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California Agriculture

Native bees enrich urban gardens

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

Focus on the future: *Implementing the ANR strategic vision*

Daniel M. Dooley
UC Sr. Vice President, External Relations; Vice President, Agriculture and Natural Resources

Twelve months ago I wrote in this journal (July-September 2009, page 82) that California is changing rapidly. In describing the pressing issues facing our state, I noted that cutting-edge research, new technologies and practical information from the UC is solving many of these problems and making a real difference in the lives of Californians.

But I also challenged colleagues in UC and the Division of Agriculture and Natural Resources (ANR) to "prepare for the future as diligently as we have fostered progress in the past." This call to action was answered last summer with the appointment of a 10-person ANR strategic planning steering committee co-chaired by UC Regent Fred Ruiz and me.

The steering committee embarked on the first phase of a demand-driven, long-range planning process in August 2008 to engage the ANR community, our stakeholders and our partners in creating the comprehensive *ANR Strategic Vision*, which anticipates the complex challenges facing California through 2025, identifies where UC research and extension can make a difference, and analyzes our current capacity to address these priorities and challenges.

My expectations for completing phase one were extremely ambitious — produce a comprehensive strategic visioning document in under 9 months — but everyone in ANR stepped up to help us reach this goal. The first task was to commission five working groups, comprised of ANR academics, staff and external stakeholders. Their charge was to develop white papers assessing the future of the demographics and structure of California, agriculture and food systems, natural resource systems, health and human nutrition systems, and human development trends affecting youth, families and communities. The working groups drew on scientific literature and surveyed leaders in their respective issue areas to document what California would look like in 2025. An independent consultant surveyed opinion leaders on the major challenges and issues facing California and assessed their views of the university's strengths and weaknesses.

The white papers and surveys, completed in early December 2008, were synthesized into a draft strategic vision document by the ANR Program Council, which includes the executive associate deans from the four Agricultural Experiment Station colleges, Cooperative Extension regional directors and statewide program leaders. The steering committee reviewed the draft in late January 2009, then circulated it to external stakeholders and the ANR community over the next 2 months, which resulted in significant additional input.

In mid-April 2009 the final draft of the *ANR Strategic Vision* was approved by the steering committee. Later that month more than 600 ANR campus- and county-based academics and staff attended a statewide conference to review the visioning document and begin discussions around the creation of an implementation plan.

The strategic vision identifies nine multidisciplinary, integrated initiatives where UC research and extension has a high probability of making a real difference for Californians through providing the scientific and technological breakthroughs our residents will need to compete in a global economy; ensure a safe, nutritious food supply; conserve natural resources; and improve health outcomes. The initiatives focus on:

- Improving water quality, quantity and security.
- Enhancing competitive, sustainable food systems.
- Increasing science literacy in natural resources, agriculture and nutrition.
- Maintaining sustainable natural ecosystems.
- Enhancing the health of Californians and California's agricultural economy.
- Promoting healthy families and communities.
- Ensuring safe and secure food supplies.
- Managing endemic and invasive pests and diseases.
- Improving energy security and green technologies.

When we began this process last summer, we anticipated taking another year to engage the ANR community and stakeholders in formulating next steps and developing an overarching strategy for implementing the *ANR Strategic Vision*. But these are unprecedented times for UC, California and the nation. The California Department of Finance projects a $24.5 billion shortfall in state general fund revenues for fiscal year 2009-10, and we will be accelerating our timelines to plan for inevitable cuts in state and county funding. Over the next few weeks we will be appointing ANR review teams to explore alternative models and options for maintaining UC Cooperative Extension–county partnership agreements; identify new opportunities for achieving greater efficiencies in statewide special programs, research and extension centers and other support units; and recommend administrative reductions.

Once we have addressed these budget cuts, I expect ANR to have a different look in terms of program delivery, support units and administration. While our strategic planning process will not make today's tough budget decisions any easier, we are fortunate to have taken steps to prepare for change through developing the *ANR Strategic Vision* and embarking on creation of an implementation plan.

With the *ANR Strategic Vision* in hand, which clearly states priorities and has broad support from the ANR community, we are positioned to take charge of our collective destiny. I am confident that our efforts will pay substantial dividends over the long term, both through increased support for UC and the recognition by university leaders and our growing base of stakeholders that ANR campus- and county-based programs are positive agents of change in an increasingly complex world.

For more information, go to http://ucanr.org/vision.

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Cover: A large carpenter bee (*Xylocopa* sp. [fam. Apidae]) visits a mint flower (*Lamiaceae*) in an urban California garden. In a recent study, a wide variety of native bees frequented ornamental plants in gardens across California (see page 113). ***Photo by Rollin Coville.***

News departments

Research and review articles

About California Agriculture

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

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

Current indexing. *California Agriculture* is indexed by Thomson ISI's Current Contents (Agriculture, Biology and Environmental Sciences) and SCIE, the Commonwealth Agricultural Bureau databases, Proquest, AGRICOLA and Google Scholar. In addition, all peer-reviewed articles are posted at the California Digital Library's eScholarship Repository.

Authors. Authors are primarily but not exclusively from UC's ANR; in 2005 and 2006, 14% and 34% (respectively) were based at other UC campuses, or other universities and research institutions.

Reviewers. In 2005 and 2006, 13% and 21% (respectively) of reviewers came from universities and research institutions or agencies outside ANR.

Rejection rate. Our rejection rate is currently 26%. In addition, in two recent years the Associate Editors sent back 11% and 26% for complete resubmission prior to peer review.

Peer-review policies. All manuscripts submitted for publication in *California Agriculture* undergo double-blind, anonymous peer review. Each submission is forwarded to the appropriate associate editor for evaluation, who then nominates three qualified reviewers. If the first two reviews are affirmative, the article is accepted. If one is negative, the manuscript is sent to a third reviewer. The associate editor makes the final decision, in consultation with the managing and executive editors.

Editing. After peer review and acceptance, all manuscripts are extensively edited by the *California Agriculture* staff to ensure readability for an educated lay audience and multidisciplinary academics.

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Bees affected by climate change?

I applaud your issue on climate change ("Unequivocal: How Climate Change Will Transform California," April-June 2009). As a commercial beekeeper, I will be affected by several aspects: the shift of agricultural and bee forage crops and native species, the increased use of pesticides, the lack of bee forage during drier summers, and increased problems with the bee parasites varroa mite and *Nosema ceranae* due to warmer winters. (I recently met with beekeepers in Hawaii. The varroa mite just reached the Big Island, where it will likely bring substantial changes for beekeepers and agriculture there.)

The aspect that most caught my attention is the poorer nutritional value of plants due to lower protein content, caused by higher CO_2 levels. It has been apparent for a few decades that bee nutrition from pollen is not what it used to be, even in nonagricultural areas. It could well be that the plant pollens necessary for bee nutrition are simply not as high in protein as they used to be.

Randy Oliver, beekeeper
Grass Valley

Need to build forestry and rangeland faculty

The recent issue clearly demonstrates the issue of global warming and how UC is actively involved. Humboldt State University is a unique CSU campus with regard to the natural resources disciplines. Programs in forestry, rangeland resources, watershed management and wildland soils produce both baccalaureate and master's graduates for employment with state and federal agencies, nongovernmental organizations, consulting firms, and forestry and rangeland industries. Some of our graduates proceed to a UC campus for graduate education. The newest direction in these disciplines is the study of carbon sequestration and global warming, demonstrating the need for faculty hires in these areas.

K.O. (Ken) Fulgham
Chair, Forestry and Wildland Resources Department
Humboldt State University, Arcata

Climate change and Chagas disease

Had I not had *California Agriculture* in my mailbox, my life would be less. Kudos for publishing the controversial climate change issue.

However, I ask why authors of "Climate change will exacerbate California's insect pest problems" (Trumble and Butler, pages 73–8) omitted mention of *Triatoma protracta,* the vector for Chagas disease. The native incidence of the disease is miniscule, but migrant workers in this country are said to number in the tens of thousands. Climate change will move the Mexican vector northward into California, and Chagas disease, already common in animal reservoirs in the state, will increase.

Bud Hoekstra
San Andreas

Author John Trumble responds: I considered including Chagas disease because, according to the National Institutes of Health, the United States has about 500,000 people infected with the trypanosome. However, the pathogen is already present in the southern United States, as is Triatoma protracta. *When so many people are infected, and the pathogen can be transferred in blood transfusions, transplacentally (from mother to fetus) and via organ transplant, it is not easy to prove that an increase in cases is due to global warming rather than immigration and noninsect transmission. In addition, vector insects are already in the United States, so it would be difficult to scientifically conclude that global warming will allow Chagas disease to expand. Finally, some of the expansion will be hindered by predicted decreases in humidity in California, which reduces the lifespan of some* Triatoma *vectors. That said, I personally believe the letter writer is correct in that there will be further northward movement of vector species (certainly within the United States) and insect-vectored cases will likely increase.*

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Cal Ag editors win silver ACE award

California Agriculture managing editor Janet Byron and executive editor Janet White received a Silver Award for Editing from the Association for Communication Excellence in Agriculture, Natural Resources, and Life and Human Sciences (ACE). The award honored their work on "Innovative outreach increases adoption of sustainable winegrowing practices in Lodi region," by Cliff Ohmart, which appeared in the October-December 2008 special issue on sustainable viticulture. Byron accepted the award on June 7 at the annual ACE conference in Des Moines, Iowa. To see the award-winning article, go to http://californiaagriculture.ucanr.org.


REVIEW ARTICLE
Innovative outreach increases adoption of sustainable winegrowing practices in Lodi region

RSVP

WHAT DO YOU THINK?

The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at 6701 San Pablo Ave., 2nd floor, Oakland, CA 94608 or calag@ucop.edu. Include your full name and address. Letters may be edited for space and clarity.

To our readers

The new home page includes dynamic content that will be updated monthly.

Past articles can be searched according to author, article text and date range.

Full text of articles from 1990 to present is available, with active links to citations and enlargeable illustrations.

Sixty-three years of California Agriculture *now online*

ON July 1, *California Agriculture* capped off a 2-year effort with a keystroke, posting the full text of 63 years — about 6,000 articles — to the World Wide Web. This rich store of peer-reviewed science dating back to 1946 is now freely accessible and searchable at the journal's redesigned Web site.

Our previous Web site included articles dating back to 2000. Until now, however, most of *California Agriculture*'s long history of research has been in the shadows, accessible only as bound volumes in the stacks of a few UC libraries and others scattered around the world.

Using "advanced search," users can now run a filtered search of the entire archive according to author last name, text, date and research-versus-news content. They can easily download, cite or assemble a collection for personal reference with the "My Folder" feature.

As indexing by Web crawlers progresses, the site will become accessible through multiple entry points. These include search engines such as Google and Google Scholar, and the scholarly databases Thomson ISI's Current Contents, the Commonwealth Agricultural Bureau, Proquest, AGRICOLA and EBSCO. The entire archive will also be posted at the California Digital Library and ANR Communication Services.

California Agriculture began as a four-page broadsheet in December 1946. Today both print and Web versions are known for presenting new, peer-reviewed research in a meaningful context with technical terms defined — making it accessible to a diverse audience of end-users. Print subscribers include 17,000 growers, faculty members, environmental and health professionals, government researchers, public officials and others.

The *California Agriculture* archive includes landmark research that knitted together understanding of food and fiber production, forestry and fisheries, and how those endeavors were influenced, and were affected by, the natural environment and ecosystems at every scale.

California Agriculture's archive includes some of the earliest reports of integrated pest management, biological control, the effects of agricultural chemicals on wildlife, causes and effects of water and air pollution, and fisheries research — to name a few. More recent articles encompass sustainable food systems, conservation tillage, biodiversity, urban encroachment, demographics, nutrition, food safety, biotechnology and climate change, all with an eye to evolving conditions in California.

The new Web site enables both scholarly and lay audiences to access this research through the assignment of a digital object identifier (DOI) to each article. DOIs are unique numbers for each article, which are deposited at CrossRef. Launched in 2000, Cross Ref is a cooperative effort among scholarly publishers to enable cross-publisher citation linking in online academic journals.

We are still fine-tuning the Web site, and welcome your comments and feedback. Please take the online survey on the home page, or write to us at calagwebmaster@ucanr.org. — *Janet White*

New *California Agriculture* Web site:
http://californiaagriculture.ucanr.org

Genetics and breeding help build a better, stronger bee

Susan Cobey, a bee breeder-geneticist at UC Davis, is out to build a better bee — lock, stock and beehive.

"With the increasing challenges of beekeeping today, the selection of honey bee stocks that are productive, gentle and show some resistance to pests and diseases is critical to the future health of the beekeeping industry, agriculture and our food supply," says Cobey, an international authority on queen-bee rearing and instrumental insemination.

Developed in the 1920s and perfected in the 1940s and 1950s, instrumental insemination provides "a method of complete control of honey bee mating," Cobey says. Cobey, manager of the Harry H. Laidlaw Jr. Honey Bee Research Facility, trained under the late Laidlaw (1907-2003), considered the father of honey bee genetics.

Her current work involves increasing genetic diversity in the general bee population and more specifically in her New World Carniolan closed breeding population, which she established in 1981.

"Major advances in agriculture are due to stock improvement and this also applies to honey bees," Cobey says. In nature, a queen bee mates with 10 to 20 drones in flight over several days and returns to her hive to lay eggs for the rest of her life. During her 2-to-3-year life span, the queen will lay approximately 1,000 eggs a day, and as many as 2,000 a day in peak season.

"Instrumental insemination allows bee breeders and geneticists to make specific crosses," Cobey says. "The closed-population breeding system can enhance the frequency of desirable traits."

Another advantage is the ability to store and ship honey bee semen. "This minimizes the risk of spreading pests and diseases," says Cobey, who this year helped develop a protocol for the international importation of honey bee germplasm.


Kathy Keatley Garvey

UC Davis bee breeder Sue Cobey shows a honey bee frame to students.


Kathy Keatley Garvey

A queen honey bee is artificially inseminated.

Since the early 1980s, Cobey has taught specialized classes in queen rearing and instrumental insemination, drawing researchers and beekeepers from South America, Europe, Asia and Africa.

The UC Davis bee geneticist works closely with the state, national and global beekeeping industry, including the California Bee Breeders, who produce half the nation's supply of mated queen honey bees. To improve stock, Cobey imports bee semen from Germany and Italy. With the German stock, she is selecting for traits of resistance to varroa mites. One cross has increased expression for hygienic behavior "and so far they look very productive," she says.

Understanding colony collapse disorder

Cobey's New World Carniolan bees are known for their high productivity, rapid spring buildup, overwintering ability, resistance to diseases and gentle temperament. "Sue's bees are polite," says Eric Mussen, UC Cooperative Extension apiculturist.

"California agriculture depends upon a healthy and viable beekeeping industry," he says. The value of California crops pollinated by bees exceeds $6 billion; bees pollinate some 100 crops in California, Mussen says, including about 700,000 acres of almonds, mostly grown in the Sacramento and San Joaquin valleys.

Improving bee stock can result in a bee that is more resistant to pests, pathogens and parasites, considered key factors in colony collapse disorder (CCD), "a mysterious malady that has killed colonies of honey bees in practically every state across the country, including California," he says.

Honey bee haven to encourage bee-friendly gardening

Plans for the Häagen-Dazs Honey Bee Haven, a half-acre bee-friendly garden on Bee Biology Road, are buzzing right along.

The haven — near the Harry H. Laidlaw Jr. Honey Bee Research Facility at UC Davis — will offer a year-around food source for the bees and other insects, raise public awareness about the plight of honey bees, and encourage visitors to plant gardens that are friendly to honey bees and a range of native bee species (see page 113).

"The winning design fits beautifully with the campus mission of education and outreach, and it will tremendously benefit our honey bees," says Lynn Kimsey, UC Davis entomology professor and director of the Bohart Museum of Entomology. Bee-friendly plants in the garden will include lavender, salvia (sage), catmint, California buckwheat, toyon, bladderpod and tower of jewels.

The haven, a $125,000 gift from the premium ice cream brand (which is produced by Dreyer's Grand Ice Cream of Oakland), will spring to life in late September and be dedicated in October. A Sausalito-based team submitted the winning design in an internationally publicized contest.

"We'll not only be providing a pollen and nectar source for millions of bees, but we will also be demonstrating the beauty and value of pollinator gardens," says Melissa Borel, program manager for the California Center for Urban Horticulture, which coordinated the competition.

In February 2008, Häagen-Dazs pledged $250,000 for honey bee research, shared by UC Davis and Pennsylvania State University; a second $250,000 donation was added in 2009. (The company depends on bee pollination for 50 ice cream flavors.)

For more information:

UC Davis bee garden:
http://entomology.ucdavis.edu/news/honeybeehavenwinner.html

Häagen-Dazs - Help the Honey Bees
www.helpthehoneybees.com

Site already teeming with native bees

Native pollinator specialist Robbin Thorp, UC Davis emeritus entomology professor, is monitoring the level of insect activity at the plot where the garden will be constructed. He began establishing baseline data in March, and is also gathering data on honey bee flower visitation, especially their pollen resources.

From just two sample days (March 20 and April 19), Thorp found a total of 27 species of bees. "Most are solitary, ground-nesting, native bee species," Thorp says. He also found that honey bees collected pollen from four of six plant species they visited.

"Currently all the bees are relying on a low diversity of weedy flowering plants in the area and planted trees such as almond, eucalyptus and walnut," he says.

"I expect these numbers — in diversity and abundance — to continue to increase as the garden matures and more bees discover a long-term, stable, food resource base. I also expect resource use by honey bees and other bees to expand as new resources become available in the garden."

— *Kathy Keatley Garvey*

A honey bee collects nectar on button willow.

Honey bee colonies began dying of what is now called colony collapse disorder in fall 2004. However, massive bee die-offs are not a new occurrence, Mussen says, and were documented under various names in 1869, 1963, 1964, 1965 and 1975.

Mussen says the die-offs may be caused by a combination of factors such as pesticides, diseases, malnutrition and stress. When the disorder strikes, nearly every adult bee leaves the hive over a period of just a few days, leaving behind the queen, various stages of brood (eggs, larvae, pupae) and stores of edible honey and pollen.

"Recently abandoned combs will kill another colony placed on them," Mussen says. However, drying, irradiating or fumigating the combs with glacial acetic acid allows a subsequent colony to use the combs safely. "This suggests a role for one or more microbial pathogens, but researchers have been unable to detect novel microbes."

Colony collapse disorder has decimated commercial bee colonies, as well as some colonies kept by hobby and organic beekeepers. However, Mussen says that urban beekeepers have three distinct advantages that tend to reduce their problems with colony collapse disorder. "First, they tend to be spatially isolated from commercial colonies that can readily share maladies. Second, urban colonies often have access to large numbers of annual and perennial plants. Mixed pollens provide the building blocks for the best bee diets and most robust bees."

"The third critical difference appears to be that local populations of honey bees and the parasitic mite, *Varroa destructor*, seem to develop an equilibrium that allows the colonies to survive without harsh chemical treatments," Mussen says. "Those regional groups of beekeepers are purposely interbreeding their 'survivor bees' and colony losses tend to be minimal." — *Kathy Keatley Garvey*

Native bees are a rich natural resource in urban California gardens

by Gordon W. Frankie, Robbin W. Thorp, Jennifer Hernandez, Mark Rizzardi, Barbara Ertter, Jaime C. Pawelek, Sara L. Witt, Mary Schindler, Rollin Coville *and* Victoria A. Wojcik

Evidence is mounting that pollinators of crop and wildland plants are declining worldwide. Our research group at UC Berkeley and UC Davis conducted a 3-year survey of bee pollinators in seven cities from Northern California to Southern California. Results indicate that many types of urban residential gardens provide floral and nesting resources for the reproduction and survival of bees, especially a diversity of native bees. Habitat gardening for bees, using targeted ornamental plants, can predictably increase bee diversity and abundance, and provide clear pollination benefits.

About 1,600 native bee species have been recorded in California. The bees provide critical ecological and pollination services in wildlands and croplands, as well as urban areas. *Above*, a female solitary bee (*Svasta obliqua expurgata*) on purple coneflower (*Echinacea pupurea*).

Outdoor urban areas worldwide are known to support a rich diversity of insect life (Frankie and Ehler 1978). Some insects are undesirable and characterized as pests, such as aphids, snails, earwigs and borers; urban residents are most aware of these. Other urban insects are considered beneficial or aesthetically pleasing, such as ladybird beetles and butterflies; this category includes a rich variety of insects whose roles in gardens go largely unnoticed and are thus underappreciated (Grissell 2001; Tallamy 2009). They regularly visit flowers and pollinate them, an important ecological service.

We report the results of a 2005-to-2007 survey of bees and their associations with a wide variety of ornamental plant species in seven urban areas, from Northern California to Southern California. While nonnative honey bees (*Apis mellifera*) are common in many gardens, numerous California native bee species also visit urban ornamental flowers. Of about 4,000 bee species known in the entire United States, about 1,600 have been recorded in California.

Our recent work on urban California bees in the San Francisco Bay Area (Frankie et al. 2005) is part of a larger movement to conserve and protect native pollinators; participants include the North American Pollinator Protection Campaign and the Xerces Society. Mounting evidence worldwide indicates that pollinators, especially bees, are declining as human populations and urban areas continue to expand (NRC 2007).

Important economic concerns are at stake, in terms of the value of bee pollination in crop systems and wildland environments (Allen-Wardell et al. 1998; NRC 2007). To recognize and protect the pollination services of native bees (Daily 1997), we must learn more about their role in natural environments, crop pollination (Kremen et al. 2002, 2004) and urban areas (NRC 2007). In the urban environment, native bees offer important benefits to people that include aesthetic pleasure, awareness of urban native fauna conservation, pollination of garden plants that provide food for people and animals, and environmental education.

Urban bee surveys

Previous surveys of ornamental plants in residential neighborhoods of the San Francisco Bay Area (Albany and Berkeley) revealed 82 bee species, of which 78 were native to California and four were nonnative, including the honey bee (Frankie et al. 2005; Hernandez et al. 2009; Wojcik et al. 2008). That work resulted in questions about whether similarly diverse native bees visit ornamental flowers in other urban areas of the state, and whether the same types of bees are associated with the same types of flowers in those urban areas. More specifically, can particular ornamental plants be used as predictors for visitation by certain taxonomic groups of bees over

Fig. 1. Ornamental plant and bee survey sites in California.

a wide geographic area, from Northern California to Southern California?

To address these questions, we conducted garden surveys in Albany and Berkeley (Alameda County) and six other medium-large urban areas throughout the state (from north to south): Ukiah (Mendicino County), Sacramento (Sacramento County), Santa Cruz (Santa Cruz County), San Luis Obispo (San Luis Obispo County), Santa Barbara (Santa Barbara County) and La Cañada Flintridge (Los Angeles County) (fig. 1). Ukiah and Sacramento are inland and subject to climatic extremes in winter and summer. Santa Cruz is coastal and has similar conditions to that of Albany and Berkeley. Santa Barbara is coastal, and San Luis Obispo is slightly inland but is also subject to nearby coastal climatic influences. Finally, La Cañada Flintridge is inland, in an upland site near Pasadena.

Neighborhood gardens. We compared gardens in Albany and Berkeley with those in the other six cities. Only gardens in residential neighborhoods were surveyed and evaluated for their bee-attractive ornamental plants. About 30 gardens were visited statewide each year. The main gardens in each of the seven cities were visited 6 to 12 times each year, depending on the city, during the 2005 through 2007 study period.

Bee plant visits. To evaluate the attraction of bees to ornamental flowers, we used visitation or frequency counts for a given plant type whenever we could study a flowering patch that was approximately 1 by 1.5 square yards (1 by 1.5 square meters). We counted visiting bees to each patch for 3 minutes on warm, sunny days, and after numerous replicated counts, we determined an average attraction level (Frankie et al. 2005).

Species identification. During the counts, native bees were identified at the species, genus or family level, and honey bees were recorded separately. General notes were also taken on other types of flowering plants adjacent to the target plants, and the bees that visited them. Sometimes a plant type could not be located in a city, or its patch was smaller than the study size. In these cases, we transported potted flowering plants of the target species from Berkeley and made frequency counts on them. The time for leaving potted plants in position before recording bees usually varied from 1 hour to 24 hours. In a few cases, we returned 3 to 5 days later. Representative (or voucher) bee collections were made for each ornamental plant evaluated, and each collection was taken to UC Davis for species identification. Voucher bee species were pinned, labeled and stored in special insect collection boxes at UC Berkeley.

Target ornamental plants. The 31 target plants were selected for evaluation mostly because they were relatively common in more than half of the surveyed cities and were all known to attract native bee species in Albany and Berkeley (Frankie et al. 2005) (tables 1 and 2). When all species, cultivars and hybrids were considered separately, the target plants actually comprised more than 50 distinct types (Brenzel 2007). Numerous other candidate plants were also evaluated in the statewide survey but not chosen as target plants because they were either rare or only present in some of the cities. Bee visitor groups were compared among the same orna-

TABLE 1. Ornamental plants and their origins, flowering season and their visitor bee groups in seven California cities, 2005–2007

A. Plants with restricted visitor bee groups	Family	Origin*	Flowering season	Restricted bee groups†
Yarrow (*Achillea millefolium*)	Aster.	CA	Summer	Halictidae
Mexican daisy (*Erigeron karvinskianus*)	Aster.	NN	Spring/summer	Halictidae, Hb, Megachilidae
Pumpkins, squash (Cucurbitaceae)	Cucurb.	NN	Summer	*Peponapis pruinosa*‡, Hb
Manzanita (*Arctostaphylos* spp.)	Eric.	CA	Spring	*Bombus*§, Hb
Palo verde (*Parkinsonia aculeata*)	Fabac.	NN	Summer	Hb, *Xylocopa*§
Wisteria (*Wisteria sinensis*)	Fabac.	NN	Spring	*Xylocopa*§, Hb
Autumn sage (*Salvia greggii* cvs¶/ 'Hot Lips' *S. microphylla*)#	Lamiac.	NN	Summer	*Xylocopa*§, Hb
California poppy (*Eschscholzia californica*)	Papav.	CA	Spring	*Bombus*§, Halictidae, Hb
Sky flower (*Duranta erecta*)	Verben.	NN	Summer	*Bombus*§, Hb, *Anthophora urbana*§
B. Plants with diverse native bees and two or three prominent bee groups	**Family**	**Origin***	**Flowering season**	**Prominent bee groups**
Blanket flower (*Gaillardia* x *grandiflora* cvs)§	Aster.	NN	Summer	*Melissodes*§, Halictidae, Hb
Sunflower (*Helianthus annuus*)	Aster.	CA	Summer	*Melissodes*§, Hb
Goldenrod (*Solidago californica*)	Aster.	CA	Summer	Halictidae, Megachilidae, Hb, *Bombus*§
Pride of Madeira (*Echium candicans*)	Borag.	NN	Spring	Hb, *Bombus*§
Lavender (*Lavandula* spp.)/cvs¶	Lamiac.	NN	Spring/summer	Hb, *Bombus*§
Russian sage (*Perovskia atriplicifolia*)	Lamiac.	NN	Summer	Hb, Megachilidae
Salvia 'Indigo Spires'	Lamiac.	NN	Summer	*Bombus*§, Hb, *Xylocopa*§
Bog sage (*Salvia uliginosa*)	Lamiac.	NN	Summer	Hb, *Xylocopa*§, *Bombus*§
Chaste tree (*Vitex agnus-castus*)	Lamiac.	NN	Summer	Hb, Megachilidae

* Origin: CA = native to California; NN = nonnative in California.
† Bee taxa listed from left to right, more frequent to less frequent; Hb = honey bee (*Apis mellifera*) (fam. Apidae).
‡ Squash bee of the family Apidae.
§ Family Apidae.
¶ cvs = cultivars. These and *S.* 'Hot Lips' were listed together because of their similar floral structure and reward (nectar), and because they attracted the same bee taxa.
# cv = cultivar 'Hot Lips'.

TABLE 2. Ornamental plants and their origins and flowering season visited by diverse bee taxa with no prominent bee groups in seven California cities, 2005–2007

Plants	Family	Flowering season	Origin*
Monch (*Aster* x *frikartii*)	Aster.	Summer	NN
Bidens (*Bidens ferulifolia* cvs)†	Aster	Spring/summer	NN
Coreopsis (*Coreopsis grandiflora* cvs)†	Aster.	Summer	NN
Cosmos (*Cosmos bipinnatus*)	Aster.	Summer	NN
Cosmos (*C. sulphureus*)	Aster.	Summer	NN
Sea daisy (*Erigeron glaucus*)‡	Aster.	Spring/summer	CA
Black-eyed Susan (*Rudbeckia hirta*)§	Aster.	Summer	NN
Tansy phacelia (*Phacelia tanacetifolia*)	Hydro.	Spring	CA
Catnip mint (*Nepeta* spp.)¶	Lamiac.	Spring/summer	NN
Rosemary (*Rosmarinus officinalis* cvs)#	Lamiac.	Spring/summer	NN
Black sage (*Salvia mellifera*)	Lamiac.	Spring	CA
Wild lilac (*Ceanothus* spp.)**	Rham.	Spring	CA
Toad flax (*Linaria purpurea*)	Scroph.	Spring/summer	NN

* Origin: CA = native to California; NN = nonnative to California.
† cvs = several cultivars.
‡ Mostly *E. glaucus* 'Wayne Roderick'.
§ Mostly large, single-flower cultivars.
¶ Mostly catnip mint species (*Nepeta* x *faassenii* and *Nepeta* 'Six Hills Giant').
# Several cultivars, especially *R.* 'Ken Taylor' and *R.* 'Lockwood de Forest'.
**Mostly *C.* 'Ray Hartman', *C.* 'Julia Phelps' and *C. thyrsiflorus* 'Skylark'.

In the seven urban areas studied, specific bees were often associated with particular ornamental plants. *Above*, a digger bee (*Anthophora edwardsii*) forages on a manzanita flower (*Arctostaphylos* sp.).

mentals in each city, using as a starting point Albany and Berkeley — where numerous and consistent bee observations and frequency counts had been recorded from 1999 through 2005.

Bee-frequency counts. In late 2005 and early 2006, continuing through 2007, we visited selected gardens periodically to locate those that had a diversity of flowering plants known to attract bees. We then solicited cooperators/owners of gardens and collected voucher bee species from candidate plants (tables 1 and 2). Bee-frequency counts were recorded every 3 to 6 weeks (in San Luis Obispo, counts began in early 2007).

During 2006 and 2007, we made 2,485 3-minute bee-frequency counts, 1,718 from Northern California and 767 from Southern California. Usually one or two but sometimes up to five recorders were present on each count day. Over this survey period, 400 recorder person-days (3 to 6 hours of observation and counts) were logged in Northern California and 220 in Southern California.

Bee-frequency counts were not equal for each of the 31 target plant types. Some easily accessible plants — such as cosmos (*Cosmos* spp.), lavender (*Lavandula* spp.) and catnip mint (*Nepeta* spp.) — received high numbers of counts, partly due to their long flowering periods. Other plants — such as manzanita (*Arctostaphylos* spp.), chaste tree (*Vitex agnus-castus*) and wild lilac (*Ceanothus* spp.) — received fewer counts, usually due to a shorter bloom period or difficulty finding enough patches to monitor.

Bee-plant associations

For almost all target plants, the same characteristically associated bee taxa were found in each of the seven cities. This was especially noticeable with native bees. As expected, nonnative honey bees used a wide variety of ornamentals, and their abundance depended on plant type. The two most attractive plant families to bees were Asteraceae (which provide pollen and nectar) and Lamiaceae (which provide nectar), consistent with the earlier survey results from Albany and Berkeley (Frankie et al. 2005).

Based on bee-frequency counts in the seven cities, we divided the plants into three categories according to their associated bee taxa (tables 1 and 2): (1) those visited by limited (or restricted) bee types, (2) those with diverse native bees that were dominated by a few prominent bee groups and (3) those with diverse native bees that were not dominated by any prominent groups.

Restricted bee types. Nine plants were in the first category, with a limited number of bee taxa (table 1A). While other bee taxa would visit some of these plant types on rare occasions, this plant visitation pattern was consistent in all seven cities. Furthermore, there was no obvious association within this category with plant family, origin or flowering season (table 1A). One of the best plants for observing restricted bee taxa was the widespread California poppy (*Eschscholzia californica*), where bumble bees (*Bombus* spp.), small sweat bees (Halictidae) and honey bees were common and predictable visitors. Other good examples included palo verde (*Parkinsonia aculeata*), wisteria (*Wisteria sinensis*) and autumn sage (*Salvia greggii/microphylla*/cvs.), all of which consistently attracted honey bees and large carpenter bees (*Xylocopa* spp.).

Diverse native bees/prominent groups. The second category of plants had diverse native bees that were dominated by a few prominent bee groups (table 1B). Each plant type in this category also attracted at least three other bee taxa, but usually at much lower frequencies. These plants were found mostly in two families (Asteraceae and Lamiaceae), were mostly nonnatives (seven of nine) and mostly flowered in summer (seven or eight of nine) (table 1B). Two common examples were blanket flower (*Gaillardia* x *grandiflora*) and sunflower (*Helianthus annuus*), both of which attracted long-horn bees (*Melissodes* spp.) and honey bees. Blanket flower also attracted halictid bees (Halictidae). Another common example of this plant type was lavender (*Lavandula*

Small urban areas can sometimes have relatively high percentages of the bee species found in the surrounding geographic region.

TABLE 3. Collected and identified bee species from seven California cities, 2005–2007

Location	Families	Genera	Species*
	..... *no. bee taxa*		
Ukiah	5	24	67
Sacramento	5	23	63
Berkeley	5	25	82
Santa Cruz	5	20	41
San Luis Obispo	5	24	59
Santa Barbara	5	19	67
La Cañada Flintridge	5	28	73

* Includes a few morphospecies, morphologically distinct bee types that could not be immediately associated with a recorded scientific name.

TABLE 4. Common native bee species found in most (> 70%) California gardens surveyed

Common name	Scientific name
Andrenidae	
Mining bee	*Andrena angustitarsata*
Apidae (Including Anthophorinae)	
Small digger bee	*Anthophora curta*
Digger bee	*Anthophora urbana*
Honey bee*	*Apis mellifera**
California bumble bee	*Bombus californicus*
Black-tip bumble bee	*Bombus melanopygus*
Yellow-faced bumble bee	*Bombus vosnesenskii*
Small carpenter bee	*Ceratina acantha*
Small carpenter bee	*Ceratina nanula*
Gray digger bee	*Habropoda depressa*
Long-horn digger bee	*Melissodes lupina*
Long-horn digger bee	*Melissodes robustior*
Squash bee	*Peponapis pruinosa*
Cuckoo bee	*Xeromelecta californica*
Large carpenter bee	*Xylocopa tabaniformis orpifex*
Colletidae	
Masked bee	*Hylaeus polifolii*
Halictidae	
Ultra-green sweat bee	*Agapostemon texanus*
Large sweat bee	*Halictus farinosus*
Spined-cheek sweat bee	*Halictus ligatus*
Small sweat bee	*Halictus tripartitus*
Tiny sweat bee	*Lasioglossum incompletus*
Megachilidae	
Leafcutting bee	*Megachile angelarum*
Leafcutting bee	*Megachile fidelis*
Leafcutting bee	*Megachile montivaga*
Alfalfa leafcutting bee*	*Megachile rotundata**
Mason bee	*Osmia coloradensis*
Blue orchard bee (BOB)	*Osmia lignaria propinqua*

* Introduced.

spp./cvs.), which mainly attracted honey bees and *Bombus* as well as lower frequencies of *Xylocopa* and leafcutting bees (Megachilidae). As in the first category of plants, these bee-plant associations were consistent throughout the state with few exceptions.

Diverse native bees/no prominent groups. The third category of plants attracted a wide variety of bee species from different genera in at least three families. These plants, again, were mostly from the Asteraceae and Lamiaceae families (10 of 13) and were a mixture of natives and nonnatives that flowered in the spring and/or summer (10 of 13) (table 2). All had long blooming periods, which means that flowers were available to the different types of bees that occurred in a seasonal sequence from spring through summer (Wojcik et al. 2008). This was particularly noticeable for the two-season plants that were visited by spring bees as well as summer bees, which are largely different from each other. The bee-plant associations in this category were consistent wherever the plants were found from Northern California to Southern California.

Urbanization and bees

Urban bees are those that lived in an area prior to urbanization and were able to adapt to anthropogenic (human) alterations to the environment. In addition, a few exotic species have become naturalized in urban areas of California: honey bees (*Apis mellifera*), alfalfa leafcutting bees (*Megachile rotundata*), *Megachile apicalis* and *Hylaeus punctatus*. *Megachile rotundata* is a commercially important leafcutting bee; *Hylaeus punctatus* is not considered commercial and belongs to a group called yellow-faced or masked bees.

We identified five bee families and about 60 to 80 species in each city (table 3). Berkeley had the most recorded urban bee species at 82. We have collected there for several years and continue to add species to our list. At 41, Santa Cruz had the fewest; the severely wet winters and springs of 2005 and 2006 are believed to have greatly reduced native bee populations there. (New collections have been made in 2008 and 2009, and the bee species totals of all the cities continue to increase.)

Some bee species have been found throughout the urban areas surveyed (fig. 1). Those commonly observed are the honey bee, the most common yellow-faced bumble bee (*Bombus vosnesenskii*), the large carpenter bee (*Xylocopa tabaniformis orpifex*) and the ultra-green sweat bee (*Agapostemon texanus*) (table 4).

Specialist bees. Most bees from our sampling are generalist flower visitors with relatively few specialists, where the females collect pollen from only one or a few closely related species of plants. Specialist bees depend on the presence of their favored host flowers for their existence. For example, many specialist bees that occur in the wild areas of the Berkeley hills are not found in nearby urban gardens because their host plants, such as buttercups (*Ranunculus californicus*) and suncups (*Camissonia ovata*), are rarely used as ornamentals. We might expect to find males or nectar-seeking females of specialist bee species in gardens near wildlands, as they are not restricted to their pollen host plants when foraging for nectar. Recent plantings of squash (*Cucurbita* spp.) flowers at the UC Berkeley Oxford Tract garden have attracted the specialist squash bee (*Peponapis pruinosa*), which has been historically recorded in urban Berkeley. We also found a female of the sunflower bee (*Diadasia enavata*), a sunflower specialist, where sunflower is present in this garden.

Specialist bees (with preferred host plant genera in parentheses) that have been encountered in our garden surveys include: *Andrena auricoma (Zygadaenus), Diadasia bituberculata (Calystegia), Diadasia diminuta (Sphaeraclea), Diadasia enavata (Helianthus), Diadasia laticauda (Sphaeraclea), Diadasia nitidifrons*

The leafcutting bee (***Megachile perihirta***) was found in many of the gardens surveyed. ***Top***, a female carries a cut piece of leaf; ***above***, a female with strongly developed mandibles lands on a cosmos flower (***Cosmos bipinnatus***).

Some 60 to 80 species were identified in each city; the ultra-green sweat bee (***Agapostemon texanus***) was among the most common. ***Top***, a female on bidens (***Bidens ferulifolia***); ***above***, a male on sea daisy (***Erigeron glaucus***).

(Sphaeraclea), *Peponapis pruinosa (Cucurbita)*, *Svastra obliqua expurgata (Helianthus)*, *Chelostoma marginatum (Phacelia)* and *Chelostoma phaceliae (Phacelia)*.

Seasonal bees. Seven plant types flowered during both spring and summer and attracted several bee taxa that were seasonal to each period (tables 1 and 2). Five of these plants were in the third category of attracting diverse native bees without prominent groups (table 2). With additional sampling, lavenders (table 1B) may eventually be moved to the third category as well. Bee species visiting bidens (*Bidens ferulifolia*) and catnip mint species provide examples of this pattern. Depending on the city, between 8 and 14 bee species visited these two plant types where adequate samples had been taken (Ukiah, Sacramento and Berkeley for bidens; Ukiah, Sacramento and La Cañada Flintridge for catnip mint). One highly diverse bee group that was attracted to both plant types in the spring was the Megachilidae, especially members of the genera *Megachile* and *Osmia*.

Timing of bee visits. Most bee-frequency counts and collections in 2005 and 2006 were done opportunistically, that is during whatever time of day bees could be observed and recorded. In 2007, more attention was paid to time of day for the main visitation period. While more focused work is needed for more plant species, bees appeared to visit flowers throughout most of the day for most plant types. However, for some plant types, the greatest bee diversity could be observed during particular times of the day (table 5). Main attraction periods could best be observed on warm, sunny days with little or no wind; however, if the day started off with fog, coolness and/or wind, these periods would be delayed or obscured, with reduced bee activity.

Bee-plant variations

As indicated, the relationships between each of the target plants and visiting bee groups (tables 1 and 2) were almost the same in Northern California and Southern California. One notable exception was observed in Sacramento, where five plant types were visited at high frequencies by a large solitary anthophorid bee (*Svastra obliqua expurgata*), a local Central Valley species. Four of the five plants — cosmos (*C. sulphureus*), blanket flower, sunflower and black-eyed Susan (*Rudbeckia hirta)* — were also visited by *Melissodes* species, a taxonomic relative of *S. obliqua expurgata* and also the predominant bee group visiting these four plants throughout the state. The fifth plant, chaste tree, was also visited at high levels by *S. obliqua expurgata*. In other cities, honey bees and leafcutting bees (Megachilidae) were the main visitors (table 1B).

There were several small variations within cities (tables 1 and 2). However, while these variations influenced monitoring, they did not change the placement of a plant in one of the three categories. In Sacramento, rosemary (*Rosmarinus* spp.) attracted diverse bee taxa in one garden but primarily honey bees and halictid bees in a second garden 2 miles (3 kilometers) away. In a large, diverse San Luis Obispo garden, long-horn digger bees were common in late spring but extremely rare to absent during summer. In contrast, in a second San Luis Obispo garden 3.1 miles (5 kilometers) away, long-horn digger bees were common all summer on plants such as cosmos (*C. bipinnatus* and *C. sulphureus*). This type of variation was addressed by increasing the replications of frequency counts and monitoring several gardens in the surveyed cities.

Solitary (nonsocial) bees will nest in a variety of substrates in urban gardens. The digger bee (*Anthophora edwardsii*) nests in bare dirt.

TABLE 5. Selected plant types and periods of greatest daily bee attraction*

Plant type	Period of greatest attraction	Floral resource	Bee taxa
Goldenrod (*Solidago californica*)	11 a.m.–3 p.m.	Pollen/nectar	Halictidae, Megachilidae, Hb†, *Bombus*
Pumpkins, squash (Cucurbitaceae)	Before 9 a.m.	Pollen	*Peponapis pruinosa*, Hb
Palo verde (*Parkinsonia aculeata*)	Before 10 a.m.	Nectar	Hb, *Xylocopa*
California poppy (*Eschscholzia californica*)	Before 11 a.m.	Pollen	*Bombus*, Halictidae, Hb
Wild lilac (*Ceanothus* spp.)	Before noon	Pollen/nectar	Diverse native bees

* See also tables 1 and 2.
† Hb = honey bee (*Apis mellifera*) (fam. Apidae).

Target plant abundance

The presence, absence or abundance of target plants in the cities also influenced bee frequencies. Target plants were infrequent in a few cities, but while this often resulted in overall lower bee counts, it did not affect the placement of plants into the three categories (tables 1 and 2). These plants include bidens (*B. ferulifolia)*, sea daisy (*Erigeron glaucus*), black-eyed Susan, tansy phacelia (*Phacelia tanacetifolia*) and black sage (*Salvia mellifera*). Some target plants, including large perennials such as pride of Madeira (*Echium candicans*), palo verde and sky flower (*Duranta erecta*), could not be found in a few cities.

The differences that we found in ornamental plant presence and abundance are important variables, suggesting different gardening practices and plant availability and selection among cities. These variables can greatly influence bee populations by determining the overall amounts of their preferred floral resources. In this regard, some urban areas (such as Monterey-Carmel-Pacific Grove, Paso Robles and San Diego) were not selected for the survey because they lacked diverse and sufficient bee plants. At the opposite extreme were the diverse gardens of Berkeley and Santa Cruz, where species-rich and abundant collections of plants that bees preferred were found. The five other surveyed cities were intermediate in bee-friendly plant diversity and abundance.

Nesting in urban areas

Bees are known to nest in various substrates in urban areas. Most solitary bees (about 70%) nest in the ground, including *Andrena* (Andrenidae), *Colletes* (Colletidae), most halictid bees (*Halictidae*), most Anthophorinae (*Apidae*) and some Megachilidae. (Solitary means a male and a female bee mate, and the female constructs a nest and lays an egg in each single cell she creates, with 3 to 10 cells per nest depending on space; there is no hive, division of labor or social structure as in the social honey bees and bumble bees.) Many of these solitary bees prefer to construct their nests in soils with specific characteristics, such as composition, texture, compaction, slope and exposure. Nesting habitat can be provided for these bees in gardens by leaving bare soil and providing areas of specially prepared soil, from sand to heavy clay to adobe blocks. Excessive mulching with wood chips will greatly discourage ground-nesting bees, which need bare soil or a thin layer of natural leaf litter.

Other bees nest in pre-existing cavities. Honey bees nest in large tree cavities, underground and in human structures such as the spaces between walls, chimneys and water-meter boxes. Bumble bees commonly nest in abandoned rodent burrows and sometimes in bird nest boxes. Most cavity-nesting solitary bees such as *Hylaeus* (Colletidae), and most leafcutting bees and mason bees (*Osmia* [Megachilidae]) prefer beetle burrows in wood or hollow plant stems. Nest habitats for these bees can be supplemented by drilling holes of various diameters (especially 3/16 to 5/16 inches) in scrap lumber or fence posts, or by making and setting out special wooden domiciles in the garden (Thorp et al. 1992). Once occupied by bees, these cavities must be protected from sun and water exposure until the following year, when adult bees emerge to start new generations.

Neglecting to protect drilled cavities occupied by bees can lead to bee mortality.

Large carpenter bees (*Xylocopa*) excavate their nest tunnels in soft wood such as redwood arbors or fences, and small carpenter bees (*Ceratina*) use pithy stems such as elderberry or old sunflower stalks. Partitions between the brood cells are usually composed of bits of excavated material.

Almost 2,500 3-minute bee-frequency counts were conducted statewide over a 2-year study period. At the UC Berkeley Oxford Tract, researchers Jaime Pawelek (left) and Katie Montgomery counted bees on purple toad flax; note the garden's close proximity to residential neighborhoods.

Bee diversity and conservation

Several studies in Europe, North America, Central America and South America confirm that urban areas can support rich faunas of bees (Cane 2005; Eremeeva and Sushchev 2005; Frankie et al. 2005; Hernandez et al. 2009; Matteson et al. 2008; Wojcik et al. 2008). Furthermore, long-term monitoring has shown that small urban areas can sometimes have relatively high percentages of the bee species found in the surrounding geographic region. For example, Owen (1991) recorded 51 bee species during a 15-year monitoring study in a small residential garden in Leicestershire, England, representing an amazing 20% of the British bee list of 256 species.

The main pattern that emerges from the statewide California survey is that a predictable group of native bee species can be expected to visit certain ornamental plants (tables 1 and 2). With this kind of information, gardens can be planned with predictable relationships between bees and ornamental plants. The California survey also revealed that not all urban areas can be expected to support measurable populations of native bees. Urban areas must have the right plant types, and enough of them, to attract native bees. Predictable bee-flower relationships are well known among wildland plants and native bee taxa that visit them in California and elsewhere (G. Frankie and R. Thorp, personal observation).

Much is still unknown about the ecology and behavior of native bees in urban environments, especially regarding how to encourage the bees to visit gardens. Our monitoring work will continue for at least two more years, with the same target plants in the same seven cities. We also added two additional cities: Redding, in far north-central California, and Riverside, southeast of Pasadena. More attention will be paid to bee-plant relationships within cities and also to temporal visitation patterns, which will provide more accurate information on the optimal times of day to record the greatest diversity and abundance of bees.

From a biodiversity perspective, it is easy to understand why we should conserve and protect native bees. The approximately 1,600 species of native California bees have had a long evolutionary history with about 6,000 different kinds of native California flowering plants. Like the plants, bees are an integral part of the heritage of the state's natural resources. Despite the fact that most gardens in the state use a high percentage of nonnative plants (instead of the native plants preferred by native bees), they are nonetheless visited by native bees (Frankie et al. 2005).

Likewise, there is still much to be learned about how to convey scientific knowledge in user-friendly language to urban audiences. Native bees can be used as "tools" for a range of activities, including habitat gardening, environmental education and scientific inquiry to solve current environmental problems. Great opportunities exist for increasing biodiversity in home, school and community gardens if the right plants are grown. Besides bees, the plants will attract other flower visitors such as birds, butterflies and beneficial flies and wasps (Grissell 2001). Once established, diverse gardens offer opportunities to observe, conserve, protect and enjoy a variety of floral ecological relationships close to home. In the case of school gardens, which usually have mixtures of food and ornamental plants, teachers have opportunities to connect students with the natural world (Louv 2008) as well as the world from which our food comes.

Information on pollinator-plant relationships can be used for more ambitious projects such as restoring ecological functions to degraded or fallowed landscapes (Peter Kevan, University of Guelph, Canada, personal communication). Some larger urban gardens with high plant diversity can be used as stations for long-term pollinator monitoring (NRC 2007) that could provide valuable information, especially as the global climate changes; in Sacramento and La Cañada Flintridge, two of our largest survey gardens are being used for this purpose. It is noteworthy that urban landscape gardens may be more suitable for monitoring certain bee pollinator species than wild areas because urban plants are usually intensively managed. Watering, pruning and replanting produces floral resources that are more consistently available to pollinators, even in times of drought.

As suggested by Owen (1991), urban areas can serve as genetic reserves for pollinators and other species that we deem beneficial for humans. Some of these may eventually be a resource for the pollination of agricultural crops (G. Frankie and R. Thorp, personal observation). The effects of colony collapse disorder in honey bees (NRC 2007) once again remind us of the need to consider the value of ecological services provided in biodiverse landscapes (Daily 1997).

The study found that while many urban gardens include a high percentage of nonnative ornamental plants, a great variety of native bees visit them. *Above*, Kimberly Gamble's garden in Soquel (Santa Cruz County).

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For more information

North American Pollinator Protection Campaign
www.pollinator.org

Urban Bee Gardens
http://nature.berkeley.edu/urbanbeegardens

The Xerces Society for Invertebrate Conservation
www.xerces.org

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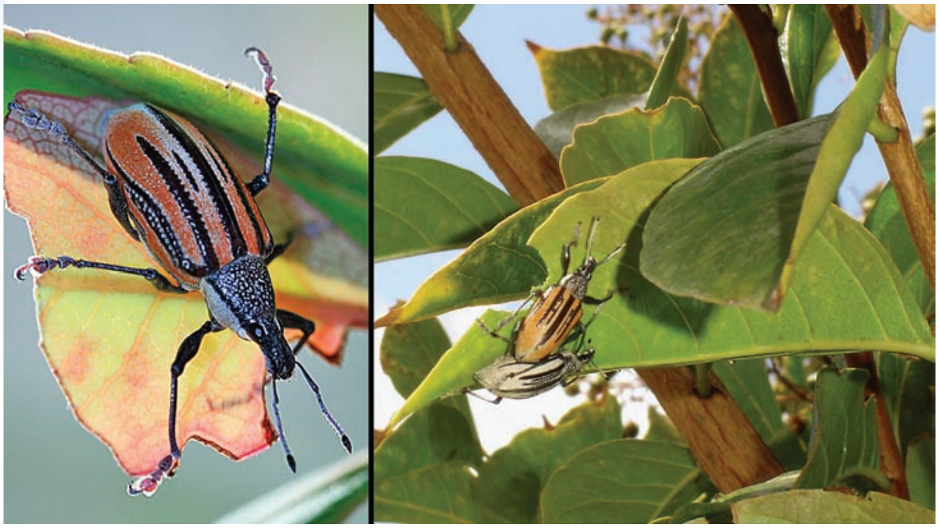
RESEARCH ARTICLE

Diaprepes root weevil, a new California pest, will raise costs for pest control and trigger quarantines

by Karen M. Jetter *and* Kris Godfrey

This study presents an economic analysis of cost increases for citrus, avocado and nursery producers should the Diaprepes root weevil become established in California. First identified in Southern California in 2005, Diaprepres would mainly affect orange, grapefruit, lemon and avocado crops. The primary impacts would be increased production costs for pest treatments and increased harvesting costs to conform to quarantine regulations, in particular to ship ornamental plants out of infested regions. The estimated increase in production cost to treat Diaprepes was $609 per acre on average for citrus and avocado and $525 per acre for infested nurseries. The average increase in total cost as a share of revenues was 21.61% for oranges, 11.35% for avocados, 9.80% for grapefruit and 5.62% for lemons; for nursery growers it was less than 1%.

John Kabashima



Susan Sawyer

The Diaprepres root weevil, native to the Caribbean, was first identified in California in 2005. *Left*, an adult feeds on a Raphiolepsis leaf in Newport Beach. *Right*, adults on an Orange County crape myrtle leave irregular semicircular feeding notches on the leaves.

The Diaprepes root weevil was first identified in California in 2005 in urban areas of Orange and Los Angeles counties, and in fall 2006 it was found in San Diego County. These areas were initially subject to state-run eradication and quarantine programs in an attempt to eliminate existing populations of the weevil and to limit its spread to other parts of the state. In July 2008, the eradication program ended due to lack of funding, while quarantine efforts remain in effect. If the current quarantine program is not successful in containing Diaprepes root weevil (*Diaprepes abbreviatus* Coleoptera: Curculionidae) it will spread, causing economic losses to growers in all areas that can support infestations. This study presents an analysis of the economic effects for California citrus, avocado and nursery producers should Diaprepes become established.

The Diaprepes root weevil is long-lived and can thrive in agricultural and urban environments; more than 290 species in 59 plant families can support at least one life stage (Simpson et al. 1996). In California, the main vulnerable food crops are orange, grapefruit, lemon and avocado. A Diaprepes infestation primarily would increase production costs for pest treatments to maintain crop yields, and increase harvesting costs to conform to quarantine regulations. While a wide range of ornamental plants is affected by Diaprepes, the main economic impact on the nursery industry would be increased production costs to meet quarantine regulations when shipping plants out of infested regions. Failure to meet quarantine regulations could result in the loss of infested nursery plants, delays in shipping product to customers and possible market losses.

Diaprepes root weevil

Diaprepes root weevil is native to the Caribbean, where it is considered a pest of citrus, sugar cane and other economically important plants (Woodruff 1968; Martorell 1976). Adult weevils, which live for approximately 4 months, do little economic damage because they feed on leaf edges, leaving irregular, semicircular notches (Woodruff 1968; Knapp et al. 2000). Only rarely do adults feed on fruit — most commonly papaya and young citrus — again doing little economic damage. If not controlled, feeding damage by larvae on roots and other belowground plant structures causes the most significant economic losses. Larvae are difficult to detect because the aboveground portions of the plant may not show any symptoms until root feeding is extensive. The youngest larvae feed on the finest roots, moving to larger roots as they develop over 5 to 18 months. Their feeding activity destroys feeder and structural roots of the plant.

Larger larvae may girdle the crown of the host plant. Young trees may be killed by larval feeding, and mature trees will decline rapidly, resulting in yield reductions and a greater chance that they will be uprooted in strong winds (McCoy 1999; Stuart et al. 2006). In one infested lemon grove in San Diego County, most of the trees are declining and approximately 10% blew over during strong winds in 2007 (Gary Bender, UC Cooperative Extension San Diego County, unpublished data). Root damage also provides openings for the entry of *Phytophthora* root rot, compounding the effects of larval damage to roots. In agricultural crops, larval feeding negates the benefits of *Phytophthora*-resistant rootstocks (Knapp et al. 2001). Florida growers treat to prevent crop losses and have been spending $400 per acre annually to protect citrus against the combination of Diaprepes root weevil and *Phytophthora* (Muraro 2000).

In nursery containers, adult weevils will feed and oviposit (lay eggs) on a large number of ornamental species, and larvae may feed on the roots of these plants, hidden in container soil. Aboveground portions of infested plants may not show any symptoms, but will succumb to larval feeding. In controlled studies, the plant height and trunk diameter of green buttonwood and live oak trees were significantly lower in infested containers than those free of Diaprepes (Diaz et al. 2006).

Despite being capable of strong, short-duration flight, this weevil prefers to "hitchhike" — as adults on plants and as larvae in soil moved by people (Woodruff 1968). Historically, the weevil has moved between and within countries in infested nursery containers (McCoy 1999). In 1964, a single adult weevil was identified from a citrus nursery near Apopka, Fla. (Woodruff 1964). Since then, Diaprepes root weevil has spread to 22 counties in Florida. Much of that spread is attributable to the movement of infested plants by people, despite quarantine regulations in place in Florida since 1968. Enforcement of regulations to contain the Diaprepes root weevil was frequently difficult (Knapp et al. 2000; Nigg et al. 1998). In 2001, Diaprepes was accidentally introduced into citrus near McAllen, Texas (Skaria and French 2001).

Despite being capable of strong, short-duration flight, this weevil prefers to "hitchhike" — as adults on plants and as larvae in soil moved by people.

In 2005, Diaprepes was identified in Southern California. Currently, it can be found in five small areas in Orange County, two areas in Los Angeles County, and along the coast of San Diego County in numerous locations from approximately Oceanside to La Jolla. A climate-matching model based on two biological attributes of Diaprepes root weevil (the lower temperature thresholds for oviposition and larval development determined in constant temperature studies) and limited temperature data (11 sites in Orange, Los Angeles, Riverside, Imperial and San Diego counties) suggests that this weevil will only survive in limited areas of Southern California and parts of the San Joaquin Valley (LaPointe et al. 2007). However, the model does not take into account the weevils' ability to adapt to environmental conditions and California's many microclimates. The weevil is already found in areas of Southern California that the model predicted would not support Diaprepes. Strict and effective quarantines are required to prevent its spread into new areas of California via nursery stock.

California is the largest producer of fresh citrus, avocados and nursery products in the United States. Average farm-gate values are $593 million for orange, $86 million for grapefruit, $307 million for lemon and $332 million for avocado. With average annual receipts of $15.7 billion, the U.S. nursery industry ranks third among all agricultural commodities after corn ($26.8 billion) and soybeans ($18.3 billion) (NASS 2006). California alone accounts for 22% by value of all U.S. nursery production. All citrus and avocado production and most nursery production in Southern California and the San Joaquin Valley are potentially at risk for Diaprepes; if this weevil becomes established, production would be significantly affected.

Estimating production costs

Cost estimates begin with determining the appropriate Diaprepres pest controls for California growers, and their costs. Once the costs of individual pest treatments for adults and larvae are estimated, total costs for different treatment scenarios can be calculated and compared. Quarantine costs are then determined based on the interior state quarantine established by the California Department of Food and Agriculture.

Citrus and avocado. For the California citrus and avocado industries,

Photos: Beth Grafton-Cardwell

Left, **root weevil larvae create "feeding galleries" on lemon tree roots;** ***middle***, **damaged roots can provide entryways for root-rot organisms;** ***right***, **a lemon tree infested by Diaprepes was defoliated and had a very small root system.**


David Kellum

Infested citrus plants in a San Diego County nursery are marked with red flagging tape.


Beth Grafton-Cardwell

The small, defoliated tree shown in a San Diego County lemon grove has numerous weevils infesting the roots.

we developed alternative Diaprepres pest-control treatments based on methods used by Florida growers. These treatments were then modified for California's agricultural and climatic conditions. Once the alternatives were determined, costs were estimated by contacting pest-control companies. For alternatives that can be custom applied, we obtained the total cost for materials and applications. For alternatives that are not custom applied, pest control companies provided material costs. The application costs to complete these pest treatment alternatives were taken from the Sample Costs of Production studies by UC Cooperative Extension (http://coststudies.ucdavis.edu/current.php). After treatment costs per acre were estimated, costs were compared to determine the options that California growers would most likely adopt, and an average value over the most likely treatments was calculated. Then the treatment costs per ton for citrus and avocado were estimated by dividing costs per acre by average tons produced per acre.

Quarantine protocols for the citrus and avocado industries were determined through interviews with county personnel from the agricultural commissioner's offices in affected counties, and industry representatives. Costs to meet the quarantine regulations were based on changes in harvesting costs per ton, taken from the Sample Costs of Production budgets for orange, lemon, grapefruit and avocado (O'Connell et al. 2005a; O'Connell et al. 2005b; Takele and Mauk 1998; Takele, Bender, et al. 2002; Takele, Faber, et al. 2002). Because the most recent budget for grapefruit was prepared in 1998, the cost to harvest grapefruit was inflated to 2005 values using the farm price index for prices paid by farmers (Council of Economic Advisors 2007). The total change in costs was then equal to treatment costs per ton plus quarantine costs per ton.

The effect of increased production costs on growers depends, in addition to the magnitude of the increase, upon its relation to current costs and revenues. A cost increase that represents only 1% to 2% of current revenues has different economic implications than one of 15% to 20%, because it is easier to pass on a 1% to 2% share of revenues than a 15% to 20% share. For this study, the relative magnitude of the cost increase was determined as a share of revenues by dividing the increased cost per ton by the price per ton. Revenues were used instead of costs at preinfestation levels because they provided a consistent comparison for all crops in this study. The price per ton is a 3-year average for California from 2004 to 2006 (NASS 2006). A 3-year average is sufficiently long to capture seasonal variations in output, but short enough to avoid capturing trend effects.

Nursery industry. Nursery production is made up of diverse operations including potted interior and exterior plants, cut flowers and foliage, bedding, starter flowering and vegetable plants, and Christmas trees. As a result, we estimated the quarantine costs for an "average" nursery that produces potted plants. However, average costs can vary widely. For example, a nursery that produces mostly bedding plants and small shrubs will have a smaller increase in costs than one that produces large landscape trees grown for several years before being sold.

Changes in nursery production costs were estimated only on a per-acre basis, since there was no consistent data on the quantities produced per acre. To place the cost increase due to Diaprepes in context, we also compared it to revenues received per acre. We used the *Floriculture and Nursery Yearbook* to compile data on revenues per acre (USDA 2006). Due to data limitations, revenues per acre for the affected items could not be separated from total revenues per acre (for example, this figure includes items such as Christmas trees, which are not a regulated host commodity). Consequently, the total revenues per acre for all floriculture and other nursery crops were used as the best approximation of revenues per acre for the items at risk from establishment of Diaprepes in California.

Because of the size of the industries potentially affected by Diaprepes, changes in production costs due to the establishment of an exotic pest may affect market prices as growers pass on higher costs or remove land from production. Higher prices would cause producers in California and the rest of the United States to increase production and consumers to reduce consumption. The establishment of Diaprepes in California would affect both consumers and producers through changes in

TABLE 1. Diaprepes treatment cost per application

Life stage	Chemical	Application rate	Applications	Materials	Application	Total
		per acre	*no.*	.... *$ per acre*	....	
Adult	Bifenthrin	40 ounces	2	68*	25*	93
	Carbaryl/oil	8 pounds	1	63*	25*	88
	Carbaryl/oil	1.5 gallons	1	68*	25*	93
Larvae	Imidacloprid	14 ounces	2.8	148*	5†	153
	S. riobravis	1.3 billion each	3	177*	5†	182

* Costs from pest control companies.
† Application costs from Sample Costs of Production budgets (http://coststudies.ucdavis.edu/current.php).

TABLE 2. Increase in production and quarantine cost if Diaprepes becomes established

Pest control/foliar spray treatment for adults	Ground treatment for larvae	Cost	Orange	Grapefruit	Lemon	Avocado
		$ per acre	....	*$ per ton*	....	
One spray carbaryl	*S. riobravis*	625*	52.8	38.0	36.7	189.2
Two sprays bifenthrin	*S. riobravis*	722	61.1	44.0	42.5	218.7
Two sprays carbaryl	Imidacloprid	599*	50.6	36.5	35.2	181.4
Two sprays bifenthrin	Imidacloprid	609*	51.5	37.0	35.8	184.3
One spray carbaryl, one bifenthrin	Imidacloprid	604*	51.1	36.7	35.5	182.8
Average treatment cost		609*	51.5	37.1	35.8	184.4
Standard deviations		(11.27)	(0.94)	(0.67)	(0.65)	(3.40)
Quarantine						
Cost per ton ($)			2.1	8.1	6.7	15.8
Total cost increase per ton ($)			53.6	45.2	42.5	200.3
Grower revenues before infestation per ton ($)			248.0	461.0	756.0	1765.0
Cost increase as share of revenues (%)			21.61	9.8	5.62	11.35

* Cost used to determine the average price per acre to treat Diaprepes root weevil.

the costs of production, market prices, market supply and consumption; these effects are estimated elsewhere (Jetter 2007). Urban landscapes would also be affected if Diaprepes continues to spread, due to larval feeding that damages the roots of host landscape plants, backyard citrus trees and avocado trees. While important and potentially significant, an estimation of these costs is beyond the scope of this study.

Pest-control alternatives

Treatments. Diaprepes control in California includes a treatment for adults that live on plant foliage to prevent egg laying, and a treatment for larvae that live in the soil and feed on plant roots (Stansly 2007; Duncan et al. 2007). In Florida's sandy soils, the treatment for Diaprepes is one foliar spray per year using carbaryl to control adults, and releases of a parasitic nematode, *Steinernema riobravis*, to control larvae (UC IPM Online 2007; Stansly 2007). If carbaryl is not used, then growers apply two sprays of bifenthrin. After 5 to 6 years, continual releases of *S. riobravis* cause natural enemies of the larvae to build up in the soil, and annual releases of *S. riobravis* may no longer be necessary (Duncan et al. 2007). In heavier soils, the success of *S. riobravis* is more variable. If parasitic nematodes are not as successful in the heavier soils of most citrus-growing areas in California, effective control of the larvae can be accomplished using soil applications of imidacloprid. Along with imidacloprid, two foliar sprays with carbaryl or bifenthrin are applied to target adult weevils.

Costs. The cost for one treatment of bifenthrin or liquid carbaryl plus oil is $93 per acre (table 1). Materials and application costs for both chemicals are the same. The cost to treat with the granular formulation of carbaryl plus oil is slightly lower than the liquid formulation due to the lower cost of materials, and the application costs are the same. Costs for single treatments of bifenthrin and carbaryl are similar, but because two treatments of bifenthrin are recommended, the total cost to use bifenthrin is greater than that of carbaryl.

The treatment cost per application for larvae is lower for imidacloprid than for *S. riobravis* (table 1). Both imidacloprid and *S. riobravis* are applied through the irrigation system during routine irrigation. The total cost and how well each treatment controls Diaprepes will determine which pest-control technique is finally adopted in California. Efficacy is determined by the total cost to treat Diaprepes and how well infestations are managed to prevent yield losses. For example, the cost for *S. riobravis* is greater than imidacloprid; however, if *S. riobravis* is better at controlling Diaprepes larvae and losses are lower, the net cost for *S. riobravis* may be lower. Due to inexperience in treating Diaprepes in California, however, net yield losses for all treatments are unknown; therefore, possible net changes in yields are not included in this analysis.

Evaluating treatment options

Adult and larva treatment options were paired to determine the alternative costs per acre to treat Diaprepes in citrus and avocado. The cost to use the most effective treatment in sandy soils — a single spray with carbaryl and three releases of *S. riobravis* — was $625 per acre (table 2). If two treatments of bifenthrin are used instead of one treatment of carbaryl, the cost increases to $722 per acre. It seems unlikely that growers would adopt this method unless pest resistance to carbaryl is a concern or other treatment considerations arise. If *S. riobravis* is not able to reduce Diaprepes larvae in California below damaging levels, growers may switch to imidacloprid; however, an additional treatment of carbaryl may be needed to manage adult infestations and reduce yield losses. Because the per-treatment costs of applying carbaryl or bifenthrin were similar, costs for the different imidacloprid treatment scenarios were similar. Except for the two sprays of bifenthrin/release *S. riobravis* alternative, control costs for the different treatments were close and ranged from $599 to $625 per acre. Given this similarity, the average of all treatment alternatives, excluding bifenthrin/*S. riobravis*, was $609 per acre, calculated to represent the potential increase in production costs for citrus and avocado growers in the United States.

Dividing the increase in cost per acre by average yields provides the average increase in cost per ton. Yields (tons) per acre varied by crop: orange, 11.8; grapefruit, 16.4; lemon, 17; and avocado, 3.3. With the highest yields per acre, grapefruit and lemon had the lowest increase in cost per ton for pest treatments due to Diaprepes infestations. The increase in average cost per acre would be $37.10 per ton for grapefruit and $35.80 per ton for lemon (table 2). The cost to grow oranges increased by $51.50 per ton. The cost to grow avocados, with the lowest yields per acre, increased $184.40 per ton.

Quarantine costs. In addition to treating infestations of Diaprepes, growers will have to meet quarantine regulations to market harvested fruit. Because Diaprepes weevils feed and oviposit on the leaves rather than fruit of susceptible plants, quarantine regulations for citrus and avocado only require that fruit leaving the orchard be free of leaves, twigs and Diaprepes adults in bins of fruit (Nigg et al. 1998). Fruit leaving quarantined areas is subject to inspection. Currently, citrus and avocado are hand-harvested into sacks, and the sacks are then carefully emptied into bins outside the orchard. Leaves that are picked during harvesting of the fruit also end up in the sack. Extra labor can be hired to carefully pick and load the fruit in a manner that does not cause leaves or weevils to fall into the sacks or bins. The extra labor was estimated to increase harvesting costs by 5% in order to meet postharvest quarantine regulations; the increase in harvesting costs per ton was $2.10 for orange, $8.10 for grapefruit, $6.70 for lemon and $15.80 for avocado (table 2).

Total cost changes. The total increase in costs per ton due to the establishment and spread of Diaprepes root weevil in California would be $53.60 for orange, $45.20 for grapefruit, $42.50 for lemon and $200.00 for avocado. While the absolute increase in cost per ton was higher for avocado than orange growers, the increase as a share of revenues was lower for avocado (11.35%) than for orange growers (21.61%) (table 2). The share for avocados was lower than for oranges because the original cost to produce avocados is higher. Grapefruit and lemon have both the lowest increase in cost per ton and the lowest share of revenues. The increase in production cost as a share of revenues was 9.80% for grapefruit and 5.62% for lemon.

Citrus growing in Southern California orchards and nurseries is at greatest risk of economic damage from Diaprepres. Nurseries infested with the weevil will pay an estimated $525 per acre to comply with state-imposed quarantines. *Above*, the soil of nursery plants is inspected for weevils.

Nursery treatment and quarantine

Quarantine regulations vary depending on whether a nursery is infested with Diaprepes. Nurseries within the quarantine area but without infestations are required to incorporate the granular insecticide bifenthrin into the soil before plants are potted. The granular treatment is good for 2 years, then growers are required to use a soil drench every 6 months. No data was available on how many acres of potted ornamental plants were sold within two years of being potted and after two years; for this analysis, only the initial granular treatment costs were included. Additional costs could be incurred for treatments to meet quarantine regulations for potted plants more than 2 years old, or for repotting into larger pots. We estimated the average cost to meet quarantine regulations for nurseries in the quarantine area — but free of Diaprepes — to be $300 per acre.

If a nursery is inspected and found to be infested with Diaprepes, an additional foliar spray treatment with carbaryl is required before plants can be

TABLE 3. Effect of Diaprepes on the nursery industry

	Clean nursery			Infested nursery		
	Floriculture	Other	Combined	Floriculture	Other	Combined
Revenue per acre ($)	93,914	41,158	66,709	93,914	41,158	66,709
Cost of quarantine protocols per acre ($)	300	300	300	525	525	525
Cost increase as share of revenues (%)	0.32	0.73	0.45	0.39	0.88	0.55

shipped. All plants must be sprayed. The additional cost for a nursery infested with Diaprepes was an estimated $225 per acre and the total cost to meet quarantine regulations was $525 per acre.

Total average revenues per acre are $93,914 for floriculture industries and $41,158 for other nursery production (table 3) (USDA 2006). The weighted average revenue of both nursery industries is $66,709 per acre. The increase in total cost as a share of revenues, to meet quarantine regulations for nurseries in a quarantine area but free of Diaprepes, is 0.32% for floriculture and 0.73% for other nursery industries, for an average of 0.45%. The cost increase for infested nurseries as a share of revenues is larger due to foliar treatments. The $525 increase in production cost for infested nurseries is 0.39% of total revenues for floriculture, 0.88% for other nurseries and 0.55% for the industries combined (table 3). While growers with infestations pay more, higher costs as a share of revenue are still less than 1%.

Implications for growers, consumers

Since the eradication program was discontinued, the quarantine program is critical to keep Diaprepres from spreading to other parts of California. If left untreated, this destructive weevil — a "hitchhiker" in plants, bins of fruit, and even inside cars and trucks — could cause serious production declines for the California citrus, avocado and ornamental nursery industries, as well as kill plants in urban, public and natural areas. Rather than let plants die or production decline, growers in Florida treat for Diaprepes, and growers in California will also need to treat.

To protect crops and meet quarantine regulations, producers of citrus, avocado and ornamental plants will need to pay hundreds of dollars in treatment costs per acre or switch to different crops or economic activities. The final effect on each industry will depend upon the magnitude of the cost changes relative to current costs and revenues. Industries for which the change in costs is large relative to current revenues will have to make greater adjustments in price and acreage than industries with smaller increases. Ultimately, given the size of these industries and their contribution to total U.S. production, product markets will also be affected, causing consumers to pay more for fresh citrus, avocado and landscaping plants.

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RESEARCH ARTICLE

Losses due to lenticel rot are an increasing concern for Kern County potato growers

by James J. Farrar, J. Joseph Nunez *and* R. Michael Davis

In recent years, lenticel rot of potato tubers, caused by the bacterium* Erwinia carotovora *subsp.* carotovora*, has become an economically important postharvest disease for Kern County growers. Disease symptoms are sunken and rotted tissue surrounding tuber lenticels, which develop after harvest and packing. In the field, the bacterium also causes Erwinia early dying, characterized by wilt and progressive necrosis of leaves, eventually resulting in potato plant death. This study confirms* Erwinia carotovora *subsp.* carotovora *as the causal agent of both problems in Kern County and establishes the link between the field and postharvest diseases. Control of both diseases is difficult and relies on the integration of cultural methods, from preplant seed-piece handling to postharvest processing.

Postharvest lenticel rot has been known in California for nearly a century, but did not reach damaging levels until the late 1990s. The rot occurs around the small ovals where air is exchanged on the potato surface.

With a $186 million market value (similar to onions), the California potato industry is small compared to that of potato-producing giants like Idaho and Washington, but potatoes are certainly an important regional crop. Kern County is California's largest potato-growing region, with 16,470 acres (6,665 hectares) planted in 2007 to red, white, russet and chipping varieties. Total harvest from Kern County was 432,000 metric tons (5,261,800 hundredweight [cwt]) in 2007, with total sales of about $60 million.

Potato cultivation in this region occurs during two seasons, the spring season from January to June and the fall season from August to December. Excessive postharvest losses, especially after potato shipments have reached the marketplace, have resulted in significant economic losses to growers in the San Joaquin Valley. Produce buyers for large national grocery outlets carefully scrutinize California potatoes for sunken and rotted tissue surrounding tuber lenticels, the small oval areas on the surface of a potato where air exchange occurs. Unsightly rotted or discolored lenticel tissues render the potatoes unmarketable, and occasionally shipments of California potatoes are dumped.

Lenticel rot has probably been in California since potato production became established in Kern County in 1912, but did not reach damaging levels until the late 1990s. Currently, we have observed that lenticel rot affects an estimated 30% of harvested potato tubers in Kern County. In the San Joaquin Valley, the warm climate and heavy irrigation of the crop may exacerbate this problem. Recently, we discovered that the same causal organism of lenticel rot is associated with a decline of potato plants called Erwinia early dying.

Description of symptoms

Lenticel rot. Lenticel rot is characterized by dry and sunken discolored lesions surrounding potato tuber lenticels. Lesions begin as swollen areas surrounding the lenticels or as small areas of white, puffy tissue pouring forth from the lenticels. Usually, affected tissue does not extend deeper than 1/8 inch (3 millimeters) into the tuber. Neighboring lesions may coalesce to form larger, irregularly shaped sunken areas. Symptoms are most often noticeable 4 to 10 days after the harvest and packaging of potatoes. If potatoes are stored wet and conditions are warm, a soft rot of the surrounding tissue may ensue, and extensive decay of the entire tuber may occur in extreme cases. Often, these symptoms become apparent in tubers during transportation to market.

Erwinia early dying. Lenticel rot is often associated with a potato plant disease called Erwinia early dying (Powelson 1985). The initial symptom is wilting of the leaflets or whole leaves on plants in adequately irrigated fields. Leaves later become necrotic (dead) beginning at the margins. Plants may defoliate from the base upward and often senesce (decline and die) prematurely. The stems appear healthy externally, but the vascular system and pith of the lower stem — extending upward from the junction with the seed piece (the piece of a potato tuber that is planted as seed) — are tan to brown in color. A soft rot of the seed pieces occurs, and yields are negatively affected.

Verticillium early dying. Symptoms of Erwinia early dying are similar to Verticillium early dying, which is caused by *Verticillium* spp. and lesion nematodes (Powelson 1985; Rowe et al. 1987). Verticillium wilt is common in other potato-growing regions of the United States. *Verticillium* spp. are common fungal pathogens of alfalfa, cotton, cucurbits, pepper and tomatoes but are only occasionally recovered from potato in the San Joaquin Valley. Lesion nematodes (*Pratylenchus* spp.) are common pests of alfalfa and orchard crops in the San Joaquin Valley but are also seldom observed in potato fields. Symptoms of Verticillium early dying are leaf chlorosis (yellowing) progressing from the lower leaves to the upper leaves, leaf necrosis and light brown discoloration of the vascular tissue. In contrast to Verticillium early dying, Erwinia-induced early dying is always associated with rotted seed pieces, warm soil temperatures and high soil moisture.

Seed-piece syndrome. Erwinia early dying can also be confused with a problem that Kern County potato growers call toxic seed-piece syndrome. This problem is caused by planting physiologically old seed and is characterized by rapid emergence, multiple stems, small weak plants, numerous small tubers, lower yields and early senescence. Physiologically "old" seed is not clearly defined, but we have observed these symptoms on plants grown from seed kept in storage for 1 year. Conversely, the characteristics of plants from young seed include slow emergence, few main stems, vigorous large plants, fewer larger tubers, higher yields and delayed senescence. Erwinia early dying affects plants grown from young or old seed.

Causal agents of potato disease

Due to the association between early dying symptoms in the field and postharvest lenticel rot symptoms, we decided to carefully examine the causal agents for both diseases.

Lenticel rot. We isolated *Erwinia carotovora* subsp. *carotovora* (more recently called *Pectobacterium carotovorum* subsp. *carotovorum*) from symptomatic lenticels. Three-hundred tubers were collected over 3 years from commercial potato fields in Kern County. In addition, 30 tubers were collected postharvest from packing sheds.

The surfaces of tubers were washed thoroughly with soap and water, then rinsed well in deionized water and air-dried. The tissue surrounding the affected lenticels was excised, dipped in 0.5% sodium hypochlorite for 1 minute, rinsed in sterilized water and macerated in a few drops of sterilized water. Approximately 10 microliters of each suspension was spread onto King's B and nutrient agar plates. Plates were incubated at 77°F (25°C) and evaluated after 48 hours. The number of visibly different colonies (based on morphology) present on each plate was noted. Unique colony types occurring on multiple plates were subcultured onto nutrient agar. Genomic DNA was then extracted from these isolates (Qiagen DNeasy kit, Qiagen, Valencia, Calif.) and the 16S rDNA gene was amplified using universal bacterial primers fp1 and rd1 (Sessitch et al. 2001). Sequences obtained from these PCR (polymerase chain reaction) products were identified based on a comparison of international DNA-sequence databases.

Fifty isolates were tested for their ability to cause tuber soft rot by stab-inoculating flame-sterilized tuber slices with twice-autoclaved toothpicks smeared in bacteria. The tuber slices were then incubated at 77°F (25°C) for 24 hours. In addition, the pathogenicity of isolates in lenticels was determined by submerging washed tubers in a pressurized (30 pounds per square inch) container of a suspension of *E. carotovora* subsp. *carotovora* cells (approximately 10^6 cells per milliliter). Inoculated tubers were then wrapped in a moist paper towel and placed in closed plastic bags to exclude oxygen. After 5 and 10 days, tubers were removed and examined for lenticel rot. Bacteria were reisolated from lenticel rot tissues and reidentified as *E. carotovora* subsp. *carotovora*.

The initial symptoms of Erwinia early dying — a potato plant disease associated with lenticel rot — include leaf wilt in adequately irrigated fields.

The bacteria that cause lenticel rot and Erwinia early dying are common on the surface of potato tubers, in soil and in surface irrigation water.

As Erwinia early dying progresses, leaves wilt further and die, sometimes killing the potato plant. When potatoes from these diseased plants are washed, bacteria can get into the lenticels and cause them to rot.

Erwinia early dying. Erwinia early dying is caused predominantly by *Erwinia cartovora* subsp. *carotovora* (Ecc) and to a lesser extent by *Erwinia chrysanthemi* (Echr). The causal agent of blackleg of potato, *Erwinia carotovora* subsp. *atroseptica*, is not associated with Erwinia early dying. Blackleg is characterized by a black to brown soft rot of the stems extending from the seed piece upward. Potato plants with blackleg are typically stunted and usually die prior to canopy closure in the San Joaquin Valley.

We determined the causes of early dying by isolating the causal agents from diseased plants and inoculating healthy plants. In a random collection of more than 100 plants with symptoms of Erwinia early dying and blackleg in 13 fields, bacteria associated with discolored stems and seed pieces were identified by fatty-acid methyl-ester analysis (MIDI Microbial Identification System, ver. 3.8, Newark, Del.) and standard physiological identification techniques (Dickey and Kelman 1988).

Sixty-two isolates were identified; 13 were *E. carotovora* subsp. *atroseptica* (Eca), 42 were *E. carotovora* subsp. *carotovora* (Ecc), two were *Erwinia chrysanthemi* (Echr) and five were *Pseudomonas fluorescens* (=*P. marginalis*). Fungi were not generally isolated from the affected stems, and nematodes were not observed on the affected plants. In Kern County, *Verticillium* spp. and lesion nematodes rarely affect potatoes. The absence of Verticillium and nematode problems may be due to routine soil fumigation with metam sodium, which is standard practice for vegetable growers in the region.

Suspensions of bacterial isolates were injected by syringe into the stems of 30 12- to 15-week-old greenhouse-grown potato plants. Sterile water was used as a control. Symptoms were noted after 2 to 3 days. Syringe-inoculated greenhouse plants developed two distinct sets of symptoms. Plants inoculated with Eca isolates developed symptoms of blackleg, which are leaf wilt, a soft black stem rot and stem collapse. Plants inoculated with the Ecc or Echr isolates developed leaf wilt, an external brown lesion at the inoculation point, brown discoloration of the vascular system and soft rot of the pith. The vascular system discoloration and pith rot extended up to several centimeters above and below the inoculation point. Bacteria were reisolated and reidentified for confirmation. The bacteria reisolated from syringe-inoculated plants was identical to the respective original isolates. Therefore, Ecc and Echr inoculations resulted in Erwinia early dying symptoms and Eca inoculations resulted in blackleg symptoms.

Epidemiology

The bacteria that cause lenticel rot and Erwinia early dying are common on the surface of potato tubers, in soil and in surface irrigation water (Romberg et al. 2002; Harrison et al. 1987). Potatoes can be freed of Erwinia contamination through tissue culture but will reacquire the bacteria when planted in soil. While soil levels of Ecc are highest immediately after the production of a susceptible crop like potatoes, carrots or onions, low background levels of Ecc are always present (Powelson and Apple 1984).

In Kern County, the major potato planting occurs in January and February for harvest in June. Potatoes are planted in cool weather, and the air and soil temperatures increase as the season progresses. Because potatoes are grown in sandy soil and are a shallow-rooted crop, growers irrigate frequently, especially when temperatures are warm. To our knowledge, there is no other large potato-producing region in the United States where the air temperature becomes as warm late in the production season. Warm temperatures and moisture are known to promote Erwinia soft-rot diseases.

During the lifting and harvest of potatoes, tubers can be smeared with soft-rot bacteria from decayed seed pieces. At the packing shed, potatoes are first dumped into a wash tank to clean them. Surface bacteria can be pushed into lenticels by hydrostatic (exerted by water) pressure in the wash tanks (Bartz and Kelman 1985). Hydrostatic pressure increases with increasing depth of the tank. Once inside the lenticel tissue, the bacteria multiply and cause lenticel rot.

Integrated controls for soft rot

There are no effective chemical controls for any of the soft-rot Erwinias. The management of all Erwinia diseases of potatoes involves integrating cultural controls from seed handling to harvest. Seed tubers should be handled carefully to avoid bruising or any other

A rotten lower potato stem with Erwinia early dying disease (left) and a healthy stem (right).

Seed-piece decay is associated with Erwinia leaf and stem symptoms; note the open lenticels on the potato tubers.

mechanical injuries. Cut seed should be allowed to heal to provide a barrier against bacteria. Management of water and soil fertility throughout the growing season is critical to reduce the incidence of disease. Tubers should be harvested when the skins are set and the lenticels are closed, since breaks in the skins and open lenticels are good avenues for infection. Since soft-rot Erwinias can be drawn into tubers through open lenticels as the warm tubers are washed in cool water during the dump wash process, tubers should not be exposed to hydrostatic pressure from either deep tanks or tall rises in flumes (pipes for moving tubers from the wash tank) in the packing sheds. Care should be taken to avoid scuffing, cutting or bruising potatoes during sorting and packaging. Finally, potatoes should be stored dry and cool.

Good calcium fertility management in the field also reduces postharvest Erwinia losses. Calcium is integral to maintaining cell-wall rigidity and it counters the activity of soft-rot Erwinia enzymes, which degrade the cell walls. Soluble calcium must be in the soil surrounding developing tubers, since tubers receive little calcium from the plant transpiration stream. Water and minerals taken up from the soil by the roots are drawn to plant parts with high evaporation rates. Since the developing tubers are in the soil, they have a low evaporation rate, therefore little calcium moves from the roots to the developing tubers.

Antimicrobial agents such as peroxyacetic acid and hydrogen peroxide, applied as a final rinse in the packing process, are effective in reducing the tuber surface populations of soft-rot organisms, resulting in less postharvest loss to lenticel rot. These agents can reduce lenticel rot, but there are no effective chemical controls for Erwinia early dying (J. Nunez and M. Davis, unpublished). Erwinia early dying is distinct from early dying due to *Verticillium* spp. and lesion nematodes, which has been reported in other potato-growing regions, and may be more of a problem in Kern County due to the routine fumigation of potato production soils and warm temperatures. If projected temperature increases due to global warming are correct, then losses from lenticel rot and Erwinia early dying can be expected to increase in the future.

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REVIEW ARTICLE

Drip irrigation provides the salinity control needed for profitable irrigation of tomatoes in the San Joaquin Valley

by Blaine R. Hanson, Don E. May, Jirka Šimůnek, Jan W. Hopmans *and* Robert B. Hutmacher

Despite nearly 30 years of research supporting the need for subsurface drainage-water disposal facilities, the lack of these facilities continues to plague agriculture on the San Joaquin Valley's west side. One option for coping with the resulting soil salinity and shallow water-table problems is to convert from furrow or sprinkle irrigation to drip irrigation. Commercial field studies showed that subsurface drip systems can be highly profitable for growing processing tomatoes in the San Joaquin Valley, provided that the leaching fraction can achieve adequate salinity control in the root zone. Computer simulations of water and salt movement showed localized leaching fractions of about 25% under subsurface drip irrigation, when water applications equaled the potential crop evapotranspiration. This research suggests that subsurface drip irrigation can be successfully used in commercial fields without increasing root-zone soil salinity, potentially eliminating the need for subsurface drainage-water disposal facilities.

Subsurface drip irrigation is allowing San Joaquin Valley tomato growers to apply water precisely and uniformly, increasing yields and reducing the runoff of saline drainage water.

The lack of widespread subsurface drainage-water disposal facilities continues to plague agriculture along the west side of the San Joaquin Valley. Despite more than 30 years of research, drainage-water disposal methods that are economically, technically, politically and environmentally feasible have not been implemented. In some areas, land retirement has been the result.

A UC study (Schoups et al. 2005) concluded that a salt balance must be maintained in the root zone for productive cropping systems to continue, and irrigation without improved management practices cannot be sustained in the San Joaquin Valley. The only options available to address salinity and drainage problems without retiring land are: (1) reducing drainage through the better management of irrigation water; (2) increasing the use of shallow groundwater for crop irrigation without any yield reductions; and (3) reusing drainage water. All three methods require adequate salinity control in the root zone. This study is an example of the first option; as a result, subsurface drip irrigation is commonly used in salt-affected soils for processing tomato production. The second option has been proposed, but little information exists on its use by growers. The California Department of Water Resources is promoting the third option, but its use is limited and still in an experimental stage.

One way to implement option one is to convert from furrow or sprinkle irrigation to drip irrigation. Drip irrigation applies water precisely and uniformly at high frequencies, potentially increasing yield and reducing root-zone soil salinity and drainage. These advantages are not only governed by the technology, but also by the design, installation, opera-

Subsurface drainage systems and drainage-water disposal methods are not needed for properly designed and managed drip irrigation systems.

tion and maintenance of drip systems. The main disadvantage of drip irrigation is its high installation cost, which ranges from $600 to $1,000 per acre. Subsurface drip irrigation, commonly used for processing tomatoes, involves placing drip lines 8 to 12 inches below the soil surface directly below the plant row; surface drip irrigation involves placing the drip lines on the soil surface.

In the late 1980s, two large-scale comparisons of subsurface drip and furrow irrigation were conducted in cotton under saline, shallow groundwater conditions (Fulton et al. 1991; Styles et al. 1997). Drip irrigation consistently resulted in higher cotton yields with less water application than furrow irrigation. However, the profit with furrow irrigation was much higher at one location, and drip irrigation was only slightly more profitable at the other. The cost of the drip systems played the major role in their profitability. As a result, growers who convert to drip irrigation of cotton assume an additional economic risk.

In 2008, the Westlands Water District — which encompasses more than 600,000 acres of farmland in western Fresno and Kings counties — reported 37,396 acres of cotton and 86,011 acres of processing tomatoes, now the largest single crop acreage; cotton production has decreased substantially in recent years (Westlands Water District 2009). Because processing tomatoes are a higher value crop than cotton, subsurface drip irrigation offers potentially higher profits. However, unlike cotton, tomatoes are moderately sensitive to soil salinity, and reduced tomato yields can result. The threshold electrical conductivity (EC), which represents the maximum root-zone soil salinity at which yield is not reduced, is 2.5 deciSiemens per meter (dS/m) for tomato compared to 7.7 dS/m for cotton (Mass and Grattan 1999).

Between 1998 and 2003, experiments in commercial fields in the Westlands Water District, on the San Joaquin Valley's west side, evaluated subsurface drip irrigation of processing tomatoes under saline, shallow groundwater conditions. In addition, starting in 2006, computer simulations using the HYDRUS-2D model (Šimůnek et al. 1999) evaluated leaching with subsurface drip irrigation under these conditions. This model has been used previously in studies of water and chemical movement under drip irrigation (Gärdenäs et al. 2005; Hanson, Šimůnek, et al. 2006). We present a review of this research.

Commercial field experiments

Experiments in three commercial fields (sites BR, DI and DE) compared subsurface drip irrigation to sprinkle irrigation (Hanson and May 2003, 2004). Drip systems ranged from 40 to 80 acres each in area, and sprinkle irrigation was used for the rest of the fields. Water table depths ranged from 2 to 6 feet. Electrical conductivity ranged from 0.3 dS/m for irrigation water from Westlands Water District to 1.1 dS/m for well water, and from 4.0 to 16.4 dS/m in the shallow groundwater. A small-scale, randomized, replicated experiment was conducted in each drip-irrigated field to investigate the relationship between yield, soluble solids (a measure of yield quality) and applied water. The soil type was clay loam at the three experimental sites.

We found that subsurface drip irrigation was highly profitable for processing tomatoes under these shallow, saline groundwater conditions compared to sprinkle irrigation. Average yields were 40.5 tons per acre for subsurface drip irrigation versus 33.9 tons per acre for sprinkle irrigation, with $484 per acre more profit on average for drip than sprinkle irrigation. The average difference in soluble solids between the two irrigation methods was not significant. The small-scale experiments showed increased yield and decreased soluble solids as applied water increased.

Yields of the drip-irrigated fields were monitored for 2 more years after

Andros Engineering

Specialized equipment (shown here, by Andros Engineering) is used to install drip tape 8 to 12 inches below the soil surface, at a cost of about $600 to $1,000 per acre. Despite this price, studies show that improved irrigation efficiency and yield benefits increase profits for growers in the San Joaquin Valley, compared with sprinkle or furrow irrigation.

the first year. Yields remained high except for one site, which had 2 years of reduced yields due to late plantings. We did not find any trends toward yield reductions with increased soil salinity near the drip lines, which ranged from values less than, to higher than, the threshold electrical conductivity of 2.5 dS/m for tomatoes.

At a fourth commercial field (site BR2), a small-scale, randomized-block, replicated experiment evaluated the response of tomato and cotton yields to different amounts of applied water under very shallow groundwater conditions of 18 to 24 inches (Hanson, Hutmacher, et al. 2006). The soil type was clay loam. Tomato yields ranged from 34.6 tons per acre for 15.6 inches of applied water to 42.8 tons per acre for 23.2 inches, even though near-saturated, highly saline soil occurred at only 18 inches deep. At 23.2 inches, water application is about equal to the seasonal evapotranspiration or crop water use for tomatoes. However, cotton yields did not respond when water was applied at amounts equal to or greater than about 40% of the potential seasonal evapotranspiration. The electrical conductivity of the irrigation water was 0.5 dS/m and of the groundwater was 8 to 10 dS/m (the threshold for cotton is 7.7 dS/m).

TABLE 1. Seasonal applied water, evapotranspiration and leaching fractions calculated from a water balance for four commercial sites

Year*	Seasonal applied water	Seasonal ET†	Leaching fraction‡
	. . . . *inches*		%
BR			
1999	16.0	20.3	0
2000	16.8	21.4	0
2001	20.5	22.9	0
DI			
1999	22.2	25.1	0
2000	29.0	25.2	13.1
2001	22.9	26.6	0
DE			
2000	28.8	24.2	13.6
2001	22.1	23.1	0
BR2			
2002	23.2	24.3	0

* BR, DI, DE and BR2 are site designations for the commercial fields.

† Evapotranspiration.

‡ Zero values indicate no leaching, which occurred because seasonal applied water values were smaller than seasonal evapotranspiration.

At all commercial sites, tomato yields increased as applied water increased. Factors contributing to this finding included higher soil-water content and reduced root-zone soil salinity due to larger zones of low salt around the drip lines as more water was applied. Cotton yields, however, were unresponsive to the amount of applied water, reflecting cotton's salt tolerance and ability to utilize saline, shallow groundwater (Wallender et al. 1979). Consequently, contributions by the saline, shallow groundwater to crop evapotranspiration should be minimized for tomato and maximized for cotton.

Soil salinity levels around the drip lines depended on the depth to groundwater, salinity of shallow groundwater, salinity of irrigation water and amount of applied water. For a water table depth of about 6 feet, relatively uniform soil salinity occurred throughout the profile, with values smaller than the threshold electrical conductivity of tomato (fig. 1A). For water table depths less than about 3 feet, relatively low levels of soil salinity occurred near the drip line, but values increased to high levels beyond the wetting pattern due to the upward flow of shallow groundwater (figs. 1B and 1C). Higher soil salinity occurred near the drip line when the salinity of the irrigation water increased (fig. 1C). Larger amounts of applied water increased the zone of low-salt soil near the drip line, even when shallow water tables had depths of less than 2 feet (fig. 2).

At all sites, water table depth showed little response to drip irrigation, except when overirrigation occurred during one year at site BR (data not shown). A subsequent reduction in applied water at that site caused the water table to decline due to reduced percolation and the natural drainage of shallow groundwater.

Determining leaching fractions

Salinity control is needed in the root zone to maintain profitable subsurface drip irrigation of tomatoes in salt-affected soils. This can be achieved by leaching or flushing salts from the

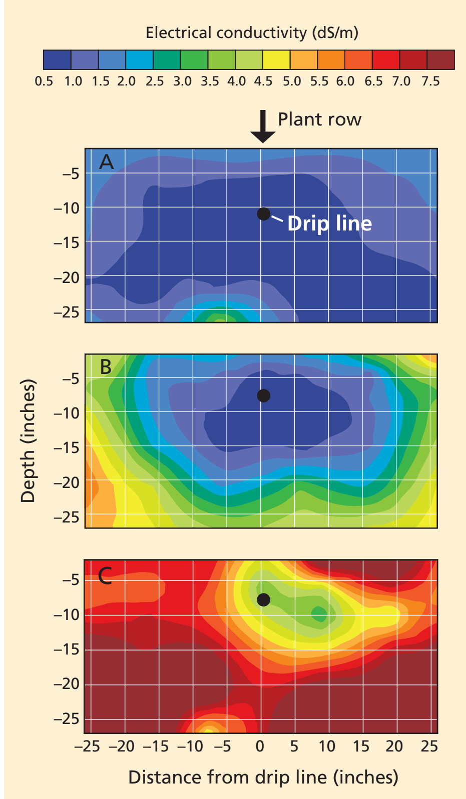

Fig. 1. Soil salinity/electrical conductivity (EC) around the drip line for water depth of about (A) 6 feet, EC irrigation water = 0.3 dS/m, EC groundwater = 8 to 11 dS/m; (B) 2 to 3 feet, EC irrigation water = 0.3 dS/m, EC groundwater = 5 to 7 dS/m; and (C) 2 to 3 feet, EC irrigation water = 1.1 dS/m, EC groundwater = 9 to 16 dS/m.

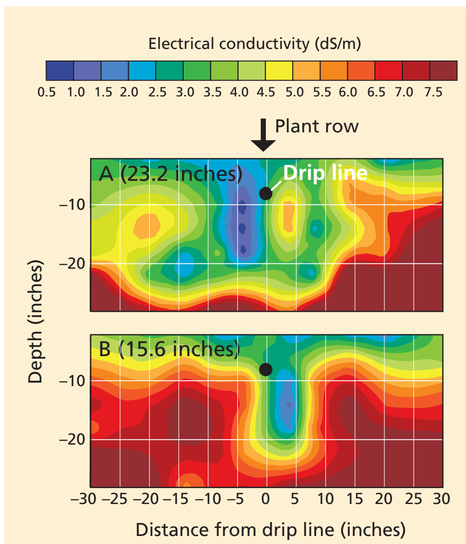

Fig. 2. Soil salinity/electrical conductivity (EC) around the drip line for water depth of about 18 to 24 inches, EC irrigation water = 0.5 dS/m, EC groundwater = 8 to 10 dS/m, for water applications of (A) 23.2 and (B) 15.6 inches.

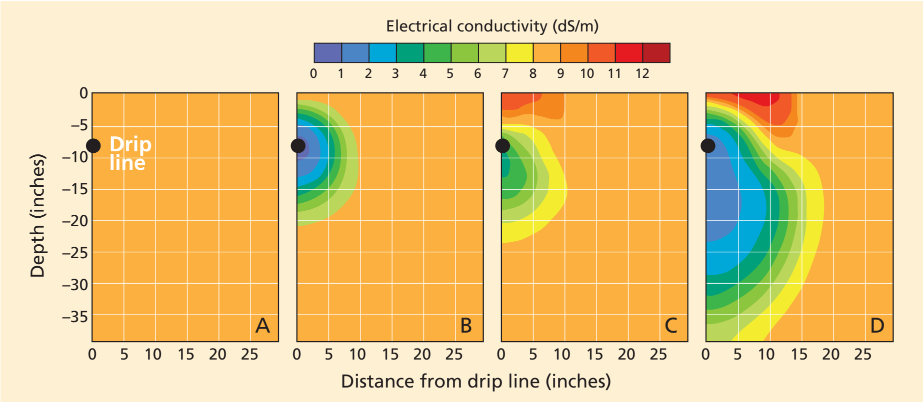

Fig. 3. Soil-water salinity/electrical conductivity (EC) around the drip lines at (A) start of simulation period (T = 0 day), (B) just after first irrigation (T = 1 day), (C) just before second irrigation (T = 3.5 days) and (D) just after last irrigation (T = 39.5 days). Applied water = 100% evapotranspiration; EC irrigation water = 0.3 dS/m.

root zone — applying irrigation water in amounts exceeding the soil moisture depletion. The leaching fraction is used to quantify leaching adequacy, and is derived from the ratio of the amount of water that drains below the root zone to the amount of water applied.

Leaching fractions can be determined several ways. One approach is to measure the average salinity of the root-zone soil and irrigation water, and then use appropriate charts or equations to determine the leaching fraction. However, soil salinity, soil-water content and root density all vary around the drip line, resulting in uncertainty about the accuracy of root-zone soil salinity.

A second approach commonly used is the water balance method, by which a fieldwide amount of leaching is calculated as the difference between the seasonal amount of applied water (measured with a flow meter) and evapotranspiration. Because actual evapotranspiration in a given field is usually unknown, it is frequently estimated using crop coefficients and a reference crop evapotranspiration value obtained from the California Irrigation Management Information System (CIMIS).

We calculated fieldwide leaching fractions for the commercial fields using the water balance method. Evapotranspiration was determined using canopy growth rates and a calibrated computer model. These calculations showed little or no fieldwide leaching at most of the sites (table 1), which suggests inadequate salinity control and raises questions about how long drip irrigation can be sustained under saline, shallow groundwater conditions. The soil salinity data, however, clearly showed that because of the wetting pattern under drip irrigation, leaching was highly concentrated near the drip line (referred to as "localized leaching"). The soil salinity data also indicated that the water balance approach is not appropriate for drip irrigation and that estimating actual or localized leaching fractions under drip irrigation may be difficult and also inaccurate. It is reasonable to expect that the salinity patterns reflect long-term behavior, as long as adequate salinity-control measures (sufficient leaching and no groundwater intrusion into the root zone) prevent salts from accumulating in the root zone.

Computer simulations

Because of the difficulties in estimating actual leaching fractions for the drip-irrigated commercial fields, we used the computer model HYDRUS-2D (Šimůnek et al. 1999) to simulate the movement of water and salt in soil under drip irrigation for a 42-day period and quantify drainage below the root zone. Simulations were conducted for water table depths of 20 and 40 inches; irrigation water salinities of 0.3, 1.0 and 2.0 dS/m; and applied water at 80%, 100% and 115% of potential evapotranspiration. For 0.3 dS/m irrigation water, we conducted an additional simulation of applied water at 60% of potential evapotranspiration. The depth of application per irrigation was based on a daily evapotranspiration rate of 0.29 inches per day, but the actual simulations varied by applied water amounts and irrigation frequency. The application rate was constant during the simulation period for a particular scenario consisting of a water table depth, an irrigation water salinity and an applied water amount.

We simulated two irrigations per week for a 40-inch water table depth, and daily irrigations for the 20-inch depth. These frequencies reflect those used in the commercial field experiments (Hanson et al. 2003). The drip line was 8 inches deep, and electrical conductivity of the shallow groundwater was 10.0 and 8.0 dS/m for the 20- and 40-inch water table depths, respectively, based on measured levels in the commercial fields. The initial soil-water salinity levels at the start of the simulation period were based on samples collected in spring, prior to drip irrigation. The simulated root distribution was based on field data of rooting patterns for drip-irrigated tomatoes at the UC West Side Research and Extension Center (Hanson and May 2007).

Simulated reclamation (salt removal) of soil near the drip line was rapid, and the simulated salinity patterns were consistent with those found in the commercial fields (fig. 3) (Hanson et al. 2008). The simulations predicted that the volume of reclaimed soil would increase over time, with most reclamation occurring below the drip line, and that salts would accumulate near the soil surface. Large seasonal applications of water would increase the zone of lower-salinity soil near the drip lines, consistent with our field data. But the larger amounts would have little effect on the volume of reclaimed soil above the drip line. As expected, salinity near the drip line would increase as irrigation water salinity increased. The root uptake of soil water would decrease as applied water decreased, suggesting the potential for decreased yields with decreasing water applications, as was found in our commercial field data for processing tomatoes.

The actual or localized leaching fractions for the 40-inch water table scenarios were 7.7% for the 60% water application treatment, 17.3% for the 80% treatment, 24.5% for the 100% treatment and 30.5% for the 115% treatment. As irrigation water salinity increased, the actual leaching fraction increased as a result of reduced root-water uptake. Even for water applications equal to or smaller than 100% of potential evapotranspiration, drainage occurred below the root zone due to the spatially variable wetting under drip irrigation.

A common assumption is that applying water at amounts equal to 100% of potential evapotranspiration results in irrigation efficiency of 100%, defined as the ratio of cumulative root-water uptake to applied water. In cases of drip irrigation at 100% of potential evapotranspiration, little drainage below the root zone is assumed to occur. However, the computer simulations showed that this assumption is not true. Because of spatially varying soil-water wetting around the drip lines, irrigation efficiency was 74.6% and 69.7% for the 40- and 20-inch water table scenarios, respectively, with the 100% water application. Very high irrigation efficiencies occurred only under conditions of severe deficit irrigation.

Because of high-frequency irrigation, the volume of drainage per irrigation was small and drainage was distributed evenly over the irrigation season. As a result, natural subsurface drainage in the commercial fields was sufficient to prevent groundwater intrusion into the root zone.

Leaching and efficient drip systems

The field research and computer simulation modeling demonstrated that subsurface drip irrigation of processing tomatoes is highly profitable compared to sprinkle or furrow irrigation under saline, shallow groundwater conditions. Tomato yields increased as applied water increased, and cotton yields were unaffected. These tomato yield results suggest that root uptake of saline, shallow groundwater should be minimized to prevent yield reductions, while the cotton yield results indicate that substantial root uptake of the saline groundwater can occur without yield reductions.

In both studies (field experiments and computer simulations), considerable localized leaching occurred around the drip lines, due to the wetting patterns of subsurface drip irrigation. The localized or actual leaching fractions determined from the computer simulations were about 25% to 30% for a water application equal to 100% of potential evapotranspiration.

Under subsurface drip irrigation of processing tomatoes, localized leaching is highly concentrated near the drip line, resulting in relatively low soil-salinity levels in areas where root density is highest. The water balance approach for estimating leaching amounts is inappropriate for drip irrigation because of such localized leaching.

The computer simulations showed that reclamation around drip lines in saline soil would be rapid. Predicted reclamation was faster for relatively infrequent large water applications per irrigation than for smaller applications. The low-salt zone around the drip line increased as the amount of applied water increased, and soil salinity around the drip line increased as salinity of the irrigation water increased.

We found that very high irrigation efficiencies under drip irrigation can only be obtained by substantial deficit irrigation, in contrast to the frequent assumption that drip irrigation is nearly 100% efficient for water applications equal to about 100% of potential evapotranspiration.

Sustainable drip irrigation

The key to sustained subsurface drip irrigation of processing tomatoes in salt-affected soils is profitability, which in turn depends on salinity control in the root zone. This requires irrigating with relatively low-salt water; applying sufficient irrigation water for adequate localized leaching; leaching salts that accumulate around the drip line; and preventing saline, shallow groundwater intrusion into the root zone. The following are recommenda-

To minimize the uptake of shallow, saline groundwater — which can affect tomato yields — sufficient irrigation water must be applied in the root zone to ensure adequate leaching. *Above*, filters, pumps and fertilizer tanks are part of drip irrigation systems.

tions for subsurface drip irrigation of processing tomatoes under conditions of the San Joaquin Valley's west side:

Water applications. Seasonal water applications should be about equal to the seasonal evapotranspiration, which is 25.5 inches in the San Joaquin Valley (Hanson and May 2006). This provides sufficient localized leaching. Higher applications could raise the water table, causing saline, shallow groundwater intrusion into the root zone. Smaller applications reduce tomato yields.

Salinity of irrigation water. The electrical conductivity of irrigation water should be about 1.0 dS/m or less; higher levels may reduce yields.

Irrigation frequency. From daily to two or three irrigations per week should occur after the start of drip irrigation (Hanson et al. 2003). Daily irrigations are recommended for very shallow, saline groundwater conditions. The amount of water application per irrigation should be determined using appropriate crop coefficients (Hanson and May 2006) and the reference crop evapotranspiration from CIMIS.

Salt leaching. Periodic leaching of salt accumulated above buried drip lines will be necessary with sprinkle irrigation for stand establishment, if winter and spring rainfall is insufficient.

System maintenance. Drip irrigation systems should be designed for a high uniformity of applied water, and should be properly maintained to prevent emitter clogging.

Drainage-water disposal

Can drip irrigation eliminate the need for expensive subsurface drainage systems and drainage-water disposal methods? We believe the answer is yes, since no subsurface drainage systems were used at our sites. Subsurface drip irrigation continues to be used at these sites along with many other fields along the San Joaquin Valley's west side.

Drip irrigation resulted in little change to the water table at these sites (except at site BR, where overirrigation occurred), and the computer simulations revealed that drainage or percolation below the root zone would occur. The field data indicated that small applications of water per irrigation and relatively uniform distribution of irrigations over time, coupled with natural subsurface drainage, prevented groundwater intrusion into the root zone. This finding suggests that, for the conditions in these fields, subsurface drainage systems and drainage-water disposal methods are not needed for properly designed and managed drip irrigation systems.

These results indicate that subsurface drip irrigation of processing tomatoes — a higher value, moderately salt-sensitive crop compared to cotton — is sustainable in the salt-affected soils that we studied. Similar results might be expected for crops of similar value that are moderately salt sensitive and suitable for drip irrigation, such as melon. Drip irrigation of salt-tolerant crops such as cotton, sugar beets and grain may not be profitable because of their relatively low cash value. While little research has been conducted in the San Joaquin Valley on drip irrigation of salt-sensitive crops under saline conditions, a literature review of numerous studies on drip irrigation of vegetable crops (Hanson et al. 2008) showed that drip irrigation may be a sustainable practice for salt-sensitive crops.

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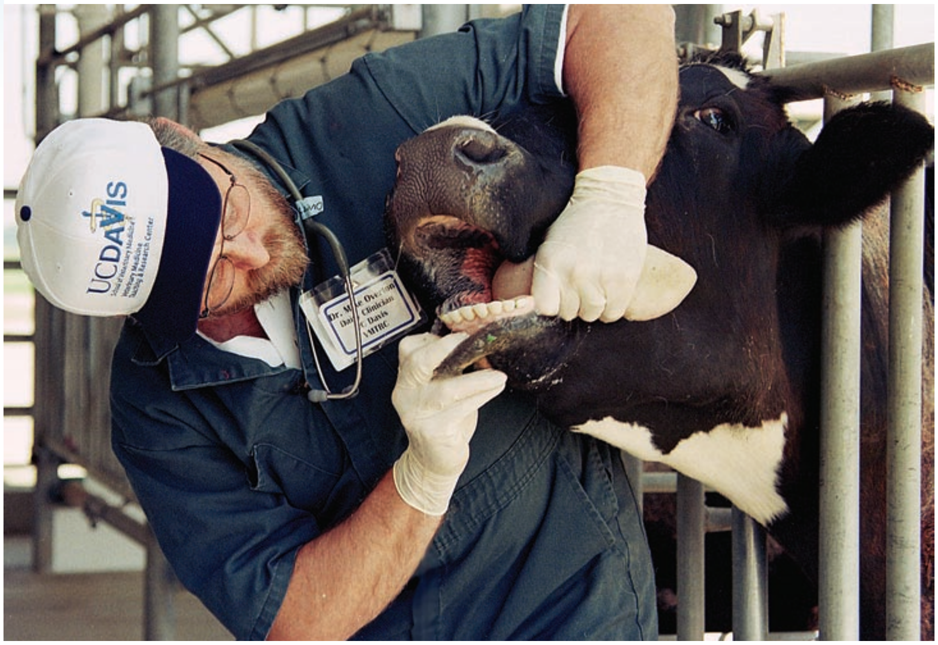
RESEARCH ARTICLE

Model could aid emergency response planning for foot-and-mouth disease outbreaks

by Mimako Kobayashi, Richard E. Howitt *and* Tim E. Carpenter

Infectious animal diseases are an ever-present threat to intensive livestock production. We analyzed control technology for foot-and-mouth disease (FMD) in a livestock-intensive region of the Central Valley, using a previously developed, numerical, optimal disease-control model. We found that the alternative FMD controls we studied (early detection, herd depopulation and vaccination) can be partially substituted for one another (substitutability) without substantially changing outbreak costs. This information can be used to develop effective and efficient policies to prepare for an FMD outbreak in California.


Lynn Narlesky

Using models to plan for outbreaks of infectious animal disease helps public policymakers to allocate resources more effectively. Michael Overton checked a healthy dairy cow for foot-and-mouth disease at UC Davis.

The risk of infectious animal diseases is an inherent and unavoidable problem in commercial livestock production. On the supply side, as production geographically concentrates and intensifies, both the risks and consequences of disease outbreaks increase. On the demand side, dependence on access to international markets increases outbreak costs, because importing countries close their markets during and in the aftermath of a disease outbreak. Because animal diseases can spread from farm to farm, a farm's actions to prevent and control diseases have positive spillover effects or "externalities" by reducing the probability that other farms are infected (Sumner et al. 2005). Economic theory tells us that in the presence of externalities, the private sector alone will not make sufficient investments in disease prevention and control. Therefore, the public sector has an important role in ensuring that mechanisms are in place to manage disease outbreaks in intensive livestock-production systems.

Public planning for potential emergency situations entails making rules and guidelines about how to respond when such events occur. The response is limited by the availability of resources. For some resources, procurement or construction is necessary before emergency situations occur. Effective planning also involves prior investments in response capacities, which determine the scale of response measures. We analyze how such investment decisions can be made when different types of response measures interact in a nonlinear way. We demonstrate that knowledge about substitutability among response measures (in this case the ability to increase some measures and decrease the others without changing the overall outbreak costs) enables the decision-maker to prioritize and target investments.

Emergency response to outbreaks

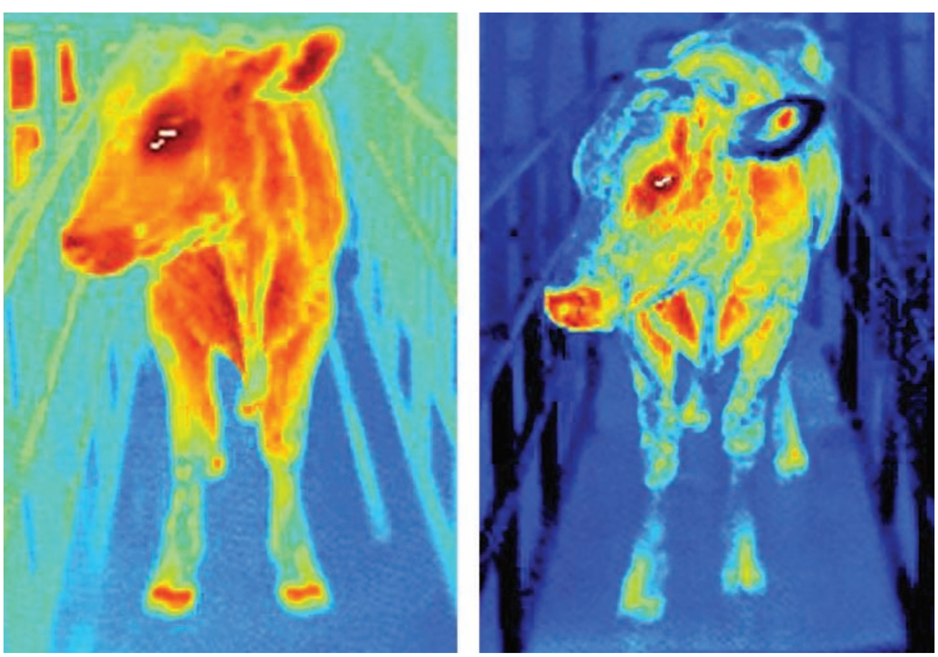
Emergency responses to an infectious livestock-disease outbreak involve several dimensions. Measures should be taken to (1) expedite the initial response, which may be partially achieved by early detection of cases and communication with decision-makers, (2) reduce the disease's spread and (3) enable a swift recovery. There are alternative approaches, however, and the process by which disease-control efforts interact is usually nonlinear and complex. For example, emergency vaccinations and bans on the movement of infected animals limit a disease's spread; but in order to find an efficient combination of the two measures, the decision-maker requires information about how effectively each measure works and whether the two measures are substitutable in achieving an overall objective. During the planning process, information about the relative effectiveness of alternative measures can be compared with their costs to determine how resources should be allocated.

Potential FMD outbreak

We analyzed a response-capacity investment problem for a potential outbreak of an exotic livestock disease in California, foot-and-mouth disease (FMD). FMD is highly contagious and if it were to infect livestock, the economic consequences could be substantial and extensive (Ekboir 1999; Paarlberg et al. 2003). Although the United States has been free of FMD since 1929, public and private preparations for a potential outbreak are important to safeguard intensive livestock-production systems in California (CDFA 2006b) and elsewhere. During an FMD outbreak among livestock herds, response measures typically include (1) movement restrictions on animals, people and vehicles, (2) herd depopulation and (3) emergency vaccination (this may not, however, be available in the United States). Active surveillance of livestock operations allows early detection of the first case and limits subsequent damage. Due to the disease's fast-spreading nature, government regulators and the livestock industry can not build or expand the infrastructure/capacity of these activities while an outbreak is in progress, so careful planning is required before a disease outbreak occurs.

Central Valley study area. We analyzed this problem for a three-county (Fresno, Kings and Tulare) region in the Central Valley. In 2002, the region housed about 1.8 million head of FMD-susceptible livestock (cattle, hogs, sheep and goats) (USDA-NASS 2004) (table 1). More than half (54%) were dairy cattle, 31% beef cattle, 11% pigs and 4% sheep and goats, and less than 1% were backyard animals. The region is characterized by a concentrated distribution of large-scale dairy operations, accounting for 43% of California's milk production and 58% of its cattle production in output value in 2005 (CDFA 2006a). Given the high asset values of dairy cattle (table 1) and the importance of dairy production to California's agricultural economy ($5.2 billion or 14% of total agricultural output in 2005 [CDFA 2006a]), the region receives much of the state's FMD preparation efforts (Richard Breitmeyer, California state veterinarian, personal communication).

Optimization model. We derived the technical interactions of FMD response measures in California using a previously developed, numerical, dynamic optimization model (Kobayashi et al. 2007a). The optimization model finds FMD control strategies that minimize the total direct costs of an outbreak for the region, given user-specified levels of resource availability (response capacity). The specification and parameterization of the optimization model were based on a detailed, spatially explicit epidemiological simulation model for FMD (Bates et al. 2003) developed for the three-county region. In this study, we considered surveillance, carcass disposal and vaccination capacities. By varying the response capacity levels, we analyzed how changes in the relative availability of response measures affect the overall outcome of FMD control.



Photos: Craig Parker/USDA-ARS

Foot-and-mouth disease is highly contagious and difficult to detect in its early stages. *Left*, an infrared image of an infected cow; the red color in the hooves indicates heat. *Right*, a healthy cow.

TABLE 1. Primary livestock industry structure in three-county California region

Herd type	Herds	Herd size	Livestock population	Livestock herd value
	no.	*avg. head*	*head*	*$*
Beef	664	853	566,392	510,194
Dairy	576	1,727	994,752	2,882,363
Swine	79	2,519	199,001	327,470
Sheep/goats	131	558	73,098	67,518
Backyard	788	5	3,940	0
Sales yard	5	na*		na*
Total	2,243		1,837,183	3,787,445

* na = not applicable; we assume that animals are moved to a non-sales-yard premises at the end of each day when FMD control measures are implemented.

Source: Parameters from optimal FMD control model by Kobayashi et al. (2007a). Herd no.: September 2000 survey, Bates, Thurmond, et al. 2003; herd size and livestock population, USDA-NASS 2004; livestock herd value, USDA-NASS 2005, USDA 2005.

Pre- and post-outbreak responses. Planning for and investing in the capacity to prevent diseases can also reduce the probability that a disease will be introduced. Since Elbakidze and McCarl (2006) studied the problem of allocating resources between prevention and post-event activities, we focused on the problem of capacity investment decisions in post-outbreak activities. Moreover, optimal capacity investments should reflect the probability of outbreaks. Although some estimates are available at the national level (USDA-APHIS 1995), to our knowledge, probability estimates of FMD virus introduction in California are unavailable. We discuss the relative, not absolute, capacity of different response measures without making assumptions about the probabilities of FMD introduction.

Measures to control FMD

FMD is a highly contagious disease affecting cloven-hoofed animals such as cattle, pigs, sheep, goats and deer, but not humans. It results in increased mortality in young animals and reduced productivity in mature animals (Hyslop 1970). Early detection and control, which includes culling herds that are infected or potentially infected, is important to limit the disease's spread and the duration of an epidemic as well as enable the reestablishment of trade with FMD-free nations (OIE 2008).

Goats/pigs: ANR Communication Services; sheep/cows: CDFA

A model was used to compare the benefits of control strategies such as vaccination, surveillance and carcass disposal. Cloven-hoofed animals — including, *clockwise from top left*, goats, sheep, pigs and cows — are affected by foot-and-mouth disease, but not humans.

FMD is difficult to detect initially and a delay in implementing control policies is almost inevitable. An animal infected by the FMD virus becomes infectious after a few days (the latent period), but clinical signs, if any, appear a few days after the subclinically infectious period. Moreover, clinical signs on an individual animal can be subtle and may not be noticed immediately or may be confused with other diseases. Because of its high infectiousness, the disease is likely to have spread to other herds by the time the first case is detected. In the 2001 FMD outbreak in the United Kingdom, the estimated detection lag between the initial infection and confirmation was 21 days, and the disease spread to at least 57 herds (Gibbens and Wilesmith 2002). Surveillance activities for early disease detection are an important investment option to prepare for a potential FMD outbreak.

Movement restrictions. Upon detection of the first case, movement restrictions on animals, vehicles and people would be imposed within a specified geographical area. In California, the restrictions would likely be imposed statewide initially, with the area subsequently reduced as more accurate information about the extent of the disease's spread was obtained (Speers et al. 2004).

Eradication. Subsequent eradication policy would be applied to all herds in which clinically infected animals had been found. Additional herds might be preemptively depopulated if they were considered potentially infected. In the 2001 U.K. outbreak, preemptive depopulation was applied to herds that were contiguous to, or had known recent contacts with, confirmed infected herds. In total, more than 4 million animals were slaughtered for disease control purposes, of which about two-thirds later turned out to be uninfected (NAO 2002). In addition, 2.3 million animals were slaughtered for animal welfare reasons, because they could not be marketed or feeds could not be procured due to movement restrictions (NAO 2002).

Vaccination. Emergency vaccination may limit the disease's spread by reducing shedding in infected animals and the exposure risk in susceptible herds. However, testing technology and its ability to discern vaccinated animals from FMD-infected ones (Breeze 2004) may not be accepted by trading partners, and international trade restrictions may nonetheless result. Even after an outbreak is contained, a country that has used the FMD vaccine may be differentiated from countries without vaccination and continue to face trade restrictions. An FMD-free country can officially gain an FMD-free-without-vaccination status by slaughtering all FMD-vaccinated animals (OIE 2005). Facing an FMD outbreak, a previously FMD-free country has three options: (1) no vaccination; (2) vaccination without slaughtering vaccinated animals ("vaccinate-to-live"), which possibly triggers trade restrictions; and (3) vaccination and then slaughter of vaccinated animals ("vaccinate-to-kill").

In the United States, decisions about the use of emergency vaccination are made at the federal level by the U.S. Department of Agriculture on a case-by-case basis. Therefore, in the absence of a specific case, the choice of vaccination options is unknown. In our three-county study region, large-scale dairy herds are expected to have disproportionately high infection rates due to the frequent movement of animals, people and vehicles to and from these operations (Bates et al. 2001). Given the high asset value of these dairy herds, local regulatory veterinarians prefer the vaccinate-to-live option to protect the herds first from infection, and then from depopulation (R. Breitmeyer, California state veterinarian, personal communication). Uncertainty surrounding federal vaccination policy poses a challenge to California's FMD preparation efforts.

Optimal FMD control model

Kobayashi et al. (2007a) developed a numerical optimization model of FMD control and parameterized it for the three-county region of California with 2,243 herds (table 1). A set of 36 disease-transmission parameters was estimated using output generated by a prior epidemic simulation model (Bates, Thurmond, et al. 2003), where herd-to-herd infection was explicitly modeled as a result of direct (animal) and indirect (vehicles and people) contact between herds and local-area spread. The 36 parameters predict the aggregate effects of the three modes of disease transmission.

While disease dynamics are initiated by specifying one index (initial infection) herd, daily disease spread is affected by control measures in the model. First, the depopulation of infected herds prevents further spread of disease by containing it at the source. Subsequent carcass disposal and cleaning and disinfection of the premises may be considered as recovery measures. However, a delay in carcass disposal can cause

The last California outbreaks of foot-and-mouth disease were in 1924 and 1929. In 1924, a Southern California dairy herd was killed and buried to prevent further spread of the virus.

secondary infections of other herds, so the effectiveness of herd depopulation in the model depends on the capacity to dispose of carcasses. Second, emergency vaccination limits further spread to susceptible herds, although the daily availability of FMD vaccine would affect the scale of vaccination.

Movement restrictions on animals, vehicles and people further reduce the disease's spread; these are accounted for by lower disease-transmission parameters in the model. The second set of 36 disease-transmission parameters was estimated using data generated by the simulation model, with equivalent movement-restriction specifications. The estimated parameters were reduced by 55% to 82%, except for sales yards, which were reduced by 100% since they would be closed immediately upon detection of the disease in the region (Kobayashi et al. 2007a).

Finally, a delay in disease detection would also affect disease dynamics and the duration and size of an outbreak. Measures that allow early disease detection, such as routine active surveillance, are another possible area of capacity investment. Kompas et al. (2006) also investigate optimal local surveillance levels in preparation for an FMD outbreak in the United States.

Cost assumptions. Given the disease spread parameters and capacity specifications for carcass disposal, vaccination and disease detection, the optimization model minimizes outbreak costs by choosing daily herd depopulation and vaccination levels. Outbreak costs includes those for implementing controls (depopulation, vaccination and movement restrictions) and the value of livestock herds depopulated for disease control (Kobayashi et al. 2007a). Caveats on the cost specifications are that we did not consider international trade consequences or linkage effects with nonlivestock sectors (such as tourism). Similarly, even though an outbreak may expand farther, we did not consider consequences outside the three-county region, and more precise cost estimations for potential negative spillover effects were beyond the scope of this study.

We solved for cost-minimizing disease control strategies assuming different levels of response capacity. The main questions were: How much flexibility does the FMD control technology in this region exhibit? Is it possible to maintain a certain level of outbreak costs when one capacity is limited but another resource is available? Or, would each measure require a minimum capacity level in order to reduce total costs to a certain level?

Response capacities. A range of response capacities was implemented in the model. Surveillance investment levels were measured in terms of the time taken for the first case to be diagnosed — between 7 and 21 days after initial infection — assuming that, with experience, the disease would be found sooner than the 21 days it took in the U.K. 2001 outbreak. For carcass disposal capacity, without estimates of current capacity in the California three-county region, we considered levels ranging from 1,000 to 20,000 head per day. (Limitations in the region's carcass-rendering capacity were confirmed when a heat wave increased mortality among dairy cattle in summer 2006 [Souza 2006].) While a wide variety of alternative methods are available, such as burial, incineration and composting (NABCC 2004), the actual choice would be based on relative costs, and public health and environmental impacts and regulations. Carcass disposal by on-farm pyre and burial during the 2001 U.K. outbreak raised concerns about air and groundwater pollution (NAO 2002). Should an FMD outbreak occur in the United States, carcass disposal procedures would face close scrutiny (NABCC 2004).

We first implemented the no-vaccination policy, since the availability of this option is uncertain. Then we implemented the vaccinate-to-live policy at various vaccine availability levels. Currently in the United States, the FMD vaccine stockpile is controlled at the federal level and a state cannot inde-

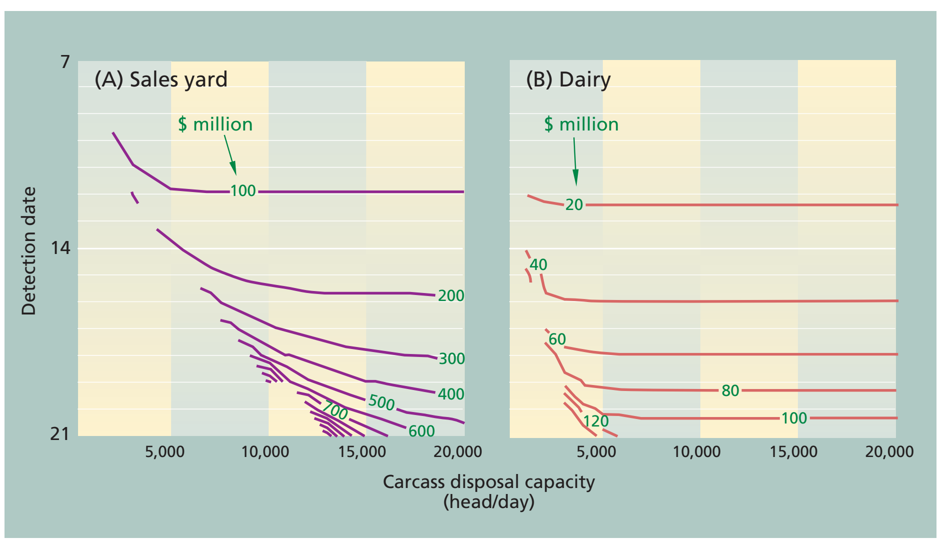


Fig. 1. Iso-cost curves under no-vaccination policy, showing combinations of detection date and carcass disposal capacity that attain the same overall cost for (A) sales yard and (B) dairy. Moving toward the bottom left corresponds with tighter capacities, increasing total outbreak cost.

pendently invest in increased vaccine availability. We used federal estimates (Speers et al. 2004), and considered one to five times the estimates as the region's vaccine availability. (The vaccine is strain-specific, posing a limitation in capacity building through stockpiling.) Speers et al. (2004) estimated that 250,000 doses would arrive 4 days after the first case was diagnosed; after 4 more days, 500,000 doses would arrive; and a week later and every week after that, a million doses would arrive.

Previous studies have found that the size of a potential FMD outbreak in this region would significantly depend on where the index case occurred (Bates, Carpenter, et al. 2003; Kobayashi et al. 2007b). An outbreak would be largest if a sales yard is the index case, followed by a dairy herd. Most results that we show were generated by specifying a sales yard as the index case, representing the worst-case scenario.

Substitutability between controls

The nature of FMD-control technology is presented by curves with constant costs over different sets of parameters (iso-cost curves) (fig. 1). The iso-cost curves illustrate how different combinations of detection date (days elapsed since initial infection, ranging from 7 to 21 days) and carcass disposal capacity (0 to 20,000 head per day) achieve different overall cost levels, when vaccination is not available and either a sales yard (fig. 1A) or a dairy herd (fig. 1B) is the index case. Downward-sloping iso-cost curves show that surveillance and carcass disposal capacity can be substituted without changing the outbreak costs. For example, an outbreak will cost $200 million with detection on day 14 and carcass disposal of about 5,000 head per day, but the same cost can be achieved with a detection delay of 1 day (detection on day 15) and an additional carcass disposal capacity of 2,500 head (fig. 1A).

Compared to the situation where a sales yard is the index case (fig. 1A), costs associated with each capacity combination are much smaller when a dairy herd is the index case (fig. 1B), because an outbreak that starts on a dairy farm would be smaller. Moreover, except with carcass disposal capacity of less than about 6,000 head per day, the iso-cost curves are completely flat, indicating that additional carcass disposal capacity would not contribute to a reduction in overall costs. This also implies that in choosing absolute levels of capacity investments, the distribution of expected outbreak size — in addition to the probability and frequency of outbreaks — should be considered.

Vaccinate-to-live policy

While current U.S. federal policy may not be favorable toward the use of emergency FMD vaccinations, California veterinary officials generally favor a relaxed vaccination policy. We implemented the "vaccinate-to-live" option to analyze its impacts on overall costs, and assumed a sales yard as the index case.

The iso-cost curves demonstrate substitutability between carcass disposal capacity and vaccine availability (ranging from one to five times the current available estimate) when the detection date is held constant at days 21, 18 and 14 (figs. 2A-C). As the disease is detected sooner, the iso-cost curves become steeper, indicating a smaller role of vaccine availability for a given carcass disposal capacity. For example, when detection is on day 21 (fig. 2A), with the current vaccine availability estimates and disposal capacity of 10,000 head per day, doubling vaccine availability would reduce costs by about $40 million (from $540 million to $500 million), whereas when detection is on day 18 (fig. 2B), the same increase in vaccine availability would reduce costs by about $20 million (from $320 million to $300 million).

The iso-cost curves are fairly flat for substitutability between carcass disposal

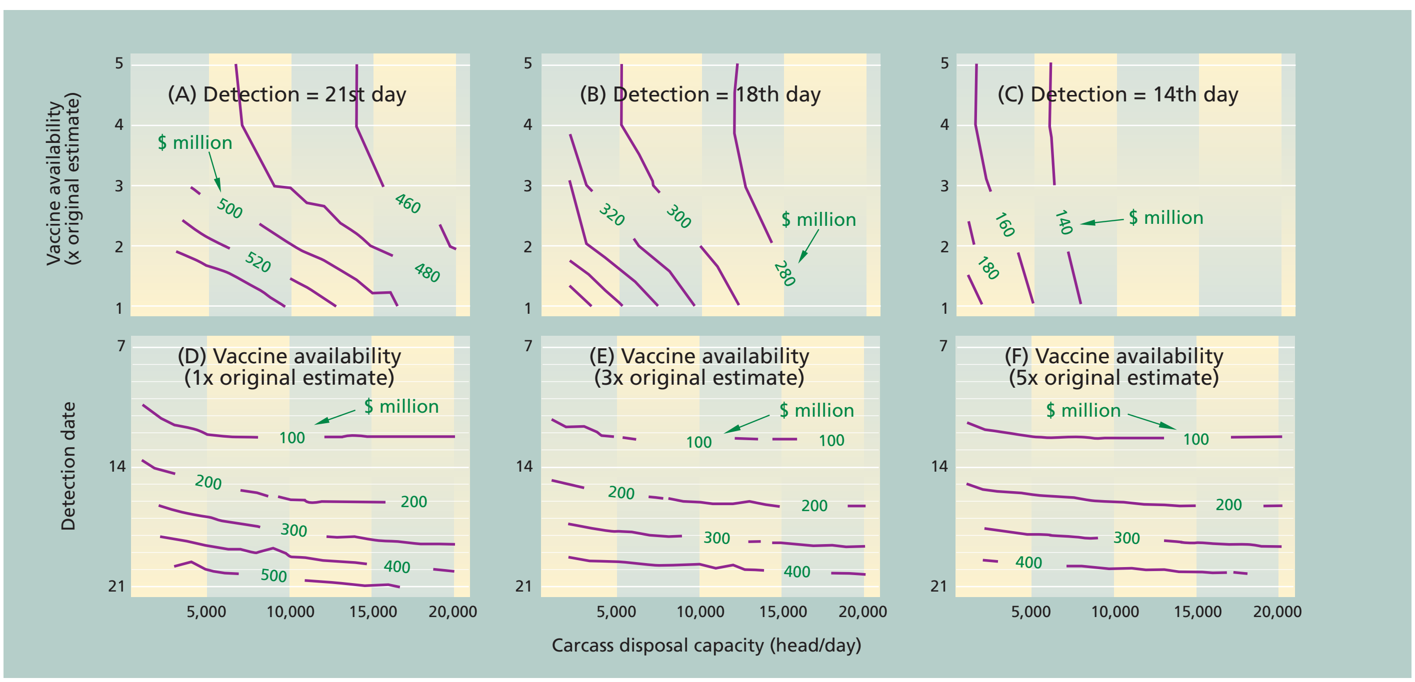


Fig. 2. Iso-cost curves under vaccinate-to-live policy (index case = sales yard), showing combinations of two capacities that attain the same overall cost levels while the third capacity is held constant.

capacity and surveillance when vaccine availability is held constant (fig. 2D-F). If the disease is detected sufficiently early, it would not spread as widely, so a small carcass disposal capacity would be sufficient to dispose of infected animals and limit further disease spread. However, to the degree that initial detection is delayed, a larger disposal capacity is required to keep outbreak costs low. The iso-cost curves are flatter for higher vaccine availability, suggesting that the role of carcass disposal diminishes due to substitutability between vaccination and depopulation (figs. 2A-C).

When disease detection is sufficiently early, the iso-cost curves for the no vaccination (fig. 1A) and vaccinate-to-live (fig. 2D) policies are similar. However, as disease detection is delayed, the iso-cost curves for no vaccination (fig. 1A) are steeper and associated with higher overall costs than those for the vaccinate-to-live policy (fig. 2D), suggesting that without vaccination, delayed detection would require compensation for a much larger carcass disposal capacity.

Flexible disease-control technology

We found technical flexibility in FMD control, in that surveillance, herd depopulation and vaccination activities can be substituted without changing the overall level of outbreak costs. The iso-cost curves clearly illustrate that substitutability between capacities exists for a certain capacity range, and the range depends on the index case.

Flexibility in control technology gives decision-makers choices in how to build capacity to control a livestock disease outbreak. With flexibility, it is possible to choose capacity combinations with lower investment costs or combinations that attain higher environmental or public health standards. Without flexibility, possible capacity combinations are determined entirely by the technology, and investments could be costlier. The iso-cost curves also show that decision-makers have a choice between achieving a low outbreak cost with high capacities (high investment costs) and achieving a high outbreak cost with low capacities (low investment costs). Balancing pre-event (investment) and post-event (control) cost trade-offs is a key element of emergency response planning and management, and the information generated in this study is useful for evaluating such decision problems.

By combining knowledge of epidemiology and economics, valuable information with direct policy implications can be obtained. We encourage continued collaboration between the biophysical sciences and economics, in order to promote efficient preparation and decision-making for potential disasters.

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Hay harvesting services respond to market trends

by Steven Blank, Karen Klonsky, Kate Fuller, Steve Orloff *and* Daniel H. Putnam

In recent years, there has been a trend in California from harvesting hay in small hay bales of about 125 pounds to very large bales of 1,300 pounds or more. This shift is driven by both production considerations and the preferences of some consumers, but has significant implications for the hay market and its many consumer segments. We conducted a survey of rates and the rate-setting methods among custom alfalfa hay harvesters in the northern intermountain region and the San Joaquin Valley. The results show that large bales are cheaper to produce than small bales.

Hay is one of the few crops that is harvested and "packaged" in the field. New harvesting technologies are having important impacts on growers and consumers. *Above*, a rotary-type swather cuts alfalfa in Butte Valley (Siskiyou County), beneath Mt. Shasta.

The alfalfa hay industry is undergoing a transition in its harvesting technologies that has significant implications for hay growers and consumers. Hay is one of the few agricultural commodities that are "packaged" for the retail market during the initial harvest. Hay buyers prefer some physical attributes over others (Ward 1987) and hay pricing is affected by quality attributes (Hopper et al. 2004), but little attention has been paid to how the alfalfa harvesting process affects hay prices and market structure. We examine how harvesting service costs charged to growers have been influenced by the shift from small to large bales.

Hay harvesting services and costs are important concerns for alfalfa growers. The functions involved in harvesting hay must be performed on a fairly rigid schedule to maximize profits (Blank et al. 2001). However, many growers cannot afford to own the complete set of machines needed to harvest hay in a timely manner, or they may be averse to the risk of harvest delays due to mechanical breakdowns of the equipment (Blank et al. 1992). As a result, those alfalfa growers hire "custom harvesters" to perform some or all of the harvest functions for them. Those functions include swathing (cutting the alfalfa), raking the cut alfalfa into rows (to facilitate the drying process), baling the dry alfalfa and roadsiding (using a mechanical bale stacker to move the harvest to the side of the field or to a barn).

Custom harvesting firms must be efficient in minimizing their costs to maintain a profit margin adequate for survival, so they are quick to adopt new technology. In California, more than 70% of custom hay harvesters have purchased new-generation balers that create large, rectangular bales. The ongoing transition from traditional bales of 125 pounds or less to large bales of 1,300 pounds or more is changing both the equipment needed to harvest the hay, and the hay market itself. This has wide-ranging implications for both hay growers and hay consumers. Many livestock producers do not own the equipment necessary to handle large bales. Only hay consumers with a hay "squeeze" (a special type of forklift used to pick up large hay bales) want large bales, so small-scale hay consumers — such as horse owners — are seeing their sources decrease in number as more growers produce only large bales.

Hay market survey

Alfalfa is important in California. It is the state's highest acreage crop, typically with close to a million acres. California produces about 7 million tons annually, more than any other state. California's more than $1 billion hay market is driven by the dairy industry and its demand for hay.

Rather than a single market, California has regional hay markets with different production practices that result in different harvest pricing practices and levels for alfalfa hay harvesting services (Konyar and Knapp 1990). Therefore, we collected data from two different regions of California: the intermountain region in the far north, and the San Joaquin Valley in Central California. About 61% of the state's total alfalfa production is in the San Joaquin Valley and 10% is in the intermountain region.

A telephone interview was conducted during autumn 2007 with some follow-up interviews in 2008. A representative sample of custom harvesters from each region was contacted and asked a series of questions about their operations. The sample included approximately one-third of the custom operators in each region, totaling 15: five harvesters from the intermountain region and 10 from the San Joaquin Valley. The respondents were selected from a list of custom operators compiled from hay industry sources and UC Cooperative Extension personnel. Respondents each served multiple alfalfa growers across the geographic regions, representing entire market areas. Our confidence in the representativeness of our results is high because we spoke to approximately one-third of the firms in the regional industries, and because the competitive nature of the industry causes harvesting firms to operate in similar ways to one another.

The results address hypotheses involving financial and performance issues arising from the shift from small to large bales. Financial issues include the hypothesis that purchasing new equipment to produce large bales increases the harvester's average fixed cost per ton. Performance issues include two related hypotheses. First, less time is needed to perform baling, and hauling and roadsiding, for large bales compared to small bales, and second, custom harvesters will charge less for harvesting large bales.

Respondents and their balers

Responses to descriptive questions provided a snapshot of the alfalfa hay harvesting industry across California. Of respondents, 60% harvested their own hay and did custom harvesting, 13% harvested their own hay only and 27% did only custom work. In total, 93% did small and about 73% did large baling, with large bales averaging 1,315 pounds. All respondents who did large baling also did small baling. Finally, 13% did silage/chop harvesting, which involves chopping wilted forage into smaller segments so the forage can be preserved as silage rather than hay. The total number of acres serviced by all the harvesters that we surveyed in 2007 was 27,290, with a range of 190 to 5,000 acres for individual harvesters. Those harvesters doing custom work had between 1 and 17 customers annually, with an average of about 7.

Respondents possessed a total of 74 balers. Fifty (68%) were small balers, while 24 (32%) were large. Forty-two (57%) were bought new, and 32 (43%), used. The years of purchase ranged from 1977 to 2007, with the oldest balers being unusual cases. The majority of purchases were made in 2004 or later. Of the used balers, the age at purchase was between 1 and 19 years, 7.2 years on average. Respondents estimated that their balers would last another 0 to 20 years, with an average of 6.2 years of lifetime from the present. The balers were purchased for between $7,000 and $95,000, at an average price of $42,081. Over the entire sample of new and used equipment, estimated annual repair costs were between $850 and $10,000 per baler, with an average of $4,165.

As hypothesized, the data indicated that purchasing new equipment to produce large bales increased a harvester's average fixed cost per ton. However, average annual operating costs appeared to decrease slightly with large balers. Harvesters that purchased new balers during 2007 paid an average price of $88,000 for large balers and $49,500 for small, with average estimated annual repair costs of $850 for large and $3,050 for small balers. Other operating costs such as labor were generally lower for large balers, so the choice between large and small balers is not obvious.

Regional production differences

Due to geographic and microclimate differences between the regions that we studied, cultural practices in each resulted in significant output differences. The intermountain region has more difficult terrain and a shorter growing season than the San Joaquin Valley. Climate differences are significant, resulting in far fewer cuttings per year and higher average yields per cutting in the wetter intermountain region (table 1). This is significant because yield is an important factor in determining custom harvesting costs. Also, harvesters gave a broad range of responses in each region to questions about their average, smallest and largest jobs in 2007, and jobs in the San Joaquin Valley tended to be bigger, on average (table 2).

TABLE 1. Differences in cuttings and yield between regions (n = 15)

Cuttings	Intermountain	San Joaquin Valley
	no. per field per year	
Average	2.8	7.1
Range	2–4	6–10
First cutting	*tons/acre*	
Average yield	2.3	1.25
Low end*	1.5	0.8
High end	2.8	1.7
Last cutting		
Average yield	1.3	0.9
Low end	0.9	0.6
High end	1.7	1.3
Average total annual yield	5.6	8.4

* Low and high end are averages of all responses.

TABLE 2. Differences in job size between regions

Job size	Intermountain	San Joaquin Valley
	acres	
Average	30–300	50–1,500
Smallest	10–40	7.5–1,500
Largest	80–1,000	180–2,000

Custom harvesting parameters

Custom harvesters' costs are affected by many variables. The two most important factors that create differences in a harvester's costs between one job and another are yield levels and the size of the job (expressed in total acres).

Fixed and variable costs. Hay harvesting has both fixed and variable costs. Fixed costs — annual costs that are generally fixed no matter how much the equipment is used — include payments on loans taken out to purchase the equipment, insurance and depreciation. Variable costs are directly related to equipment operation and vary by how much the equipment is used; these costs include fuel, labor and repairs.

Fixed costs expressed on a per-acre basis are most useful in explaining cost differences between one harvester and another, but do not normally influence costs specific to one job versus another. Two custom harvest firms will most often have different fixed cost totals, and in turn, different average fixed costs per acre harvested, even if they harvest the same number of acres per year. In addition, because different numbers of acres


Steve Werblow

There has been an ongoing transition from small bales averaging 125 pounds to very large bales of about 1,300 pounds or more. This trend is influencing how hay-harvesting services are priced in California's intermountain region (shown, Butte Valley) and the San Joaquin Valley.

are served each year, average fixed costs per acre differ between firms. As a result, two or more harvesters can be expected to have different rate structures for a similar harvest job due to their differences in fixed costs.

Variable costs per acre are often similar between two or more harvest firms in a region, because fuel, labor rates and other costs tend to be similar. As a result, two or more firms bidding on the same job will have similar variable costs on a per-acre basis, assuming that they use similar equipment. If less time is needed to perform baling, and hauling and roadsiding, for large bales compared to small bales, as hypothesized, then custom harvesters may charge less for harvesting large bales because those bales are less costly to make.

Yield. Yield was the single most important job-specific influence on alfalfa hay harvester costs on a per-acre basis; survey respondents indicated that more time was needed per acre as yield increased. In both the intermountain region (table 3A) and San Joaquin Valley (table 3B), more time was needed to perform harvest operations as average yields increased for both small and large bales. Basically, higher yields take more time per acre to harvest because the equipment has to slow down to process the more-dense alfalfa fields. More time means more variable costs, justifying a higher price.

In addition, baling, and hauling and roadsiding, were both faster for large bales compared to small bales in

TABLE 3A. Acres per hour by operation at varying yields, intermountain region

Operation		1 ton/acre	2 tons/acre	3 tons/acre
		. . . . acres per hour		
Swath (n = 5)	Low	7.0	6.0	4.0
	High	18.0	16.0	14.0
	Average	12.2	10.0	8.3
Rake (n = 5)	Low	6.0	7.0	*
	High	*	15.0	*
	Average	10.6	10.4	9.9
Bale/small (n = 5)	Low	*	4.0	2.0
	High	10.0	8.0	5.0
	Average	7.4	5.6	3.6
Haul small bales off field (n = 5)	Low	3.5	1.7	1.5
	High	17.5	10.5	7.0
	Average	11.2	7.0	4.8
Bale/large (n = 3)	Low	10.0	9.5	7.0
	High	17.0	15.0	10.0
	Average	13.0	12.2	8.7
Haul large bales off field (n = 3)	Low	10.0	8.0	6.0
	High	20.0	17.0	10.0
	Average	15.0	12.5	8.0

* No difference between values in this column and middle column.

TABLE 3B. Acres per hour by operation at varying yields, San Joaquin Valley

Operation		0.75 ton/acre	1.25 tons/acre	2 tons/acre
		. . . . acres per hour		
Swath (n = 10)	Low	*	5.0	*
	High	*	16.0	*
	Average	9.1	8.8	7.5
Rake (n = 10)	Low	*	12.0	*
	High	*	35.0	*
	Average	19.0	18.8	18.6
Bale/small (n = 9)	Low	6.0	5.0	4.0
	High	20.0	15.0	10.0
	Average	11.7	9.4	7.3
Haul small bales off field (n = 5)	Low	*	10.0	7.5
	High	31.0	25.0	18.0
	Average	19.5	14.6	11.3
Bale/large (n = 8)	Low	10.0	9.0	8.0
	High	50.0	40.0	30.0
	Average	22.5	19.3	16.2
Haul large bales off field (n = 4)	Low	*	13.0	7.2
	High	*	50.0	30.0
	Average	28.0	23.6	20.0

* No difference between values in this column and middle column.

TABLE 4A. Custom rates by operation and job size with fixed yield of 2 tons/acre, intermountain region

Operation(s), aggregated total hay charge		Job size: Smallest	Average	Largest
		. . . .	$/ton	. . . .
Small bale without hauling (n = 5)	Low	38.00	36.00	*
	High	50.00	45.00	*
	Average	44.00	40.20	*
Small bale with hauling (n = 5)	Low	41.30	38.00	*
	High	52.00	47.00	*
	Average	46.50	42.70	*
Large bale without hauling (n = 3)	Low	35.00	32.00	31.00
	High	45.00	40.00	*
	Average	39.30	36.70	36.30
Large bale with hauling (n = 3)	Low	37.00	34.00	33.00
	High	48.00	43.00	*
	Average	41.70	39.10	38.70

* No difference in value between rates in this column and middle column; signifies rate clustering.

TABLE 4B. Custom rates by operation and job size with fixed yield of 1.25 tons/acre, San Joaquin Valley

Operation(s), pricing		Job size: Smallest	Average	Largest
Swath (n = 5), $ per acre	Low	*	10.50	*
	High	*	17.00	*
	Average	12.96	12.70	*
Rake (n = 5), $ per acre	Low	4.50	3.50	*
	High	*	6.00	*
	Average	5.20	5.00	*
Swath and rake (n = 6), $ per acre	Low	*	14.00	*
	High	*	22.00	*
	Average	17.22	16.83	*
Small bale: Bale (n = 5), $/bale	Low	*	0.75	*
	High	1.10	1.00	*
	Average	0.95	0.92	*
Swath, rake and bale (n = 2), $/ton	Low	*	27.00	*
	High	*	29.00	*
	Average	*	28.00	*
Small bale: Haul off field (n = 2), $/bale	Low	*	0.36	*
	High	*	0.40	*
	Average	*	0.38	*
Small bale: Aggregated total hay charge with hauling (n = 3), $/ton	Low	*	30.00	*
	High	*	39.14	*
	Average	35.45	34.03	*
Small bale: Aggregated total hay charge without hauling (n = 4), $/ton	Low	*	21.91	*
	High	*	29.00	*
	Average	*	26.41	*
Large bale: Bale (n = 5), $/bale	Low	*	7.50	6.50
	High	*	11.00	*
	Average	9.50	9.10	*
Large bale: Haul off field (n = 2), $/bale	Low	*	3.00	*
	High	*	3.90	*
	Average	*	3.50	*
Large bale: Aggregated total hay charge with hauling (n = 3), $/ton	Low	*	30.00	*
	High	*	40.90	*
	Average	*	35.30	*
Large bale: Aggregated total hay charge without hauling (n = 4), $/ton	Low	*	24.00	*
	High	*	29.00	*
	Average	*	26.70	*

* No difference in value between rates in this column and middle column; signifies rate clustering.

both regions. At all yield levels, those functions favored large bales (table 3). Statistical *t*-tests indicated a clear difference in the baling capacities per hour of large versus small balers in our sample. This is a major result because it indicates why custom harvesters may prefer to make large bales: they require less time, hence labor costs are reduced per job and, possibly, more jobs can be completed per year.

Job size. The average size of harvest jobs, expressed as total acres, differed significantly between the two regions (table 2) and affected harvester costs and rates. Harvesters tended to charge more per unit of output for small harvest jobs than for average or large jobs (table 4). This is true when harvesting prices are expressed as a single charge per ton, as is common in the intermountain region, and when they are priced separately for each operation, as in the San Joaquin Valley. (For example, swathing and raking in the San Joaquin Valley are typically charged per acre and baling and hauling are priced per bale.) Harvesters appear to be pricing each job separately, and some harvesters may be pricing jobs based on fixed costs per job rather than for total acres served annually, as would be expected. Harvest costs appear to be affected by job-specific factors such as the shape and condition of the field and distances the equipment must be moved to reach a job site.

In addition, custom rates on a per-ton basis tended to go down as yields increased for an average job size, but surprisingly, not in consistent amounts across the range of yields. The rates charged to growers decreased between low and average yields, but did not decrease as much between average and high yields (tables 5A and 5B). As hypothesized, harvesters charged less for large bales than they did for small bales.

Rate-setting practices

In California, the prices for harvesting services are presently expressed in two different ways: rates per acre and rates per ton. Both alfalfa growers (for whom this is a business cost) and custom hay harvesters (for whom this represents the price of their services) have expressed some dissatisfaction with each of these methods. Neither seems to fit all situations. For example, custom harvesters want to charge on a per-ton basis when yields are high, while growers want to pay on a per-acre basis. The reverse is true when yields are low. Either the grower or the custom harvester may be dissatisfied at any particular time.

However, our survey results indicated that the rates custom harvesters charge alfalfa growers are more often correlated with the costs of harvesting tasks as expressed on a per-ton basis, but not perfectly so. For example, higher yielding fields slowed down the harvesting process (table 3A), causing higher variable costs to be incurred per acre by the harvester, yet the rates being charged by harvesters were lower per acre for higher yielding fields (table 5A). This implies that some bargaining takes place between harvesters and growers, with rates more often quoted on a per-ton basis, and that some factors other than direct costs are considered during the rate-setting process.

The survey results also indicated that the two most common methods of setting rates are to focus either on variable costs or on fixed costs, with minimum rates set according to those cost levels. Focusing on variable costs led harvesters to set minimum rates per acre, while focusing on fixed costs resulted in minimum rates per job. Some harvesters used both methods; minimum rates help a harvester cover the costs of moving equipment and workers to each job site.

Many harvesters had a minimum charge per acre. In the intermountain region 60% had a minimum, which averaged $42.80 per acre, and only 40% of San Joaquin Valley harvesters had a minimum, averaging $21.70 per acre. The differences in minimums are due partly to the differences in average yields per cutting. Clearly, the two regions are separate markets.

Fewer harvesters used a minimum charge per job. In the intermountain region 40% charged a minimum, which averaged $500 per job. Just 10% of harvesters in the San Joaquin Valley charged a minimum, averaging $200 per job. Again the rate differences between regions reflect market conditions. Harvesters in the San Joaquin Valley have more jobs per year, on average, and

The ongoing transition from traditional bales of 125 pounds or less to large bales of 1,300 pounds or more is changing both the equipment and the hay market itself.

TABLE 5A. Custom rates for total hay harvest of average size jobs at varying yields, intermountain region

Total hay harvest		Average yield: 1 ton/acre	2 tons/acre	3 tons/acre
		$/acre		
Small bale roadside (n = 5)	Low	*	36.00	*
	High	50.00	45.00	43.00
	Average	41.20	40.20	39.80
Small bale in shed (n = 5)	Low	*	38.00	*
	High	52.00	47.00	45.00
	Average	43.70	42.70	42.30
Large bale roadside (n = 2)	Low	38.00	34.00	32.00
	High	*	40.00	*
	Average	38.70	37.30	36.70
Large bale in shed (n = 2)	Low	40.00	36.00	34.00
	High	*	43.00	*
	Average	41.10	39.70	39.10

* No difference in value between rates in this column and middle column; signifies rate clustering.

TABLE 5B. Custom rates by operation for average job size at varying yields, San Joaquin Valley

Operation(s), pricing		Average yield: 0.75 ton	1.25 tons	2 tons
Swath (n = 5), $ per acre	Low	*	10.50	*
	High	*	17.00	*
	Average	12.96	12.70	*
Rake (n = 5), $ per acre	Low	4.50	3.50	*
	High	*	6.00	*
	Average	5.20	5.00	*
Swath and rake (n = 6), $ per acre	Low	*	14.00	*
	High	*	22.00	*
	Average	17.90	17.40	*
Small bale: Bale (n = 6), $/bale	Low	*	0.75	*
	High	1.10	1.00	*
	Average	0.95	0.92	*
Swath, rake and bale (n = 2), $/ton	Low	*	27.00	*
	High	*	29.00	*
	Average	*	28.00	*
Small bale: Haul off field (n = 2), $/bale	Low	*	0.36	*
	High	*	0.40	*
	Average	*	0.38	*
Small bale: Aggregated total hay charge with hauling (n = 3), $/ton	Low	*	30.00	28.46
	High	50.90	39.14	32.54
	Average	42.43	34.03	30.33
Small bale: Aggregated total hay charge without hauling (n = 4), $/ton	Low	27.00	21.90	17.71
	High	37.30	29.00	*
	Average	31.11	27.90	26.11
Large bale: Bale (n = 2), $/bale	Low	*	7.50	6.50
	High	*	11.00	*
	Average	9.50	9.10	*
Large bale: Haul bales off field (n = 2), $/bale	Low	*	3.00	*
	High	*	3.90	*
	Average	*	3.50	*
Large bale: Aggregated total hay charge with hauling (n = 3), $/ton	Low	*	30.00	*
	High	45.70	36.10	35.00
	Average	36.90	33.70	31.90
Large bale: Aggregated total hay charge without hauling (n = 4), $/ton	Low	27.00	24.00	18.60
	High	33.60	29.00	*
	Average	29.90	26.70	24.90

* No difference in value between rates in this column and middle column; signifies rate clustering.

Small bales averaging about 125 pounds are collected in a bale wagon in Scott Valley (Siskiyou County).

Debbie Aldridge/UC Davis

If the trend toward large bales continues, equestrians may be forced to pay higher prices as the supply of small bales declines. *Above*, girls prepare for a lesson at the UC Davis Equestrian Center.

those jobs tend to be larger in size so that fixed costs (and possibly variable costs) can be spread wider, resulting in lower minimum rates than those charged by harvesters in the intermountain region.

Harvesters were also asked to explain how they believe custom rates should be set. About two-thirds or 67% thought that custom charges should be calculated by a combination of factors, while 13% thought they should be based on yield only and 7% based on acreage only. Reasons given for responses favoring only one factor were "can't think of a better way to do it" and "otherwise it is too complicated." Many reasons were given for basing rates on a combination of factors. Some of the most common were:

- There is no one-size-fits-all method.
- A large, high-yielding field can have a lot of problems that drive costs up for the harvester.
- What is important is tonnage per hour, and many factors go into this.
- It must make economic sense to run a machine, and this is not determined by any one factor.

We found that rate setting is a competitive process, but not perfectly so. In a competitive market, prices for fairly standardized services, like custom hay harvesting within a geographic area, are expected to be clustered in a narrow range as different firms bid against one another for jobs. This does not mean that different harvesters will offer the same price to a particular grower. Fixed costs vary among custom harvesters resulting in differences in rates. Yet, the rates showed obvious signs of clustering within each region (tables 4 and 5). For example, in the tables, an asterisk denotes where there is no difference in the value for that column compared to the value in the middle column in that row; a high number of asterisks signals rate clustering.

The competitive aspect of rate setting by custom harvesters means that the cost differences between large and small bales will influence rates to some degree. Specifically, the time savings that come from making large bales compared to small bales enables harvesters to offer growers lower rates for large bales, on average. This, in turn, creates an incentive for growers to request that their alfalfa be made into large hay bales.

Market implications

The cost differences between small and large bales create economic incentives for custom harvesters to purchase new balers that produce large bales, potentially reducing supplies of small bales and reducing access to hay supplies for many small-scale retail hay consumers, such as horse owners. This raises the question of whether small-bale consumers will have to pay higher prices to maintain access to hay supplies. The market for large bales — which includes dairy operations and cattle producers — may see hay prices decline relative to prices for the same volume in small bales, due to both the reduced cost of production and the increased supply of large bales. However, the market for small bales may shrink in size unless consumers pay higher prices to get the product in small-bale form. In essence, hay production changes are causing hay market segments to be redefined.

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PERSPECTIVE

Whole-farm nutrient balances are an important tool for California dairy farms

by Alejandro R. Castillo

In terms of nutrient balances, modern dairy systems are more complex than ever before. Feed is the primary nutrient input on the average California dairy farm. Whole-farm nutrient balances are an important tool for evaluating the economic and physical viability of each dairy farm, improving nitrogen imbalances and complying with environmental regulations. This article discusses the concept of nutrient balances and variables affecting the improvement of nitrogen imbalances in California dairy systems.

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Dairy operations in California are becoming more concentrated, with more cows, more milk produced per cow, and more feed purchased off-farm. In order to limit pollution from nutrient-laden runoff, California dairies in the Central Valley face new water-quality-related rules.

IN May 2007, California's Central Valley Regional Water Quality Control Board (Region 5) adopted new regulatory waste-discharge requirements for all existing and new milk-cow dairies in the Central Valley (CRWQCB 2007). Dairy farmers were required to complete and submit an existing conditions report and preliminary dairy facility assessment (PDFA) by Dec. 31, 2007. This includes a complete description of the dairy facility and an estimation of major sources of nutrients potentially present to apply to cropland. They are required to include a waste management plan (WMP) to control dry manure and wastewater, and an annual nutrient management plan (NMP).

The WMP and NMP will be important objectives for California dairy producers in the coming years. According to the WMP requirements for each dairy, producers must be prepared with sufficient storage capacity to contain all the manure that their dairy produces, to avoid illegal discharges on or off site. They must also be prepared to apply manure according to an NMP based on the chemical composition of their manure and soil, as well as crop requirements.

Modern dairy farms are more complex than ever before. They have become more concentrated in recent years, with cows producing more milk, and more feed purchased from off-farm sources. Feed is the primary nutrient input into the average California dairy farm. Improving the efficiency of nutrient utilization presents important economic and environmental challenges. The relationship between nutrient balances and how nutrients are utilized on the farm is not well understood. This article discusses the concept of "nutrient balances" and variables affecting the improvement of nitrogen imbalances in California dairy systems. Nitrogen from different industries is an important pollutant of California air and waterways.

Whole-farm nutrient balances

A whole-farm nutrient balance can be defined as the difference between farm nutrient imports and exports; it provides a general indicator of whether a farm is at risk of building up nutrients and releasing them into the environment. The quantification of these losses can be used as an indicator of air, soil and underground water contamination. Imbalances represent the quantity of direct losses (such as ammonia volatilization) or increased nutrient inventories in soil and groundwater (such as salts and nitrate leaching) (fig. 1). The three primary components that must be integrated are nutrient imports, nutrient exports and the dairy facility itself.

Software can be used to calculate nutrient balances, with information generated by dairy operators and/or private consultants. UC Cooperative Extension, the California Dairy Quality Assurance Program, regulatory agencies and the dairy industry are assisting dairy producers with educational programs to understand and comply with the new regulations.

On a normal dairy farm, nutrient imports and exports are highly diverse and variable, influenced by factors such as season, on-farm crops grown, forage availability, commodity prices and availability, and calving periods. Consequently, producers should use a minimum of 1 year to estimate a whole-farm nutrient balance, and maintain on-site records for 5 years. A recent study concluded that improvements to data collection methods for whole-farm nutrient balances will require increased skills and training for farmers and those assisting them in on-farm data collection and analysis (Powell et al. 2006).

CDFA

By calculating nutrient balances for the whole dairy operation, operators can improve feed efficiency and protect water quality. More-efficient cropping practices on dairies that grow their own silage and hay, as well as manure management, are important strategies.

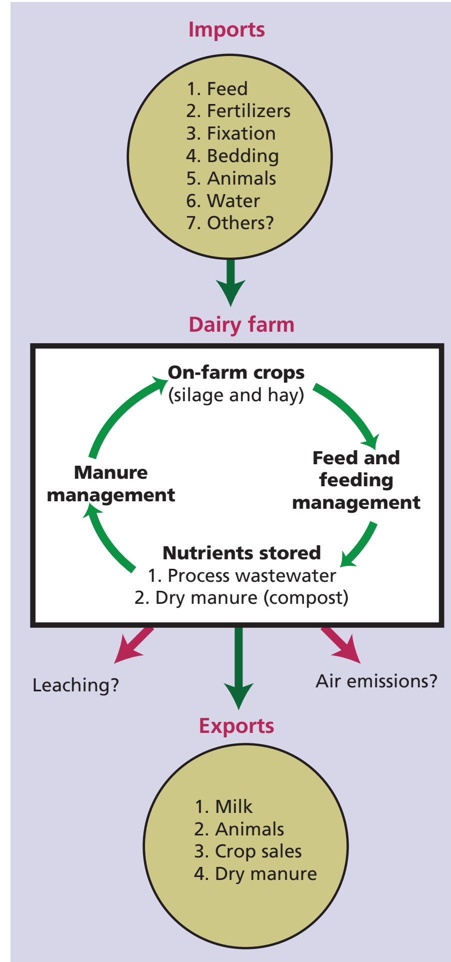

Fig. 1. A whole-farm nutrient balance.

In addition to the whole-farm nutrient balance previously discussed, two additional balances can be estimated: (1) when diets are adjusted according to animal requirements and (2) when manure is applied to the soil according to crop requirements (fig. 1). In both cases, nitrogen is one of the most studied nutrients used to estimate whole-farm nutrient balances.

Nitrogen utilization

Rasmussen et al. (2006) analyzed nutrient balances from 38 dairy and beef farms in New York, and found that there are currently no benchmarks to measure a livestock farm's nutrient management performance. They suggested several indicators that include: the quantity of nutrients imported, exported and remaining; nutrients remaining per animal unit; percentage of nutrients remaining; distribution of farm imports and exports; crop sales; and percentage of farm-produced forage and feed.

Most studies that estimate whole-farm nitrogen utilization express balances as a proportion. For example, Koelsch (2005) reviewed information from different dairy whole-farm balances in the United States, and found imbalances or direct losses of nitrogen value ranging from 59% to 84%. Researchers from Cornell University did whole-farm balances on 24 dairy farms in northern New York, and the average nitrogen remaining (imports-to-exports) was 46% (Larry E. Chase, Professor, Cornell University, personal communication). Castillo et al. (2000) analyzed information on whole-farm nitrogen balances from European dairy farms, including high and low nitrogen inputs, and estimated that harvested nitrogen in the outputs ranged from 44% to 84%. Likewise, Spears et al. (2003) found that in whole-farm nitrogen balances carried out on 41 Western dairy farms, on average 36% of the inputs were accounted for in the outputs.

All the research cited was carried out with different methodologies and situations. No scientific information has been produced specifically for California dairy systems to indicate an average or an optimal value for the efficiency of whole-farm nitrogen utilization.

Adjusting nitrogen balances

Strategies to improve nitrogen utilization include decreasing inputs, increasing outputs, or both. In practical terms, if the objective is to maintain the number of animals and acres, reduce inputs and/or increase outputs, improvements should be based on (1) the efficiency of feed and feeding management and (2) manure management practices.

The following examples, based on Spears et al. (2003) (table 1), analyzed the impact of several strategies to improve average nitrogen balances and present achievable goals for California dairies.

Whole-farm nutrient balances provide a general indicator of whether a farm is at risk of building up nutrients and releasing them into the environment.

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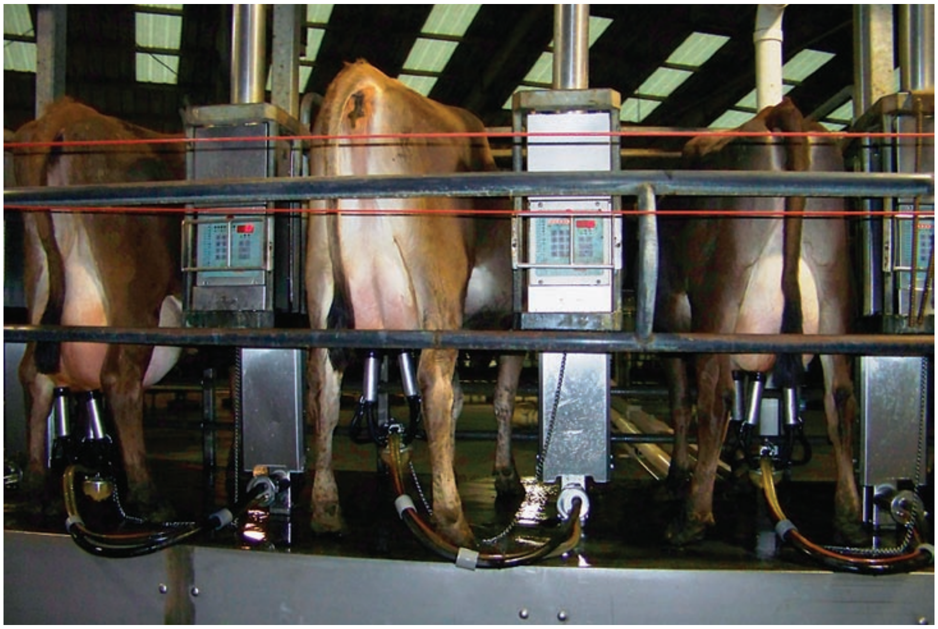

Increasing milk yield per cow and milk nitrogen output are additional strategies for managing nutrients on dairies. *Above*, Jersey cows are milked twice a day at the Hilarides Dairy in Lindsay, Calif.

Decreasing inputs 20%. To decrease nitrogen inputs by 20%, nitrogen intake in feed by dairy cows could be reduced by 10% (NRC 2001; Broderick 2003; Olmos Colmenero and Broderick 2006) and the on-farm growing of crops that take up nitrogen could be increased by 10%. To this end, UC Cooperative Extension researchers are currently evaluating on-farm data using triple-cropping on a minimum tillage system.

Increasing outputs 20%. Increasing milk output and the resulting levels of nitrogen in the milk was estimated to increase the nitrogen output to 5 tons per year, which may be obtained by increasing milk yields by about 10% (Wang et al. 2000). Also, to increase outputs by 20%, it would be necessary to increase the export of nitrogen in manure from 15.5 to 19 tons per year.

Reducing nitrogen intakes and increasing crop production — thereby increasing the nitrogen harvested (see total inputs, fig. 1) represented more than 70% of the total nitrogen-balance improvements, estimated as tons nitrogen per year per dairy (126-101/81-47 = 0.74). Increasing milk yields per cow by 10% and manure nitrogen exports by 3.5 tons per year are important efforts (see total outputs, fig. 1), but they represent a lower proportion (less than 30%) of the total nitrogen-balance improvement (54-45/81-47 = 0.26).

Dairy farm strategies

Whole-farm nutrient balances are an important tool for understanding and evaluating the economic and physical viability of each dairy farm, improving nitrogen imbalances and complying with environmental regulations. Strategies to improve nitrogen balances for the average California dairy farm include adjusting diets according to animal requirements in order to decrease nitrogen import in feed, increasing on-farm crop production and milk yields per cow per day, and exporting manure to cropping and/or other production systems.

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TABLE 1. Improving whole-farm nitrogen (N) balances

	Spears et al. (2003)	Improved N balance
	tons nitrogen per year per dairy farm	
Total inputs	126	101 (–20%)
Feed	106	81*
Fertilizer	5	5
Bedding	1.3	1.3
Animals	1	1
Fixation	13	13
Total outputs	45	54 (+20%)
Animal products	28.5	34†
Crops	1.0	1
Dry manure	15.5	19‡
Balance (tons/year)	81	47
Balance (%)	36	53

* Reduce nitrogen imports in feed by 20%, by increasing crop uptake 10% and restricting nitrogen in the diet 10%.
† Increase nitrogen in animal products by 5.5 tons per yr.
‡ Increase exported manure nitrogen by 3.5 tons per yr.

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COMINGUP *in California Agriculture*

Chao Wei Yu

Miscanthus is being field-tested for its biofuel potential at UC Davis.

Understanding biofuels: Possibilities and pitfalls

Global demands for energy, combined with climate change and national security concerns, have generated intense interest in biofuels as an alternative to fossil fuels. Biofuels are liquid, gaseous or solid fuels obtained from biological materials such as plants. By some estimates, biofuel production in California has the potential to exceed 2 billion gallons of gasoline-equivalent annually. In the United States, corn grain for ethanol, and oilseed crops such as soybeans and canola for biodiesel, currently dominate biofuel production; however, scientists are studying a wide range of new crops and refining technologies.

Important concerns have been raised about the effects that converting farmland to fuel crops would have on global food prices, as well as the long-term environmental sustainability of biofuel crops and their actual potential to reduce overall levels of greenhouse-gas emissions. In the next issue of *California Agriculture*, scientists examine the potential for biofuel production in California and elsewhere, looking at public policy, economics, research needs, new crops and technologies, competing uses, and sustainability.