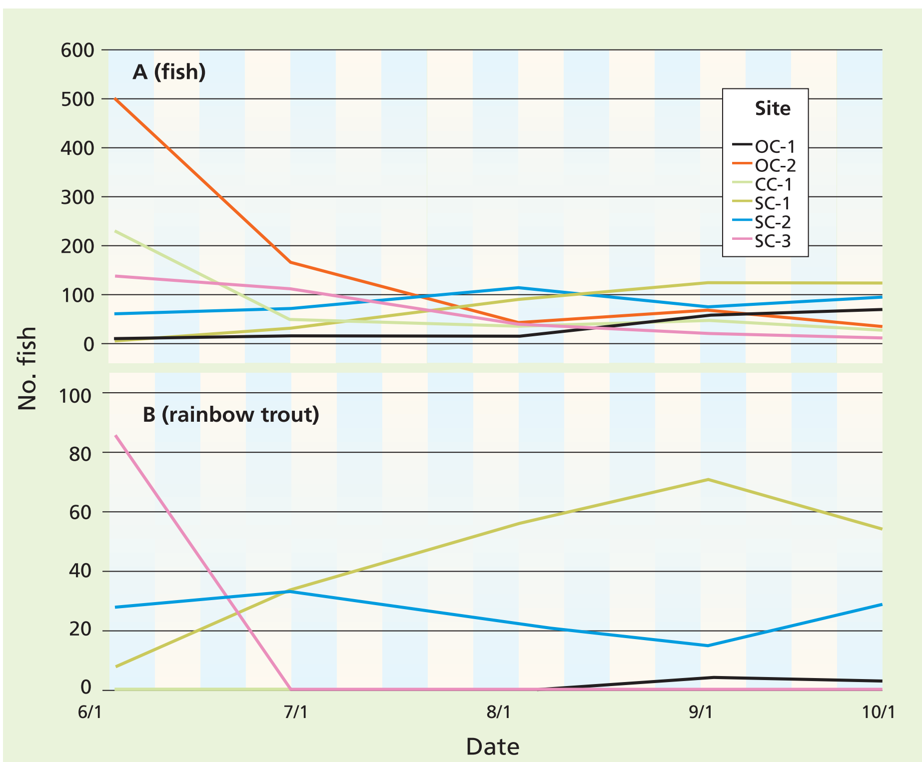


Fig. 2. Total number of (A) fish and (B) rainbow trout observed at six pools in tributaries of Cow Creek, 2003.

pikeminnow, Sacramento sucker and speckled dace. Nonnative species observed were: green sunfish (*Lepomis cyanellus*), largemouth bass (*Micropterus salmoides*) and smallmouth bass (*Micropterus dolomieu*). Chinook salmon were observed only in the fall, during their upstream spawning migration, when most irrigation diversions had ceased. Since rainbow trout/steelhead are of great interest to fishery managers, and potentially of concern to landowners who use stream water for irrigation, we focused on rainbow trout/steelhead, and grouped the rest of the species together.

The declines in fish numbers between June and July reflect the mortality of large numbers of young-of-the-year fish, likely due to predation by birds or aquatic predators (fig. 2a). Rainbow trout/steelhead were observed in at least one pool in each of the sampling visits, including the hot summer months. Trout numbers increased in higher elevation pools as the season progressed (fig. 2b). Trout density was positively correlated with Julian day ($P = 0.058$) for the period from June to October. Young-of-the-year trout emerge from the gravel in early spring, and thereafter total trout densities may be expected to decline due to mortality. The increase in trout density in higher elevation pools may indicate that trout are moving upstream toward cooler waters, or out of riffles and into pools in search of depth (cover) or food. Trout were observed in midsummer (sample visits June 30 to Sept.2) in three pools (table 1). We considered these pools to be summer temperature refugia, although the pools did not stratify.

TABLE 1. Characteristics of study pools in Cow Creek watershed

Pool	Elevation	Area	Maximum depth*	Flow min.-max.	Temp. stratification†	Trout refugia‡
	ft	*yd²*	*ft*	*cfs*	*°F*	
OC-1	1,331	339	4.0	4 –155	–0.10	Yes
OC-2	568	854	7.0	21 –170	–0.01	No
SC-1	1,718	165	4.5	29 –141	–0.03	Yes
SC-2	1,053	227	4.5	11 –57	–0.08	Yes
SC-3	614	685	3.0	32 –136	–0.10	No
CC-1	402	303	6.0	36 – 356	–0.03	No

* Maximum depth observed at lowest stream-flow conditions during study period.
† Temperature at bottom of pool minus temperature at top (°F).
‡ At least one trout was observed in the pool during midsummer observation.

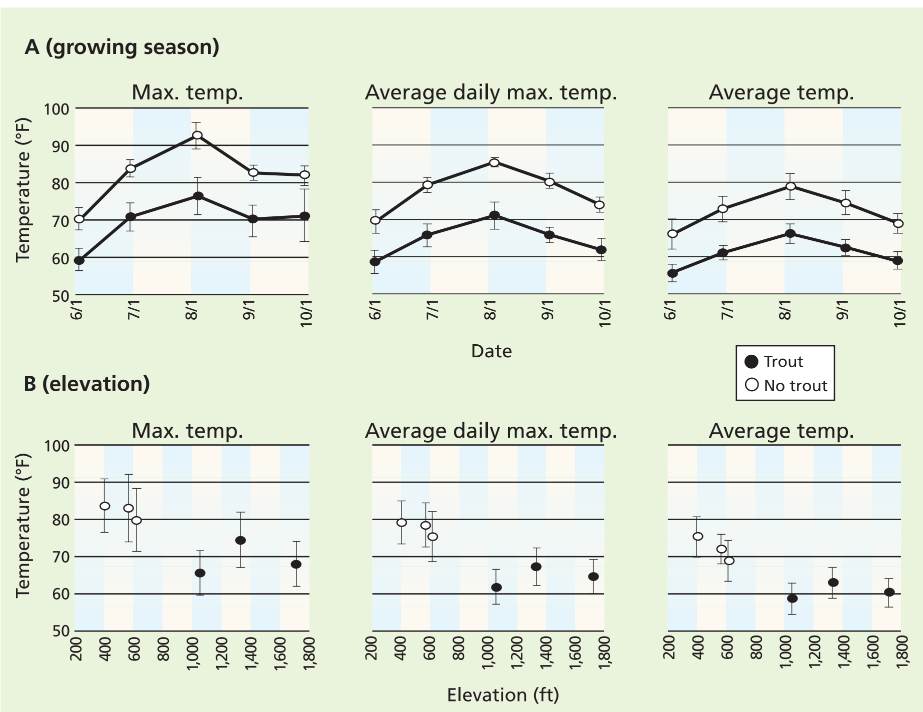


Fig. 3. Stream water temperature across (A) agricultural growing season and (B) elevation in pools in tributaries of Cow Creek, 2003. Values are grouped according to whether or not pools were occupied by rainbow trout in midsummer. Error bars are one standard deviation. Each point represents the average of five monthly samples (June to October) for one pool. Max. temp. is the highest temperature observed since the previous fish observation; average daily max. temp. is the average of the highest temperature observed each day since the previous fish observation; average temp. is the overall average temperature observed since the previous fish sampling.

Pools with trout in midsummer were cooler than pools without trout (fig. 3a, table 2). For example, the period maximum temperature for August in pools without trout in midsummer was over 90°F, while in pools with trout it was well below 80°F. This corresponds with the temperature tolerance value of 75°F for juvenile Chinook salmon. The period average temperature in pools with trout in midsummer was about 65°F in August, which corresponds to the optimal growth temperature ranges observed for juvenile Chinook salmon and steelhead.

Stream temperature was correlated with elevation (fig. 3b). Higher elevation pools were cooler and contained trout in midsummer. Pools that contained trout in midsummer contained only native fish species. Other pools contained a higher proportion of native species in spring and fall, when water temperatures were cooler.

Flows declined across the summer months, then began to increase in October (fig. 4). Flows were higher in pools with no midsummer trout, because these pools were farther downstream in the system where more tributaries, surface runoff and groundwater flow had joined the stream. This suggests that flow volume alone is not a good predictor of the presence of trout, and that other factors such as water temperature and dissolved oxygen should also be considered. In general, it is important to determine whether increased flows in lower pools reflects the return of potentially warm tailwater from irrigated pastures, a determination critical to BMP development and implementation.

For the sites on South Cow Creek and Cow Creek, water flow did not increase steadily with decreasing elevation (fig. 5). Throughout the season,

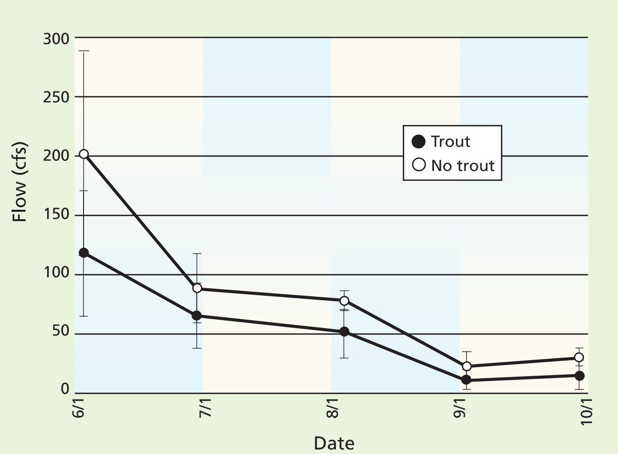


Fig. 4. Flow (cubic feet per second) across the agricultural growing season in tributaries of Cow Creek, 2003. Values are grouped according to whether or not pools were occupied by rainbow trout in midsummer.

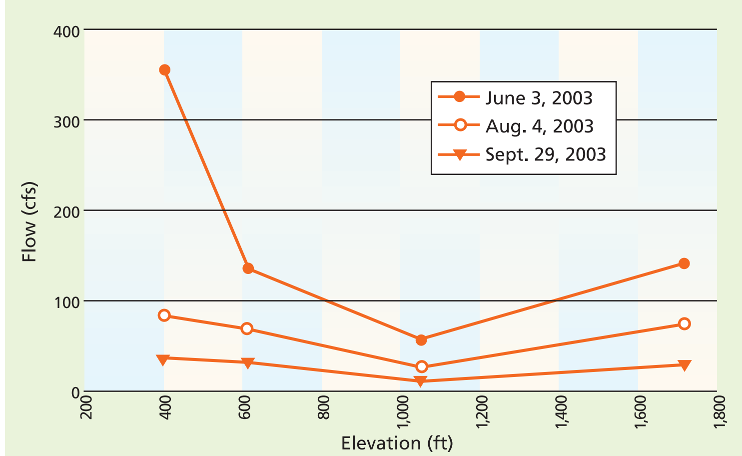


Fig. 5. Flow (cubic feet per second) and elevation on South Cow Creek and Cow Creek (SC-1, SC-2, SC-3, CC-1), June 3, Aug. 4 and Sept. 29, 2003. Flows at site SC-2 were consistently lower than flows at site SC-1, likely due to the diversion of water to the South Cow Creek Powerhouse upstream of site SC-2.

flows at site SC-2 were lower than at site SC-1, which was farther upstream. This observation is due to the diversion of water from the mainstem of South Cow Creek between sites SC-1 and SC-2, for use at the Pacific Gas and Electric Company's (PG&E) South Cow Creek Powerhouse. The water is returned to South Cow Creek between sites SC-2 and SC-3 via a PG&E canal, restoring much of the creek's volume.

Linear mixed-effects statistical analysis was done on the full data set (i.e., six pools, with five monthly visits per pool between June and October). The resulting seven models indicated that the presence of trout was negatively correlated with temperature and positively correlated with pool depth, but not correlated with pool area, elevation or flow (table 2). The model term "trout present" in table 2 can be directly interpreted as the average difference of pools occupied by trout compared to unoccupied pools.

For example, the maximum daily temperature of pools occupied by trout was 12.86°F cooler than pools not occupied by trout. Conversely, pools occupied by trout were 0.52 feet deeper on average compared to unoccupied pools. Two relatively deep pools, OC-2 and CC-1, did not have trout in midsummer, likely because temperatures were too high (table 1).

Fish and farm implications

Our study looked at fish distribution in the Cow Creek watershed across the spring-summer-fall season, roughly correlated with the agricultural growing season and the use of stream water for irrigation. The results suggest that the distribution of fish species in pools in rangeland streams varies across the growing season, and is correlated with factors such as stream temperature and pool depth. Lower elevation pools may provide habitat for cold-water species such as rainbow trout/steelhead and salmon in spring and fall, but not in midsummer when pool temperatures increase. In contrast, higher elevation pools may provide cold-water fish habitat throughout the year. It is likely that rainbow trout/steelhead populations are limited by the stream area that is habitable in midsummer, and that lengthening the part of the stream that is cold enough year-round to support cold-water species will allow populations to increase.

Since species distribution is elastic over the season, the species observed in a given pool depends on the time chosen for sampling. This phenomenon may assist in the design of habitat monitoring and fishery restoration projects where funds are limited. Midsummer is likely to be the most efficient time of year to assess the abundance, size and age composition of resident rainbow trout populations and other cold-water native species, since cold-water fish are confined to cooler (generally higher elevation) areas.

Irrigation diversions may affect pool characteristics such as flow, maximum depth and temperature. If irrigation practices tend to cause stream water temperatures to increase, it may be possible to adjust agricultural water-use practices so that tailwater is no warmer than the stream water to which it is returned. It would then be possible to extend the length of the stream that is cool enough to be habitable for trout throughout the summer, and increase the minimum habitat area available.

TABLE 2. Results of linear mixed-effects analysis to predict pool characteristics by the presence of trout

Pool characteristics	Model term	Coefficient (S.E.)*	*P* value
Max. temp. (°F)	Intercept	82.13 (2.07)	< 0.001
	Trout present	–12.86 (2.92)	0.012
Avg. daily max. temp. (°F)	Intercept	77.60 (1.43)	< 0.001
	Trout present	–13.10 (2.02)	0.003
Avg. temp. (°F)	Intercept	72.13 (1.59)	< 0.001
	Trout present	–11.46 (2.24)	0.007
Pool depth (ft)	Intercept	–0.72 (0.10)	< 0.001
	Trout present	0.52 (0.14)	0.020
Pool area (yd²)	Intercept	273.56 (70.12)	< 0.001
	Trout present	–122.08 (99.16)	0.286
Elevation (ft)	Intercept	–300.56 (72.30)	< 0.001
	Trout present	133.68 (102.25)	0.261
Flow (cfs)	Intercept	84.00 (19.46)	0.002
	Trout present	–31.93 (22.98)	0.237

* Significant coefficients for "trout present" model term are directly interpreted as the difference in pool characteristics for pools where trout are present compared to pools without trout (e.g., pools with trout averaged 0.52 feet deeper than pools without trout).

To spawn and thrive, fish have specific water temperature and flow requirements. Best management practices for irrigation can minimize adverse effects on stream habitat. Author Thompson snorkels in South Cow Creek to observe and count fish.

Preferably these management practices would be implemented without excessive costs to irrigators. Such practices would have the added benefit of reducing regulator concerns about the impacts of rangeland agricultural practices on streams and native fish.

This study provides a foundation for understanding the current conditions and relationships among stream habitat, fish distribution and habitat use, as they correspond to the period of agricultural irrigation-water extraction and return to Cow Creek. Fish habitat use and distribution is not static and is driven by factors (temperature and pool depth) that could logically be affected by stream-based irrigation diversion and return irrigation practices (Tate, Lile et al. 2005; Tate, Lancaster et al. 2005). The next focus of research on the potential linkage between irrigation management and habitat factors should be strategic stream temperature and flow monitoring of lower elevation pools. Tate, Lancaster et al. (2005) provide an example of such a monitoring strategy in similar streams in northeastern Modoc County. The results of the current study — and future studies to assess relationships between BMPs, stream temperature and flow — will allow more informed choices about which BMPs to implement and their prioritization. This should result in fewer adverse effects on stream habitat, and the avoidance of unwarranted impacts on agricultural stakeholders in the watershed.

L.C. Thompson is Assistant Specialist, Department of Wildlife, Fish, and Conservation Biology, UC Davis; L. Forero is County Director and Farm Advisor, UC Cooperative Extension, Shasta County; and Y. Sado is Postgraduate Researcher and K.W. Tate is Specialist, Department of Plant Sciences, UC Davis. *The authors gratefully acknowledge the landowner cooperators in the Cow Creek watershed who gave access to their properties for this study; Mike Berry, California Department of Fish and Game, for his advice on field protocols; and Peter B. Moyle and anonymous reviewers for reviewing the manuscript.*

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RESEARCH ARTICLE

EU support reductions would benefit California tomato growers and processors

by Bradley J. Rickard *and* Daniel A. Sumner

Many countries apply import barriers for processing tomatoes, but the European Union is the main producer that uses export and production subsidies. We modeled and measured the potential impacts on global markets and the California industry that would result from reductions in trade barriers (such as import tariffs) and subsidies for the European Union's processing tomato industry. A multi-equation simulation model showed that reducing trade barriers in Europe and elsewhere (including the United States) by 50% would raise the market price for California tomatoes by about 6%, improve net returns to California processing tomato producers by $34 million per year, and improve net returns to California tomato processors by $19 million per year. We also found that a 50% reduction in EU domestic support would improve the net returns of California producers and processors by about $8.5 million per year. Based on these results, we believe that negotiating reductions in subsidies, and especially in global trade barriers, would make economic sense for the California processing tomato industry.

California growers produced $670 million worth of processing tomatoes in 2004, making it the state's 11th most valuable crop. More than 10% of the California crop is processed into products for export, such as tomato paste and sauce.

California produces 95% of the processing tomatoes grown in the United States, and the processing tomato industry is an important component of California agriculture. Its total revenue was $670 million in 2004, ranking processing tomatoes 11th among all agricultural commodities produced in California (USDA 2005). Processed tomato products are also a major California export commodity. About $250 million of processed tomato products were exported in 2004, accounting for approximately 12% of the crop; the industry ranked eighth among California agricultural commodities in value of exports (Bervejillo and Sumner 2005).

The United States and European Union each supply approximately one-third of the world's processing tomatoes (fig. 1). There is little or no direct subsidy for processing tomatoes in the United States; however, processing tomato production is directly subsidized in the European Union with payments to growers. The EU subsidy regime for processing tomatoes is part of their overall system of subsidy, which also applies to other fruit and vegetable industries.

We investigated the consequences of EU processing tomato subsidies and global trade barriers for tomato producers and processors, especially in California. Through a simulation model, we show quantitatively how the removal of EU production subsidies would reduce EU production and exports, and raise prices in the global market. We also show that trade barriers (such as import tariffs) have even larger effects than subsidies.

The Doha Round of trade negotiations under the World Trade Organization (WTO) contained a number of proposals to reduce agricultural subsidies, lower import barriers and eliminate export subsidies on a global basis. A relevant option based on the discussions in those negotiations includes the following: eliminating export subsidies and a 50% cut in both tariffs and domestic support for agricultural commodities (WTO 2004). Our analysis shows what the California processing tomato industry can expect if these negotiations are successful in reducing EU subsidies and protection.

Support for EU industry

The EU policy for processing tomatoes includes domestic support in the form of subsidies, import tariffs and an export subsidy (European Commission 2005). The subsidies are payments tied to the production of processing tomatoes. Import tariffs are a tax applied to processed tomato products entering the European Union, and export subsidies are paid to EU processors for selected tomato products that are exported. From 1978 to 2000, EU domestic support included a complex array of direct transfers to processors (processor aid),

Model parameterization

The proportional changes in prices and quantities are functions of various elasticity and share parameters. (Elasticities are used to represent the ratio between proportional change in one variable and proportional change in another.) The price elasticities of demand for the five processed tomato products were calculated from an overall price elasticity of demand for all processed tomato products, an elasticity of substitution between processed products and consumption shares (Armington 1969). The overall elasticity was set to –0.5, and was based on estimates from George and King (1971) and Huang (1985). The elasticity of product substitution was set to 5.0, reflecting the fact that tomato products are relatively close substitutes for each other.

The consumption shares were based on per-capita-consumption rates for processed tomato products (USDA 2005). The price elasticity of supply for processing tomatoes was assumed to be relatively inelastic and was set to 0.5, based on an estimate from Chern and Just (1978). The price elasticity of the manufacturing input supply was set to 1.0. The cost share for processing tomatoes was set to 45% for tomato paste and 20% for canned tomato products (based on estimates from a survey of industry experts). We allowed for some substitution between processing tomatoes and the manufacturing input, and this parameter was set to 0.1. (A value of 0 would indicate no input substitution; for perfect substitutes, the elasticity would be infinite.) The simulation model included raw tomatoes and processed tomato products, and we used a conversion rate of 6.1 tons of tomatoes per ton of tomato paste and 1.2 tons of tomatoes per ton of canned tomato products.

The effects of alternative values of several of these parameters, especially supply and demand elasticities, were also examined to test sensitivity in Rickard (2003). Our results are robust to changes in key parameters across a plausible range, and the main results for the most likely parameter values are reported here.

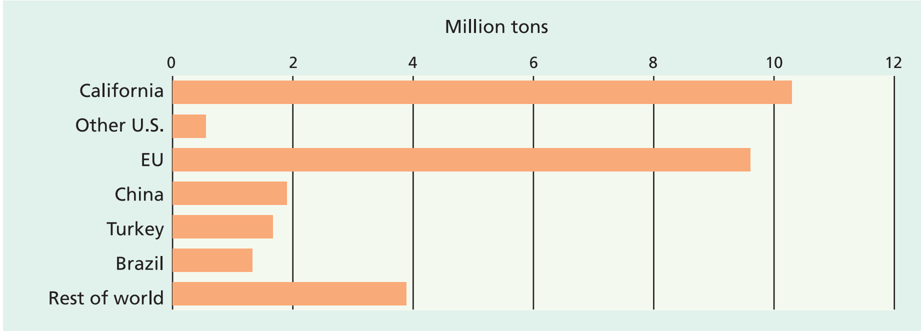

Fig. 1. Average processing tomato production globally, 1999 to 2003. Source: Tomato News 2004.

minimum prices for growers, and a quota that set a limit on the quantity eligible for the processor aid and minimum price. In 2000, processor aid was approximately $165 (€163) per ton of tomato paste; the minimum price for processing tomatoes was $81 (€80) per ton; and the minimum price was applied to approximately 7.7 million tons of processing tomatoes grown in Europe. (In January 2000, $1 was equivalent to €0.99; in January 2006, $1 was equivalent to €0.82.)

This subsidy program was changed beginning with the 2001 crop, and the changes have further stimulated EU production (Rickard 2003). Since February 2001, EU growers of processing tomatoes have received a per-ton subsidy from the European Union, as long as total EU production does not exceed the threshold limit of 9.1 million tons (8.25 million metric tons). In 2005, the subsidy rate was approximately $39 per ton and therefore, approximately 43% of per-unit revenue.

Since 2001, the EU tariff has been set at 14.4% for processed tomato products such as tomato paste and tomato sauce. The tariff rate has been reduced by one-fifth since 1995, in accordance with the Uruguay Round GATT deal, which is administered by the WTO. This tariff is refunded when the imported product is used in, or offset by, exports of processed tomato products. The European Union also allows reduced or zero tariffs for imports from selected developing countries. Export subsidies apply to certain canned tomato products, which make up a relatively small share of total processed tomato production in the European Union. For reference, the United States applies an import tariff of 12.5% to processed tomato products, and the average (nonweighted) tariff in other tomato-importing regions is approximately 20%.

The simulation model

We used an economic simulation model to assess the effects of lower EU domestic support and reduced border measures on the global processing tomato industry. There are three regions in our model: the European Union, the United States and the rest of the world. The model accommodates five processed products that are less-than-perfect substitutes for each other in consumption: (1) European Union–produced canned tomato products, (2) canned tomato products from other sources, (3) European Union–produced paste, (4) U.S. paste and (5) paste produced in other countries. In each of the three regions, two inputs (raw tomatoes and other inputs) are used in the production of these five processed tomato products. There is trade among the regions in processed tomato products but not in raw tomatoes.

The simulation model is used to perform experiments in policy reform; that is, to examine the effects that alternative policy scenarios would have on the processing tomato industry. We focus on reductions in domestic subsidies, export subsidies and tariffs. The European Union has the world's only significant program of domestic subsidies for processing tomatoes, but many countries, including the United States, have import tariffs. It is implausible that import tariffs in the European Union would fall unilaterally; therefore, we considered multilateral reductions in import tariffs across all tomato-producing regions,

TABLE 1. Simulated effects of policy changes on prices and quantities

Variable	50% reduction in: Import tariffs	EU domestic support	Import tariffs + EU domestic support
	% change		
EU tomatoes			
Grower price	1.4	–9.3	–7.9
Processor price	1.4	12.2	13.6
Quantity	0.7	–4.6	–3.9
EU processor inputs			
Price	0.8	–3.1	–2.3
Quantity	0.8	–3.1	–2.3
U.S. tomatoes			
Price	6.2	1.0	7.2
Quantity	3.1	0.5	3.6
U.S. processor inputs			
Price	3.4	0.5	3.9
Quantity	3.4	0.5	3.9

TABLE 2. Simulated effects of policy changes in the U.S. processing tomato industry*

Benefit or cost to:	50% reduction in: Import tariffs	EU domestic support	Import tariffs + EU domestic support
	change in U.S. $ millions		
U.S. tomato producers†	34.6	5.5	40.3
U.S. tomato processors	18.9	3.0	22.0
U.S. govt. budget (tariff revenue)	–2.4	–1.6	–3.2
U.S. consumers of processed tomato products	–19.8	–6.2	–24.6
Total U.S. economy	31.3	0.6	34.5

* Effects for the European Union and the rest of the world are available from the authors.

† California growers would earn more than 90% of the benefits. The gain of $34.6 million represents 6.4% of total producer revenue and a significantly larger percentage of net revenue.

combined with reductions in EU export subsidies and EU domestic support.

The simulation model used a set of equations to describe the supply and demand conditions for the processing tomato sector. Equilibrium adjustments can be simulated by specifying changes in the policy parameters, such as changes to EU domestic support or tariff rates. The model is used to simulate proportional changes in prices and quantities (and ultimately benefits or costs to producers and processors) for selected input and output markets in the processing tomato industry (see box, page 208).

Effects of policy reform

The simulation results describe how changes in EU export subsidies, global tariffs and EU domestic support would affect prices, quantities and net benefit measures, such as revenues and government expenditures. The focus is on the effects in the European Union and, especially, in California.

Export subsidies. The complete elimination of export subsidies would lower EU export tonnage by only 0.6%. The small impact of export subsidy reform is mostly attributed to the fact that the export subsidy rate is low and applies to only a small portion of total EU production. Because the impact of the EU export subsidy on the California industry is so small, the rest of our analysis focused on the effects of reductions in import tariffs and EU domestic support.

Tariffs. We found that a 50% cut in tariffs would increase the price and quantity produced in the European Union and the United States because both would export more to third markets, which begin with higher tariff rates (table 1). The price and quantity of processor-supplied inputs would also rise.

Domestic support. If EU production subsidies were cut by 50%, we found that per-unit grower returns in the European Union would fall, and market prices paid by EU processors for tomatoes would rise by 12.2% (table 1). The result is a decline in the quantity of tomatoes used and a decline in processor-supplied inputs as well. Cutting EU domestic support by this magnitude would have positive effects in the United States.

Import tariffs and domestic support. If the European Union cut production subsidies and all countries cut tariffs, there would be an increase in the price paid for tomatoes and a decrease in the price received by growers in the European Union (table 1). Reducing global tariffs and EU subsidies together would raise prices and quantities in the United States.

Benefits to U.S. producers and processors. The changes in prices and quantities (table 1) were then used to calculate changes in net producer revenues, net government expenditures or tariff revenues, and consumer benefits from tomato consumption in the United States (table 2). The annual net benefits to producers and processors from cutting the domestic subsidy in the European Union would be $5.5 million per year for U.S. growers and $3.0 million per year for U.S. processors.

The reduction in tariffs on a global basis would have a significantly larger effect on tomato producers and processors in the United States. The benefit to U.S. producers of tomatoes would be approximately $34 million per year, with about $32 million per year of that for growers in California. The increase in benefits to U.S. processors would be approximately $19 million per year, with almost all of that amount again benefiting California processors. Benefits to tomato producers and processors would total $53.5 million per year. Part of this net revenue increase would come from U.S. markets and part from additional export revenue. The cost to U.S. consumers from higher prices for U.S. tomato products would be about $20 million. The United States would also lose $2.4 million in tariff revenue, so the net gain for the United States would be about $31 million per year.

Negotiating reductions in subsidies, and especially in global trade barriers, makes economic sense for the California processing tomato industry.

Implications for the U.S. industry

Farmers and processors in the United States would benefit more from reductions in import tariffs than from reductions in EU domestic support, even though that would also mean reductions in the U.S. tariff. However, reductions in import tariffs would place pressure on the EU domestic support regime. Reducing import tariffs would increase the production of tomatoes

Morning Star Company

If the European Union reduced its trade barriers for processing tomatoes by 50%, California producers and processors stand to gain an estimated $53.5 million annually.*

in the European Union, and thereby increase the taxpayer cost of the EU domestic support regime. This would place additional pressure on EU budgets that could lead to reductions in subsidies as a response.

Producers and processors in the United States would gain about $8.5 million annually from a reduction in the EU subsidies, and the gain from tariff elimination would be even larger. This result of the simulations may seem surprising, because the initial tariff is only 14.4%, while the subsidy is 43%. The relative magnitude of the two impacts is driven by three factors.

First, the supply response of processing tomatoes in the European Union to lower per-acre returns (including policy benefits) is relatively inelastic in the intermediate time-frame because — for this analysis, and in the context of trade negotiations — we envision reductions in support for processing tomatoes as part of a larger, multicommodity package. Second, EU domestic support applies to the farm-produced product, and import tariffs apply to processed products. The farm product represents only 45% of the cost of tomato paste and 20% of the cost of canned tomato products, and barriers that apply at the border have bigger effects on trade than do subsidies for raw materials that are inputs to the tradable product. Third, the EU domestic support program drives a wedge between the price that growers receive and the price that processors pay for tomatoes. Reducing EU domestic support would reduce that wedge, and the burden of any reduction would be shared between the grower and processor.

Effects of trade negotiations

Trade negotiations have the potential to reduce trade barriers and farm subsidies on a global basis. The California processing tomato industry has long been concerned with subsidies and import barriers in the European Union. Our research shows that this interest is well placed, and although the effects of domestic subsidies are significant, to increase net returns the negotiations should emphasize trade barriers more than domestic subsidies in Europe. We also show that the California processing tomato industry would receive considerable benefits from global tariff reductions, even though that would mean giving up some of its own protection from imports.

B.J. Rickard is Assistant Professor, Agribusiness Department, California Polytechnic State University, San Luis Obispo; and D.A. Sumner is Director, UC Agricultural Issues Center, and Frank H. Buck, Jr., Chair Professor, Department of Agricultural and Resource Economics, UC Davis.

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* Photo at left added postpublication, 10/6/06.

Weather-based yield forecasts developed for 12 California crops

by David B. Lobell, Kimberly Nicholas Cahill, *and* Christopher B. Field

Crop-yield forecasts provide useful information to growers, marketers, government agencies and other users. Yields for several crops in California are currently forecast based on field surveys and farmer interviews, although official forecasts do not exist for many crops. Because broad-scale crop yields depend largely on the weather, measurements from existing meteorological stations have the potential to provide reliable, timely and cost-effective predictions. We developed weather-based models of statewide yields for 12 major California crops and tested their accuracy using cross-validation from 1980 to 2003. Many of the weather-based forecasts were highly accurate, as judged by the percentage of yield variation explained by the forecast, the number of yields with correctly predicted direction of yield change, or the number of yields with correctly predicted extreme yields. The most successfully modeled crop was almonds, with 81% of yield variance captured by the forecast. Predictions for most crops relied on weather measurements well before harvest time, in many cases allowing longer lead times than existing procedures.

Weather-based yield predictions were developed for 12 major California crops, based on more than 20 years of daily weather records and actual yield data. The highest correlation between weather and yield was seen in almonds.

Forecasts of crop yields can provide important information about commodity markets and are frequently used by growers, industry and government to make decisions (Vogel and Bange 1999). For instance, growers may use forecasts to plan their harvest, storage and distribution strategies: California growers used the 2004 forecast of a large rice harvest to arrange greater storage capacity, and used a 2005 forecast of reduced almond production to allocate limited quotas among preferred customers (D. Flohr, CASS, personal communication). Similarly, industries involved in handling and trading commodities often use information on future harvests to make logistical decisions (Hammer et al. 2001).

Each year, the California Agricultural Statistics Service (CASS) estimates the size of the coming harvest for various major California crops, including almonds, grapes, olives, oranges and walnuts (NASS 2005a, 2005b). These estimates are categorized as either subjective or objective. The former are based on phone interviews with hundreds of farmers to assess their opinions of crop development, and the latter are based on field samples taken from hundreds of fields. Forecasts are generally made public 1 to 3 months before the end of harvest (NASS 2005a).

It is common knowledge that one of the main factors causing yields to change from year to year is climate variability — no two growing seasons experience exactly the same weather. Indeed, grower expectations of crop yields are likely to be based at least partially on subjective weather observations and perceived relationships between weather and yields. To our knowledge, objective, quantitative weather measurements are not currently used in existing yield-forecast procedures. Such an approach would be attractive because yields could potentially be forecast at lower cost, with greater accuracy and longer lead times.

Building forecast models

To test the ability of weather measurements to forecast crop yields prior to harvest, we studied the statistical relationships between historical weather

TABLE 1. Economic value and national importance of production for crops studied

Crop	2003 value*	U.S. production
	$ millions	%
Grapes, wine	1,828	96
Lettuce	1,634	88
Almonds	1,506	99
Strawberries	973	83
Grapes, table	953	91
Hay	950	12
Oranges	949	22
Cotton	774	10
Tomatoes, processing	571	95
Walnuts	434	99
Avocados	402	95
Pistachios	173	99

* Values are taken from CASS (2004a), and are based on free-on-board (FOB) prices that include value-added items such as packing and inspections.

Yields could potentially be forecast at lower cost, and with greater accuracy and longer lead times.

TABLE 2. Months and weather variables* used for yield forecasts

	Year prior to harvest					Year of harvest								
Crop†	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Grapes, wine		ppt							tmn		ppt			
Lettuce			tmx				tmx		tmx					
Almonds						ppt	tmn							
Strawberries				all										
Grapes, table			ppt			ppt			tmn			tmn		
Hay							ppt				ppt			
Oranges					tmn					ppt				
Cotton										tmx	tmn			
Tomatoes, processing									tmx		tmx			tmn
Walnuts				tmx			ppt							
Avocados	tmx		ppt							tmn				

* tmn = average minimum temperature; tmx = average maximum temperature; ppt = total rainfall; all = all three variables.
† No weather variables are shown for pistachios, which were modeled using only previous years' yields.

and crop-yield records. We selected 12 crops (wine grapes, lettuce, almonds, strawberries, table grapes, hay, oranges, cotton, processing tomatoes, walnuts, avocados and pistachios) that are among the most valuable in California (table 1) (CASS 2004a), and obtained state yield data for 1980 to 2003 from California county agricultural commissioners (CASS 2004b). Several crops have exhibited significant positive yield trends since 1980 due to management and cultivar changes, so we removed a linear trend from each crop to produce a time series of yield anomalies, or departures from expected yields. A positive anomaly indicates yields higher than expected based on time trends, and a negative anomaly indicates yields lower than expected.

Daily weather records for the same period were obtained for 382 stations throughout California from the California Climate Change Center at the Scripps Institution of Oceanography (M. Tyree, staff scientist, personal communication). The average daily minimum and maximum temperature and precipitation for each month in each county were then computed, resulting in a monthly time series of three variables for 24 years. For each crop, a statewide monthly time series for each meteorological variable was calculated by weighting each county by the relative area of the crop in that county in 2003 (Lobell et al. 2006).

The weather and yield data were then combined in linear regression models to test how well yield anoma-

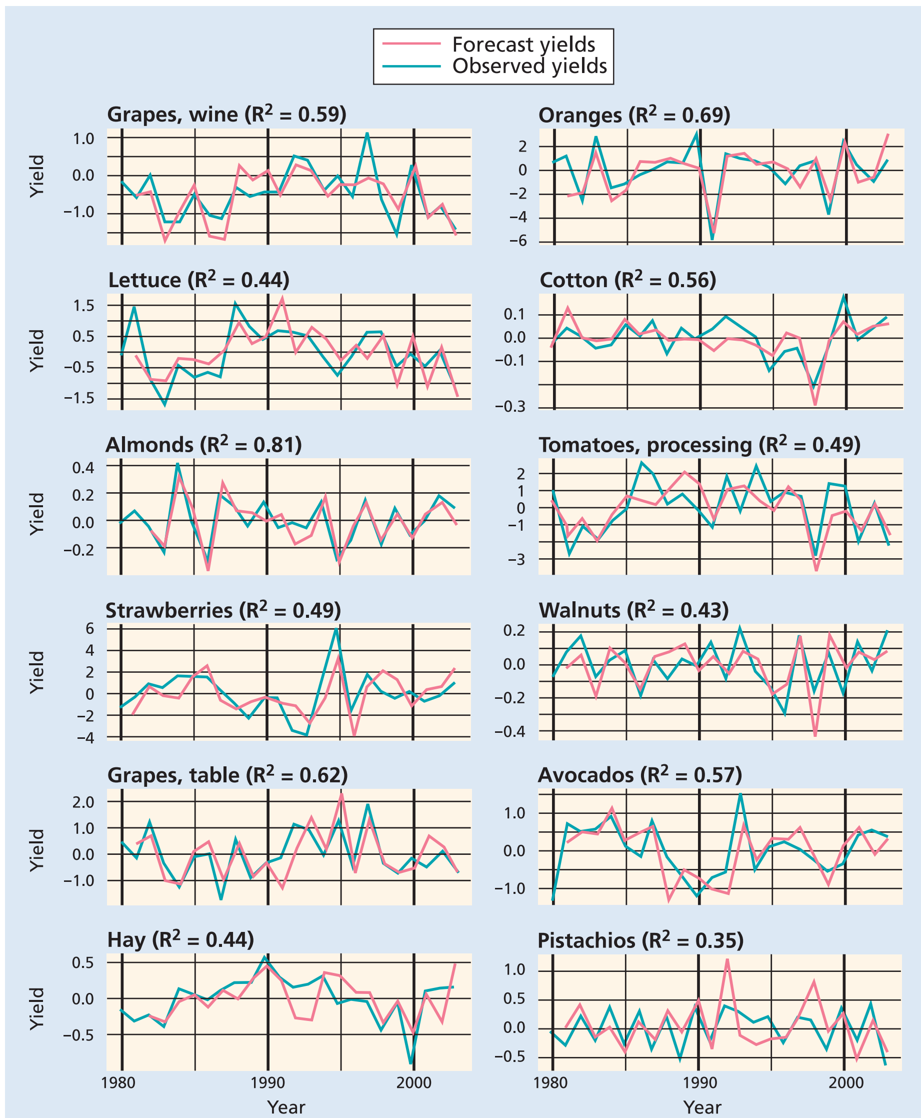

Fig. 1. Observed and forecast yields from 1980 to 2003. Forecasts were derived for each year using a model fit to data in all other years. Coefficient of determination (R^2) between observed and forecast yields is shown for each crop.

TABLE 3. Summary of forecast accuracy and timing for crops evaluated

Crop	R^2cv*	RMS† (%)	R^2 using only previous yields‡	Fraction yrs. with forecast in correct direction	Last month used in forecast	Month of USDA forecast§	Peak harvest period	Months between forecast and harvest end
Grapes, wine	0.59	6.4	n/a	0.61	June	July–August	August–October	4
Lettuce	0.44	4.0	n/a	0.61	April		Continuous	—
Almonds	0.81	7.8	0.17	0.73	February	May (subjective); June (objective)	August–October	8
Strawberries	0.49	4.6	n/a	0.48	Previous November	April	Continuous	—
Grapes, table	0.62	6.7	n/a	0.61	July	July–August	July–September	4
Hay	0.44	3.9	0.01	0.55	June	August	March–November	5
Oranges	0.69	8.8	0.22	0.68	May	Navel: September; Valencia: March	November–May; May–Oct¶	6
Cotton	0.56	6.3	n/a	0.54	June	June–August	October–December	6
Tomatoes, processing	0.49	3.1	n/a	0.67	September	May and September	June–November	2
Walnuts	0.43	7.3	0.06	0.57	February	September	September–November	9
Avocados	0.57	16.7	n/a	0.70	May		Continuous	—
Pistachios	0.35	27.5	0.42	0.70	n/a	August	September–November	—

* R^2cv: Cross-validated R^2, the proportion of yield variance explained by the weather predictor variables.
† RMS: Root mean squared difference between forecast and observed yield, expressed as a percentage of average yield for 2000 to 2003.
‡ Only crops that exhibited alternate bearing were modeled with previous years' yields.
§ Available in California Crop Production Reports (www.nass.usda.gov/ca).
¶ The first period refers to navel orange harvest and the second to Valencia oranges.

lies could be predicted before harvest based on monthly weather measurements. Between two and four weather variables were selected for each crop, based on a combination of objective (good model accuracy) and subjective (physiologically reasonable) criteria (table 2). Because temperature and precipitation can have a nonlinear effect on yields, with yields maximized at intermediate values, we included the squared values of the weather variables in the regression model along with the variables themselves. For crops such as pistachios that are known to exhibit alternate bearing, with years of high reproductive growth (high yields) alternating with years of high vegetative growth (low yields), yield anomalies from previous years were also included in the model. The total number of predictors — including the weather variables, squared variables and previous years' yields — ranged from four to eight. (The model equations are omitted for brevity, but can be obtained from the authors.)

An important step in building statistical models is to independently test model predictions, because tests using the same data that was used to calibrate the model tend to be overly optimistic (Hastie et al. 2001). The straightforward approach of reserving part of the data during model calibration, however, is problematic when the quantity of data is limited. An alternative approach, which we employed here, is "leave-one-out" cross-validation. In this approach, a single year is left out of the calibration step and subsequently compared to model predictions in that year. This comparison is done for each year, in this case resulting in 24 comparisons between model predictions and observations.

Forecast accuracy

The results of the cross-validation analysis suggest that yields of some crops can be forecast with fairly high accuracy based on objective weather measurements (fig. 1; table 3). For many crops, the model forecasts captured close to or more than 50% of the variability in yield anomalies, meaning that the selected weather variables explained over half of the variations observed in crop yields. Interestingly, the models did fairly well at forecasting extremely low yields, such as almonds in 1995, oranges in 1991, and processing tomatoes and cotton in 1998 (fig. 1). Almonds were particularly well modeled, with over 80% of variance captured by the model.

For a few crops, some of the power of the models came from knowing the previous year's yield (table 3). For instance, including weather information did not improve the pistachio model, where the biological pattern of alternate bearing seemed to dominate effects on yield more than any weather signal. For all other crops, however, most or all of the predictive power came from weather variables.

As an alternative measure of forecast skill, we considered the fraction of years in which the model correctly predicted the direction of yield anomoly (table 3). That is, we examined the frequency with which the model correctly predicted whether the yield would be above or below the trend. For a random forecast, this statistic has a distribution whose mean is 0.5 and whose 90th percentile is 0.625 for a 24-year record (15 out of 24 years). Six of 12 crops had a forecast with skill greater than a random forecast using this criterion and significance level. Three others (wine grapes, table grapes and lettuce) fell slightly below this value.

Another criterion is the ability of forecasts to correctly predict unusually high or low yields, which is of particular interest to many forecast users. For each year, both the forecast and the actual yield were classified into one of four classes: below one standard deviation (SD) from zero, between minus one SD and zero, between zero and one SD, and above one SD from zero. The first and fourth of these classes represent unusually low or high yields, respectively, and the middle two represent more moderately negative or positive years. We then computed the number of years when the forecast correctly predicted the yield class, was off by one class (in either direction), two classes or three.

Most crops did not exhibit any years when the forecast was off by more than one class. There were some exceptions; for example, lettuce yields in 1981 were forecast to be slightly negative but were actually very high (above one SD), and the reverse was true for hay in 1995. Overall, the forecasts were usually no more than one class off. Most of the cases discussed above — where the forecast predicted an anomaly in the wrong direction — corresponded to years with moderate yields, so the forecast was in fact not far from the observed yield. None of the crops exhibited any years with a forecast error of three classes.

To test the significance of these class accuracies, we performed 1,000 simulations using two 24-year, random-noise variables with a normal distribution. The average percentage of years with an error of zero, one, two or three classes was 28%, 45%, 22% and 5%, respectively. Only 10% of the simulations had more than 40% of years (10 out of 24) classified correctly by chance, while all crops except strawberries, pistachios and walnuts met this criterion. This indicates that the forecast accuracies for most of the crops were statistically significant by this measure.

It is well known that climate is an important factor influencing crop yields from year to year. Weather-based yield forecasts can be developed at lower cost than field surveys, and with longer lead times. *Above*, a weather monitoring station.

Importance of timing

Forecast timing can be as important as accuracy. A "forecast" made after harvest, for example, would not be very valuable. Most of our models are capable of providing forecasts at least several months before the end of harvest, giving growers and others an opportunity to use the information to make decisions (table 3). For instance, our models for almonds and walnuts relied mainly on winter weather, while harvest does not begin until late summer.

We compared the times that our modeled yield predictions could be made available to growers with the times that currently available USDA forecasts are released (table 3). The two approaches were similar for wine grapes, table grapes and cotton, and existing forecasts were available 4 months earlier for processing tomatoes than our models. However, our models offer significant timing advantages over existing forecasts for almonds (3 to 4 months earlier than current forecasts), hay (2 months earlier), strawberries (5 months earlier) and walnuts (7 months earlier).

Potential improvements

The current analysis was limited to only a dozen of the many crops grown in California and considered only statewide yields. We chose to aggregate several crops over different subcrop groupings, such as by combining varieties of hay and lumping navel and Valencia oranges together. In addition, we used only monthly averages of three meteorological variables (number of frost days per month was also considered, but did not substantially improve any of the models).

These decisions reflect an explicit desire to test forecasts of state yields for major crops using commonly reported climatic data. However, data for many additional crops is currently available at both state and county levels, as are additional weather measurements at time scales from hourly to monthly. Open questions are how well other crops can be modeled and whether different scales of analysis and meteorological indices would substantially improve forecast accuracies. Additional information such as remote sensing data might also aid predictions.

It is also possible that different model formulations could improve results. For example, in certain situations, process-based models that rely on a mechanistic understanding of crop growth and yield may outperform statistical models such as the ones developed here, which are derived from observed relationships without explaining the mechanisms causing the relationships. Alternative statistical approaches to the multiple linear regression that we used may also improve accuracies. (For example, we tested the use of regression trees, which did not perform as well.) Whether these more sophisticated approaches offer worthwhile improvements can be tested only on a case-by-case basis, using actual observations and well-defined criteria for an ideal forecast.

Weather promising for forecasts

The models developed in this study are promising for forecasting statewide crop yields based on weather measurements. Because the significance levels for the models depend on specified performance criteria, the eventual value of such forecasts will depend on the acceptable types and magnitude of errors for particular applications. The potential to forecast yields also depends on crop type. In general, almonds had significantly greater forecast accuracies than the other crops that we considered. Because almonds are California's most valuable export crop and account for over 80% of global almond production (Almond Board of California 2004), such forecasts could be of great relevance to almond trade and management decisions. For example, an almond grower could have used data on January rainfall and February nighttime temperatures to correctly predict the low yield in early March 1995 and adjust cultural or marketing practices accordingly, well before the forecasts from USDA became available in May and June.

Although field-based surveys are likely to be more accurate than weather-based forecasts, it is important to consider the tradeoff between forecast accuracy, cost and timing. The low cost and long lead times that are possible with weather-based models would likely provide a useful complement to existing approaches for crops that are currently surveyed. For crops that are not currently forecast by USDA, such as avocados, these models present an opportunity to develop forecasts with minimal cost by using existing weather measurements.

D.B. Lobell is Lawrence Research Fellow, Energy and Environment Directorate, Lawrence Livermore National Laboratory; K.N. Cahill is Ph.D. Candidate, Department of Global Ecology, Carnegie Institution, Stanford, Calif., and Interdisciplinary Graduate Program in Environment and Resources, Stanford University; and C.B. Field is Director, Department of Global Ecology, Carnegie Institution, Stanford. *The authors are grateful to Mary Tyree for providing the climate data, Doug Flohr for information on current forecast applications, and anonymous reviewers for comments that improved the manuscript. Funding for this work came in part from an Environmental Protection Agency (EPA) Science to Achieve Results (STAR) Graduate Fellowship to D.B. Lobell; a David and Lucile Packard Foundation Stanford Graduate Fellowship to K.N. Cahill; and the Office of Science, Biological and Environmental Research Program (BER), U.S. Department of Energy (DOE), through the Western Regional Center of the National Institute for Global Environmental Change (NIGEC). This work was performed under the auspices of the DOE National Nuclear Security Administration, by the UC Lawrence Livermore National Laboratory, under contract No. W-7405-Eng-48.*

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COMINGUP

Ralph L. Phillips

Blue oak regeneration and survival

Blue oak trees are a valuable economic and aesthetic resource in California oak woodlands, which provide some of the richest wildlife habitat in the state. However, their current regeneration rates may not be adequate to replace mortality, due to a variety of factors. In some regions, the regeneration of blue oak is limited by the ability of seedlings to survive long enough to become larger saplings. Two related, long-term studies by UC researchers examine the growth of blue oak seedlings and the effect of exclosures — which protect seedlings from livestock and wild-animal grazing — on their survival.

Also:

Coyote lure operative device revisited

Size trends in fresh-market peaches

Evaluating quality control in the packingshed

Editor's note: In honor of our 60th anniversary, *California Agriculture* has been publishing excerpts from past issues. Thirty years ago, *California Agriculture* was a mostly black-and-white, monthly, 16- to 24-page magazine, with a smattering of color photos and inks on the cover and inside. A timeline celebrating the journal's 60 years is on page 174.

The early 1970s were a time of increased oversight and scrutiny for agriculture. The U.S. Environmental Protection Agency was formed in 1970 with broad powers to regulate land, air and water; Jim Hightower published a widely read report on land-grant colleges, "Hard Tomatoes, Hard Times"; and Ralph Nader's consumer movement was increasingly influential. Editorials in *California Agriculture* by **J.B. Kendrick, UC vice president for agricultural sciences,** reflected these new realities. For headlines from 1976, go to http://California Agriculture.ucop.edu.

Accentuating the Positive (February 1976)

Often it has been said that agriculture has a poor image, that it talks to itself instead of delivering its message to the urban majority, and that it is the only major U.S. industry without an effective public relations program directed to the ultimate consumer. We have a story to tell — a factual, positive story of an industry that is indispensable to the welfare of every citizen. I submit that now is the time to get off the defensive and accentuate the positive!

Because it is large and complex, agriculture is like the elephant being examined by blind men. The public's concept of it may depend on the part of it with which they have had contact. We must accept that environmentalism and consumerism are here to stay, and welcome the interest of a wide variety of previously uninterested individuals, organizations, and agencies.

Hard Tomatoes and Hardy Myths (March 1976)

A myth, according to one of Webster's definitions, is "an ill-founded belief held uncritically especially by an interested group." There is a growing body of mythology concerning our food supply which seems to fit Mr. Webster's definition. Its general theme is that those responsible for our food supply, including the agricultural scientists and land-grant universities, have devised a system to drench soil and crop plants and embalm meat animals with harmful chemicals later reinforced by a deadly array of additives and preservatives. All of this provides us with food that is tasteless, expensive, poisonous and nutritionally deficient, and best exemplified by the tomato which has been designed with the performance characteristics and taste of a tennis ball.

Our Client "The Consumer" (June 1976)

Our diet and our lifestyle have been transformed because we have sought new ways to make nature work for us. Scientific, agricultural and food research has freed us from problems of survival and food preparation and done wonders for the American menu. What has been accomplished has been one of the most successful, but little recognized consumer movements the world has ever known. It must be admitted that consumer benefits have evolved largely as the by-product of the free enterprise system and the necessity for agriculture to remain economically viable in the face of rising costs. But nevertheless, the final participant in the food complex system — the consumer — is the one who benefits most.

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http://CaliforniaAgriculture.ucop.edu

ANR UNIVERSITY of CALIFORNIA

calag@ucop.edu
Phone: (510) 987-0044
Fax: (510) 465-2659