California Agriculture

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Delta resources at risk

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

Aquatic resources critical to California's productivity, quality of life

Christopher M. Dewees
Sea Grant
Extension Program,
UC Davis

Nutrient-rich waters make California's coastal ocean one of the most productive in the world. However, California's rapid population growth from 20 million to 35 million since 1970 is increasingly stressing these and other finite aquatic resources. What were once considered boundless resources are now in danger.

Before the arrival of Europeans, Native Americans harvested an estimated 8.5 million pounds of salmon yearly from Central Valley streams. After statehood, the ability to collect, store and deliver fresh water was critical to the growth of California's premiere agricultural industry as well as its urban centers and suburban communities.

Commercial fisheries developed rapidly at first, but sometimes plummeted later due to environmental or fishing pressures. In 1882, 12 million pounds of salmon were harvested from the San Francisco Bay-Delta for canning. The canneries closed by 1919 and the fishery moved onto ocean waters as statewide landings declined to less than 5 million pounds in recent years. From the 1920s to 1940s, the Pacific Coast sardine fishery was the largest fishery in the Western Hemisphere, with up to 700,000 tons landed annually. The fishery declined rapidly during the 1950s due to a combination of cyclic changes in the ocean environment and heavy fishing. Ocean conditions more favorable to sardine populations over the past 20 years have led to recovery of the sardine resource and rebirth of the fishery.

As California's population grows, stresses on our aquatic and ocean resources intensify. Many Californians are aware of these cases in point:

- Battles over complex water allocation issues persist in the Klamath Basin, San Francisco Bay-Delta and Salton Sea. High-quality water is in demand for irrigation, drinking, industry, wildlife and fish.
- Along the coastal zone, where over 75% of our population lives, beaches are often posted or closed to swimming due to unhealthy water quality, affecting the state's multibillion-dollar coastal tourism industry.
- Large sections of our coastal waters are closed to fishing for species such as rockfish and abalone due to large declines in their abundance. Rebuilding these populations will take decades.
- Introductions of nonnative aquatic nuisance species are altering estuary ecosystems significantly (see page 102). A major source of introduced species is ballast water from ships, which deliver approximately 30% of the nation's imports through California ports. It will be difficult to find feasible solutions for this problem.
- The majority of the spawning habitat for salmon and steelhead was lost during the 20th century. This is only partially mitigated by hatchery production and habitat restoration efforts. Some salmon stocks have been listed under the Endangered Species Act, which has heightened conflicts over fish habitat and water.

Today the UC Division of Agriculture and Natural Resources (ANR) is well positioned to play a major role in addressing California's aquatic resource issues. Solutions to these complex problems should integrate the human resources, natural resources and agricultural sciences expertise available within ANR.

When I was hired as the Extension Marine Resources Specialist in 1972, I felt like a "fish out of water." Most of my UC Cooperative Extension (UCCE) colleagues were focused on production agriculture, home economics and 4-H youth education. While some faculty were involved in aquatic and marine research, most academic departments working on wildlife, fisheries, and environmental sciences and policy were in their infancy.

But the early 1970s were a time of revolutionary change in environmental policy in the United States, signaled by passage of the federal Clean Water and Clean Air Acts, Endangered Species Act, Marine Mammal Protection Act and the Magnuson Fisheries Conservation and Management Act. Environmental and wildlife disciplines, including aquatic sciences, thrived and expanded.

Today my UCCE colleagues embody this change in emphasis. Seven county-based Sea Grant Extension Program marine advisors are working on ocean and coastal aquatic issues; numerous county-based advisors have full or partial natural resources or watershed assignments; farm advisors are working on water quality, policy and conservation; and 4-H youth programs involve aquatic education.

UC faculty at most campuses are now working on aquatic topics including anadromous and inland fishes, aquatic nuisance species, water quality, riparian habitat improvement in agriculture, management and conservation of fisheries resources, the San Francisco Bay-Delta ecosystem, water policy, oceanography and aquatic resources economics.

This issue of *California Agriculture* features two studies on the aquatic ecosystem of the Sacramento-San Joaquin Delta. These papers provide insights useful in guiding the multi-billion-dollar restoration efforts by CALFED (a consortium of state and federal agencies) in California's important delta-estuary system (see pages 104, 110).

Solving California's aquatic problems will require improved understanding of human, biological and physical aquatic ecosystems and the crafting of policies that will sustain the state's productivity and quality of life in the long term.

Continuing and expanding the focus of ANR's multidisciplinary expertise on aquatic issues can have major impacts on these critical problems even with the current difficult state budget climate. Partnerships with UC and CSU campuses, agencies and private-sector groups with expertise and resources devoted to aquatic issues can further enhance ANR's statewide efforts to serve California.

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COVER: Aquatic resources have been a critical component of California's growth and prosperity, but scientists warn that human uses have taxed these resources to the limit. Efforts are under way to restore aquatic ecosystems statewide.

***Above*, Mildred Island is a 1,000-acre "lake" formed in 1983 when large storms breached a levee and flooded a farm tract. Located in the interior San Joaquin-Sacramento River Delta, this site represents a shallow-water habitat type that will be constructed by CALFED to promote the recovery of native fish.**

Research is helping to inform this effort. On page 104, scientists measure supplies of phytoplankton, an essential component of the Delta food web. Also, studies on biomarkers (page 110) aid in understanding how environmental factors affect Delta wildlife. *Infrared photo by ©Herb Lingl/aerialarchives.com*

News departments

Editor's note: Due to cutbacks related to the state's budget deficit, *California Agriculture* will be publishing four issues in 2003 instead of six.

Research articles

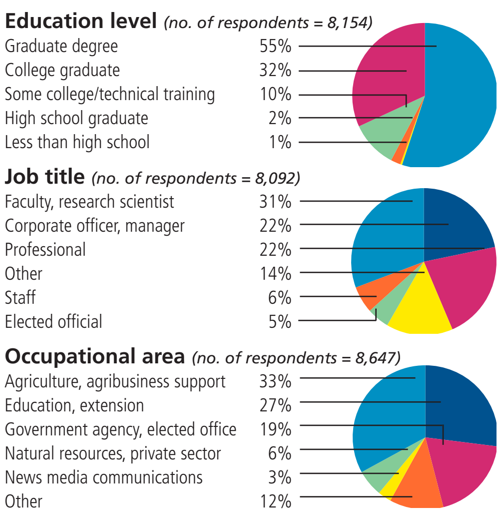
Delta resources at risk

California Agriculture readers diverse, well-educated

California Agriculture readers are a well-educated audience of 15,000 business leaders, faculty, scientists and policymakers, a recent survey shows.

In September and November 2002, *California Agriculture* sent 19,025 U.S. readers a resubscription notice on the dust cover of the magazine and posted similar forms on the Web site. The twofold purpose was to purge subscribers with no current interest, and to collect current information on reader interests and characteristics.

Of recipients, 66% or 12,593 resubscribed. (The balance of the 15,000 are chiefly foreign subscribers.) Of respondents, 87% are college graduates; 55% of readers hold advanced degrees (see figure). Not surprisingly, 31% identify themselves as faculty members or research scientists. Another 22% describe themselves as either corporate officers or managers. The category of professional — doctors, attorneys and lab technicians, for example — was chosen by 22% of those responding.



Reader responses to *California Agriculture* survey.

Readers also revealed that their occupational fields are broad-based. While a core of 33% work in agriculture (25% in production or processing, 8% in agribusiness), two-thirds work in other areas such as government regulation and research (in water resources or food safety, for example).

"The audience is a good match to content," says Steve Nation, director of ANR's Office of Governmental and External Relations. "While the journal is peer-reviewed to ensure that the science is sound, the text is edited to be accessible to a cross-disciplinary and professional audience."

The journal's authors are primarily, but not exclusively, UC faculty who wish to disseminate peer-reviewed research to an audience that extends around the world.

"The profile of readers indicates that *California Agriculture* performs a broader educational function than faculty normally can achieve with technical publication in a disciplinary journal," notes Associate Editor Al Sokolow, UC Davis public policy specialist. "It extends significant new research findings to a wider readership, informing decision-makers who are not in the same disciplinary field of important developments."

In addition to domestic subscribers, there are 1,740 foreign recipients, including 1,323 overseas libraries. International subscribers pay a subscription fee or must request an exception. Of journals sent to foreign libraries, 600 are distributed through UC Berkeley's library exchange program.

"*California Agriculture* is one of the most important titles of the 70 that we exchange. It is actively used at the institutions to which we send it. It unquestionably extends the University's presence very broadly around the world," says Frank Carothers, head of the Gifts and Exchange Division of the UC Berkeley library.

While *California Agriculture*'s audience is worldwide, its research focus is primarily on California. As a natural outcome, two-thirds of U.S. subscribers (8,305) live in California.

Readers were asked to check as many work interest areas as applied. They reported their chief interests were agriculture (33%), pest management (29%), the environment (28%), water (26%) and horticulture (26%). Other interest areas were land use (21%), forestry (13%), ranching (13%), food safety (12%), energy (11%) and nutrition (10%).

While the audience is computer savvy (3,173 or 25% resubscribed on line), most said they did not read the magazine online. This is consistent with other research showing that many people read while commuting or during leisure hours, when printed publications are more convenient.

Studies also show that readers prefer to have access to both online and printed sources, with many preferring the Internet to perform research. Close to 2,500 readers submitted their e-mail addresses, and are now receiving e-mail notification of the Web site posting of *California Agriculture*, with table of contents and links.

Findings reported here are based on approximately 8,000 to 11,000 responses depending on the question. Survey data was compiled and statistically analyzed by Brent Donnellan, former postdoctoral researcher, Human and Community Development, UC Davis. (Donnellan is now an assistant professor at Michigan State University.)

California Agriculture gratefully acknowledges the contribution of the late Associate Adjunct Professor Curt Acredolo, also of Human and Community Development, UC Davis. Acredolo consulted extensively on the postcard design and the input procedures and ideas.

— Janet White

To receive e-mail notification or update subscriber information, go to http://danr.ucop.edu/calag.

Antioxidants and pesticides

The science brief "Pesticide-free produce may contain antioxidants" in the April-June 2003 issue deals with a controversial subject. Such claims for differences between organic (or sustainable) production and conventional agriculture have not yet been scientifically demonstrated.

The word "may" in the title is especially appropriate for data derived from "matched plots," a test procedure that is not normally considered to be statistically valid, and for produce "grown by a farm in Oregon, then frozen, freeze-dried or air-dried before the nutrients were measured" without any indication of who actually planted, grew and harvested, as well as prepared the produce for analysis. Further, there is no indication of the number of samples of each produce type for each plot; nonetheless, the text claims that the percentage values are "nutritionally significant," but fails to note what the range of values (standard deviations) were for each group or the statistical significance of the percentage values for each group. This speculation about the biochemical justification for the differences is meaningless unless the validity of the claimed effect can be statistically demonstrated.

If the research had been published in a peer-reviewed journal, as was the following piece on the breakdown of pesticides by microorganisms, these comments would not have been made since that would have demonstrated that the information was supported by adequate statistical information not included in the article.

Jack C. Schwegmann, Retired Plant Pathologist
Alameda

Editor's note: The science brief in question was based on a peer-reviewed article published in the Journal of Agricultural and Food Chemistry *(Feb. 26, 2002). Reference to this article was cut due to space constraints;* California Agriculture *regrets any confusion that resulted.* California Agriculture*'s research articles (labeled above the title) present peer-reviewed data. Science briefs are simply news summaries, reviewed by sources for accuracy.*

UC Davis scientist Alyson Mitchell responds: This research has generated a running debate in the pages of the scientific press. Although limited in its design, our study and others like it demonstrate a trend of higher phenolics in organic produce. We hope this debate leads to increased research evaluating relationships between cultural practices and phenolic levels in crops. My colleagues and I have prepared a further response, to be published in a future Journal of Agricultural and Food Chemistry*. Readers can also obtain an overview of this subject by reading the July 16, 2003,* New York Times *article, "Is Organic Food Provably Better?" by Marian Burros.*

Genetically modified foods

The article by N. King ("Low income consumers, though less aware of genetically modified foods, are concerned and want labels," July-September 2003) was good, fairly done and interesting. Usually your authors report about what they have done or can accomplish to please the farmer, but say less on how they are pleasing the consumer. This survey did reveal the latter, and more.

To an ole horticulturalist who has written chapters and given many lectures on pests and pesticides, the engineers made a mistake on the "Bt" insecticidal gene, which is now almost across the board in our food. How in the world this mistake can be corrected is a mystery to me. While the engineers do have a future, they're moving too fast; they need to take a little of their big grants to run and publish feeding tests to prove to EPA and consumers the safety of their products.

California Agriculture is still about the best of its kind around. I wouldn't want to miss reading it.

Norm Childers, Professor
Institute of Food and Agricultural Sciences
University of Florida, Gainesville

Cal Ag an "information bulwark"

California Agriculture has proven a bulwark of information for many of my professional and personal decisions over the years. Not the least of these has been irrigation-system details, fruit-tree selection and pruning, turf-grass culture and selection, and beekeeping. The many articles on water resource development have prompted my attendance at Commonwealth Club sessions on water distribution politics and appropriate technology conferences at UC Davis over the years.

John Baird
Napa

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

With profound sadness, *California Agriculture* reports the death on Sept. 3 of Associate Editor Donald Lee Dahlsten, UC Berkeley professor of insect biology and leading expert in biological control and forest entomology. Dahlsten died at age 69 after a 2-year battle against skin cancer. *California Agriculture* deeply appreciates his service to the magazine. Please send donations to support outreach programs for K–12 students to: Donald Dahlsten Outreach Fund, c/o College of Natural Resources, UC Berkeley, 101 Giannini Hall, #3100, Berkeley, CA 94720-3100.

Rachel Woodfield, Merkel & Associates

◀ **A highly invasive seaweed, *Caulerpa taxifolia* was discovered among eelgrass shoots in Agua Hedionda Lagoon in Carlsbad, *left*. Vast, feathery carpets of the green alga cover the bottom of the Mediterranean, but biologists are cautiously optimistic that its spread is under control in California.**

Killer algae under control, for now

Scientists are cautiously optimistic that the nation's first outbreak of "killer algae" — a nonnative seaweed called *Caulerpa taxifolia* that was discovered in two Southern California coastal harbors in June 2000 — is under control, due to an aggressive response by multiple agencies, including California Sea Grant.

Caulerpa is a decorative aquarium plant with feathery green fronds. The outbreaks, in Agua Hedionda Lagoon in northern San Diego County and Huntington Harbour in Orange County, were likely caused by someone dumping a home saltwater aquarium into a waterway.

California Sea Grant participated in the Southern California Caulerpa Action Team or SCCAT, a statewide effort to prevent the highly invasive, saltwater seaweed from spreading as it has in the Mediterranean, with devastating consequences for marine life.

As of September 2003, *Caulerpa* had not been detected for 12 months in Agua Hedionda Lagoon and 9 months in Huntington Harbour. "We're very optimistic that we probably will be able to eradicate Caulerpa from these two systems," says Bob Hoffman of the National Marine Fisheries Service (NMFS).

Caulerpa's ability to grow rapidly over boulders, seawalls, in mud, sand or on rocks has the effect of severely reducing populations of native seaweeds and grasses. Because fish, invertebrates and seabirds need native habitats to survive (see page 104), *Caulerpa* outbreaks dull the biological richness of marine ecosystems.

Caulerpa presents a global threat to marine ecosystems. From just 1 square meter in the mid-1980s, more than 32,000 acres of the Mediterranean Sea floor is now smothered by the weed. In the last 5 years, the alga has spread to North Africa and Australia (both of which also have native *Caulerpa* species) and California. Genetic tests have shown that *Caulerpa* specimens in California and the Mediterranean are clones of specimens cultured and displayed at the Stuttgart Museum in Germany in the early 1980s.

California Sea Grant funded several projects to reinforce and expand the SCCAT program. Susan Williams, director of the Bodega Bay Marine Lab of UC Davis, mapped out the potential geographic range of *Caulerpa* based on available light, salinity and coastal ocean water temperatures.

"All lagoons in Southern California are at potential risk, as well as waters in Oregon, Washington and Mexico," Williams says. "San Francisco Bay is at high risk because it is a destination for 'live rock' shipped overseas for the aquarium trade." Live rock is coral covered with living marine organisms; *Caulerpa* has been found on live rock imports.

Based in part on a Sea Grant–funded survey of retail aquarium stores in Southern California, which found that 10% were selling an invasive strain of *Caulerpa,* the California Legislature in 2001 banned the importation, possession and intrastate sale of nine *Caulerpa* species. Interstate sale is illegal under the Noxious Weed Act of 1999.

The California Regional Water Quality Control Board led the eradication program, with the California Department of Fish and Game, California Department of Food and Agriculture (DFG), NMFS, U.S. Fish and Wildlife Service and California Sea Grant.

A biological consulting firm performed the eradication, which involved putting thick, black, plastic tarps over the *Caulerpa* patches, sealing them to the bottom and chlorinating the patches.

Despite the eradication program's success so far, Williams says, "*Caulerpa* has underground tissue, rhizoids, the algal equivalent of roots, that go 15 centimeters into the sediments." She believes the chlorine might not be reaching their roots.

Environmental factors such as water pollution and nutrient levels (see page 110) may also influence *Caulerpa*'s ability to invade, Williams says. "Based on scientific studies in the Mediterranean and on my research, sea grass beds that are degraded are less resistant to *Caulerpa* invasion."

Ultimately, public outreach and education may be the key to stopping *Caulerpa*. "People need to know they cannot release the contents of their home aquariums into lagoons and harbors," says DFG biologist Bill Paznokas.

SCCAT advises not disturing a suspected *Caulerpa* outbreak, and reporting it immediately at (858) 467-2952. — *Compiled from Sea Grant reports*

Invasive marine animals get bigger

For a wide group of marine pests, invasion is coupled with a marked increase in body size, a new study has found.

Edwin (Ted) Grosholz, UC Cooperative Extension specialist at UC Davis, and Gregory M. Ruiz of the Smithsonian Environmental Research Center in Edgewater, Md., compared the body sizes of 19 species of nonnative marine and estuarine invaders. These included crabs, shellfish and starfish, in their native habitats and other parts of the world where they have become invasive pests.

Twelve of the 19 showed increases in maximum size of up to 40%. European green crabs and Chinese mitten crabs, both prominent nuisance species in U.S. waters, were about 20% bigger than in their native habitats. Only one, the gem clam, showed any sign of a decrease. The increases in body size were not clearly linked to differences in latitude between the native range and invaded areas or to the length of time since invasion.

The changes could be because the animals are no longer held back by predators or parasites, Grosholz says. "Animals and plants that are innocuous in their home environment can become rampaging pests when they invade a new area."

The results could have implications for understanding both how modern-day nuisance species become successful, and for interpreting fossil evidence of changes in populations of marine animals over millions of years.

The findings, published in the August 2003 *Ecology Letters*, appear to be unique to marine animals, as research in other taxa shows invading species both increasing and decreasing in size. "For example, the data for European plants invading California suggests that nearly 30% of invading species got smaller in the introduced range," Grosholz and Ruiz wrote.

Food web changes documented in Lake Tahoe

Dramatic food web changes have occurred as a result of the introduction of nonnative species into Lake Tahoe, according to a study by researchers at UC Davis and the University of Wisconsin, Madison.

The scientists documented important ecological changes in Lake Tahoe spanning the past 120 years. The researchers reconstructed the dietary niches of Lake Tahoe fishes dating back to 1872 by conducting stable isotope analysis of museum specimens and comparing them to fresh catches.

In particular, introduced lake trout *(Salvelinus namaycush)* and a freshwater shrimp *(Mysis relicta)* appear to have especially altered the food web, which may have implications for mounting efforts to restore populations of native Lahontan cutthroat trout *(Oncorhynchus clarkii henshawi)*. Named for the distinctive red streak under its chin, this trout once topped the lake food chain at weights of 40 pounds. Due to overfishing, dam-building and habitat destruction, this species is now among the most endangered western salmonids and has been extinct in Lake Tahoe for 70 years. Some related but genetically distinct strains still live in lakes and streams outside of the Tahoe Basin.

At the 1997 Lake Tahoe Presidential Forum, then-President Bill Clinton and then-Interior Secretary Bruce Babbitt called for the Lahontan cutthroat trout to be restored to the Tahoe basin. For the past 2 years, the UC Davis/UW Madison research team has been collaborating with the U.S. Fish and Wildlife Service, assessing the current Lahontan cutthroat trout reintroduction efforts in Fallen Leaf Lake, a small lake located in the headwaters of Lake Tahoe.

"Fallen Leaf is turning out to be an ideal lake for Lahontan cutthroat trout reintroduction," says Jake Vander Zanden of UW Madison. "Plus, we're learning valuable lessons that will ultimately be transferred to other systems." The study was published in the April 2003 *Ecosystems*.

Brant Allen, UC Davis

Once abundant in Lake Tahoe, Lahontan cutthroat trout are now extinct from the lake. These year-old fish were raised at the Lahontan National Fish Hatchery in Minden, Nev., and reintroduced into Fallen Leaf Lake.

RESEARCH ARTICLE

Phytoplankton fuels Delta food web

Alan D. Jassby
James E. Cloern
Anke B. Müller-Solger

Populations of certain fishes and invertebrates in the Sacramento-San Joaquin Delta have declined in abundance in recent decades and there is evidence that food supply is partly responsible. While many sources of organic matter in the Delta could be supporting fish populations indirectly through the food web (including aquatic vegetation and decaying organic matter from agricultural drainage), a careful accounting shows that phytoplankton is the dominant food source. Phytoplankton, communities of microscopic free-floating algae, are the most important food source on a Delta-wide scale when both food quantity and quality are taken into account. These microscopic algae have declined since the late 1960s. Fertilizer and pesticide runoff do not appear to be playing a direct role in long-term phytoplankton changes; rather, species invasions, increasing water transparency and fluctuations in water transport are responsible. Although the potential toxicity of herbicides and pesticides to plankton in the Delta is well documented, the ecological significance remains speculative. Nutrient inputs from agricultural runoff at current levels, in combination with increasing transparency, could result in harmful algal blooms.

William Sobzcak, former U.S. Geological Survey postdoctoral researcher, samples for zooplankton in the Delta.

The Sacramento–San Joaquin River Delta is a complex mosaic of waterways that forms the transition zone between San Francisco Bay and its watershed (fig. 1). Over the last century, the original dominant marsh habitat has been lost through filling and diking. Water flows have changed radically. Exotic plants and animals have invaded or been introduced intentionally, and toxic contaminants have become widespread (CALFED 2000). The Delta is now a focus of ecosystem restoration because these changes have been accompanied by declines in the abundance of many fish species that use the Delta as a migration route, nursery or permanent habitat. Some species (thicktail chub) have already become extinct; others (winter-run chinook salmon) are now at risk of extinction; and still others (splittail, striped bass) have dramatically reduced populations.

Several lines of evidence suggest that food limitation has played a role in these declines. Many fish populations in the Delta are declining because of poor survival during the first year of life, which can be caused by food shortages (Bennett and Moyle 1996). Sport fish such as striped bass (Morone saxatilis), native species such as delta smelt (Hypomesus transpacificus), and commercial species such as chinook salmon (Oncorhynchus tshawytscha) all show evidence of food limitation during their first year. Zooplankton, a key food for young fishes, has also declined (Orsi and Mecum 1996). Some declining zooplankters, especially a mysid shrimp (Neomysis mercedis) and smaller species, also appear to be limited by food supply, as does the clam Corbicula fluminea, a dominant benthic invertebrate.

Zooplankton, benthic invertebrates and the larger, more visible fish and waterfowl that feed on them form a food web that depends ultimately on inputs of organic matter at its base (fig. 2). In many systems, phytoplankton species play a fundamental role in the organic matter supply to food webs. These microscopic plants are responsible for primary production, the photosynthetic production of organic matter. Other sources of organic matter are often present, however, and can even be dominant, especially in estuaries. In fact, there has been speculation for many years that organic matter carried in from upstream and from adjacent terrestrial sources is the main source sustaining the Delta's food web. What, then, are the relative roles played by phytoplankton and other sources in the organic matter supply to Delta waterways? The question is a basic one for restoration of the Delta, because it determines the focus for increasing food supply to declining populations. In addition to investigating this, we examine evidence for a long-term decline in the primary food supply and consider the role of agriculture.

Food comes in many forms

To determine the most important organic matter sources for Delta waterways, we combined decades of data collected by the California Department of Water Resources (CDWR), U.S. Bureau of Reclamation (USBR) and U.S. Geological Survey (USGS), using a variety of estimation techniques (Jassby and Cloern 2000).

Glossary

Algae: Primitive plants usually living in water and occurring as single cells, filaments, colonies and irregular aggregations.
Aquatic vascular plant: Higher plants living in water bodies. May be free-floating or rooted. Also known as aquatic macrophytes.
Benthic invertebrates: Invertebrates living on or in the bottom sediments.
Benthic microalgae: Microscopic algae living on or just under the surface of the bottom sediments.
Biomass: The weight of biological matter, usually measured in terms of carbon, dry weight or fresh weight, and expressed on an areal (g m-2) or volumetric (mg m-3) basis.
Chlorophyll: A green pigment present in most plants and essential for the process of photosynthesis, by which these plants obtain most if not all of their energy. Chlorophyll a is one form that is often assumed an approximate index of algal biomass.
Detritus: Nonliving particulate and dissolved organic matter.
Metazoa: Multicellular animals, in contrast to the more primitive protozoa.
Phytoplankton: The plant plankton, consisting mostly of microscopic algae.
Plankton: The community of passively suspended or only weakly swimming organisms in a body of water, which drift along with the water currents; planktonic organisms range in size
from tiny plants and animals to large jellyfish, and include the larval stages
of many fishes.
Primary productivity: The rate at which plants incorporate inorganic carbon into organic matter. Usually measured on a volumetric (mg C m-3 d-1) or areal (mg C m-2 yr-1) basis. Primary production is often used to refer separately to the amount of organic carbon produced in a particular time interval (mg C m-3 or mg C m-2).
Protozoa: Single-celled animals, including amoeba, ciliates and flagellates in aquatic systems.
Suspended sediments: Small mineral (clay and silt) particles suspended in waters.
Turbidity: The scattering effect that suspended and dissolved solids have on light, imparting a cloudy appearance to water. Primary contributors include suspended sediments, soluble colored organic compounds and microscopic organisms.
Zooplankton: The animal plankton, in estuaries consisting mostly of protozoa, rotifers and two crustacean types, the cladocerans and the copepods.

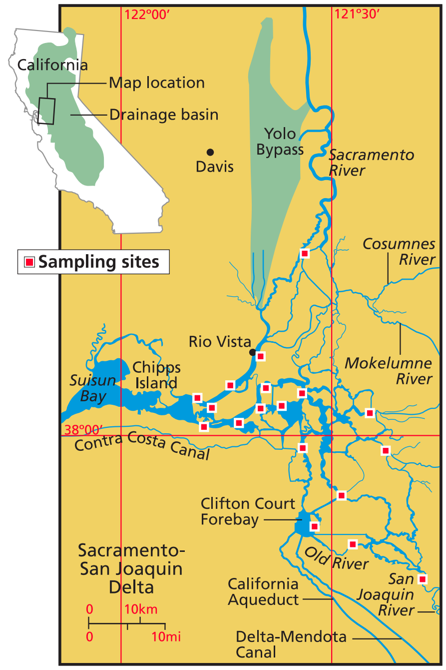


Fig. 1. The Sacramento-San Joaquin River Delta extends upstream from Chipps Island to include leveed islands, river channels, sloughs, flooded islands and tidal marshes. Boxes mark stations used by the California Department of Water Resources to assess water quality, in some cases since the late 1960s.

Organic matter sources are usually compared in terms of their total organic carbon (TOC) content; TOC can come in both particulate (POC) and dissolved (DOC) forms. River input — organic material carried in by the Sacramento, San Joaquin and other rivers and creeks — is the largest TOC source overall (fig. 3). Some of this river-borne material is actually phytoplankton and phytoplankton-derived detritus transported from upstream of the Delta.

Phytoplankton production within the Delta and organic matter in agricultural drainage directly into the Delta are next in importance. Agricultural drainage upstream of the Delta is included in river inputs and cannot be estimated separately with any confidence. Much of the organic matter in agricultural drainage originates from leaching of DOC from island peat soils. Discharge from wastewater treatment plants, drainage from tidal marshes and production of aquatic vascular plants such as the submerged Egeria densa are tertiary sources. Urban runoff, primary production by benthic microalgae and other sources — although sometimes important in other estuaries — are negligible sources of organic matter in the Delta. Phytoplankton is clearly the Delta's dominant primary producer, whereas river input of organic material from upstream is dominant among external sources (fig. 3). Many of these sources are distributed unevenly throughout the Delta, and we can identify areas where aquatic vascular plants, tidal marsh drainage or another source may dominate at times. Nevertheless, phytoplankton production, river inputs and agricultural drainage

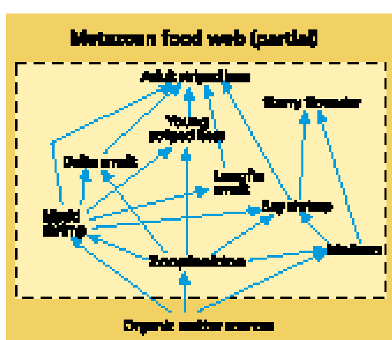


Fig. 2. The metazoan food web can be extremely complex, especially in estuaries, and only a small portion of the Delta's food web is portrayed here. The energy and nutrient needs of the metazoan food web are supported by a variety of organic matter sources.

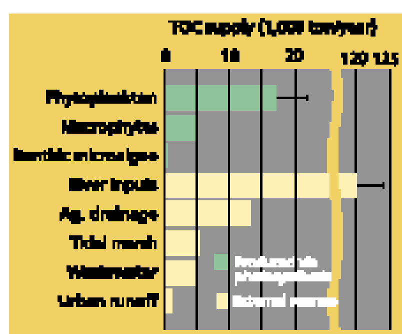


Fig. 3. Organic matter, measured as total organic carbon (TOC), is produced in Delta waterways by photosynthesis and enters from a variety of external sources. Phytoplankton is the biggest internal source and river transport is the biggest external source. Error bars represent standard error among years.

together account for 90% of average annual Delta-wide organic matter sources.

Drinking water and organic matter

Aside from its ecological significance, organic matter also has implications for drinking-water quality in the Delta. The Delta provides all or part of the drinking-water supply for about 22 million California residents. When disinfectants such as chlorine are added to drinking water to kill microbial pathogens, they react with bromide and naturally occurring organic matter to form disinfection byproducts (DBPs). The main DBP groups are total trihalomethanes, haloacetic acids, bromate and chlorite. When these are consumed over years in excess of federal standards, some people may experience problems with the liver, kidneys or central nervous system, or may have an increased risk of cancer or anemia (Bull and Kopfler 1991).

A current major challenge for water suppliers in the Delta and elsewhere is how to balance the risks from pathogens and DBPs; it is important to provide protection from these pathogens by using disinfectants while simultaneously containing health risks from DBPs. One way to limit DBP formation is to limit TOC levels in raw water supplies. Our organic matter assessment implies that phytoplankton production, river-borne loading and agricultural drainage should each be a focus of source-control measures with respect to the DBP problem: they are all important sources of naturally occurring organic matter in the Delta.

The participation of phytoplankton in ecosystem food supply and drinking-water quality points to one example of conflicting aims in the Delta. Although higher phytoplankton production may be a boon to certain food-limited organisms, it can degrade drinking-water quality through the formation of DBPs. The diversity of issues in the Delta creates a complex balancing problem: human health versus ecosystem health. The balancing of different aims is particularly difficult with regard to phytoplankton, which has many other effects. Negative impacts include clogging filters, producing undesirable tastes and odors, and contributing dangerous substances directly to raw water, such as the liver toxin microcystin-LR and neurotoxin anatoxin. On the positive side, phytoplankton is central in the bioconcentration of contaminants, transport and cycling of plant nutrients, and the atmospheric carbon dioxide balance.

An inefficient food source

The bulk accounting in figure 3 is an inadequate guide to the relative value of different organic materials for primary consumers such as zooplankton and clams. Particulate and dissolved forms of organic matter differ markedly in their availability to the food web, making further refinement necessary. POC enters the Delta mostly as phytoplankton, bacteria and protozoa, particles of decaying organic matter, and suspended mineral particles carrying organic matter on their surfaces. These particles can be utilized directly by primary consumers such as clams and zooplankton.

In contrast, most dissolved organic carbon must first be transformed into particles before it can be consumed. This transformation happens primarily via the uptake and metabolism of DOC by bacteria; in other words, the DOC is converted to bacteria cells. Much of the DOC is not very bioavailable (not easily assimilated and metabolized) and is simply flushed downstream before bacteria can utilize it. Moreover, much of the remaining DOC that is metabolized by bacteria is lost to respiration and does not end up as bacterial biomass.

We refined our estimates of the three major organic-matter sources by accounting for bioavailability of DOC and respiratory losses, based on generalizations from previous empirical studies (Jassby and Cloern 2000). We then categorized each year as either drier or wetter than average and plotted the refined estimates of TOC in each category by season (fig. 4). The relative importance of organic matter sources changes dramatically because so much of river input and agricultural drainage is in dissolved form. Phytoplankton production is seen as a significant source of bioavailable organic matter in all seasons, except for winters with above-normal precipitation. Moreover, phytoplankton production is comparable to and sometimes greater than river inputs in spring and summer of both above-normal and below-normal years. Spring and summer are particularly critical seasons for survival and growth of young fish and successful recruitment to fish populations. In contrast, agricultural drainage is almost never a significant source of bioavailable organic matter. Consequently, plans to control organic matter in agricultural and Delta island drainage because of the DBP problem should have little impact on food supply to the Delta's food web.

Recently this work was corroborated with an extensive set of bioassays that assessed the food value of the Delta's organic matter sources (Sobczak et al. 2002). Although dissolved organic matter is the major energy and carbon source for bacterial metabolism, the dominant food supply to the planktonic food web is bioavailable, particulate organic matter derived primarily from internal phytoplankton production.

Differing nutritional quality

Just as dissolved organic-matter sources contribute little to the food supply compared with particulate sources, the particulate sources themselves vary in quality. Delta phytoplankton are a better food source for zooplankton than other kinds of particles in the POC pool — decaying organic matter, bacteria and organic matter clinging to the surface of clay and silt particles. The zooplankter *Daphnia magna*, which occurs in the Delta, feeds nonselectively on particles smaller than 40 micrometers (µm). In a series of laboratory feeding assays (Müller-Solger et al. 2002), *Daphnia* were exposed using a flow-through system to water from four Delta habitat types collected during all four seasons, and growth rates were measured. While POC concentrations were only weakly related to *Daphnia* growth, concentrations up to a threshold of about 10 µg/L chlorophyll *a* — a pigment found in phytoplankton — predicted *Daphnia* growth rates across all habitats and seasons (fig. 5). Chlorophyll is not a nutrient; it is merely a marker for the phytoplankton fraction of particulate organic matter and a convenient way to estimate phytoplankton biomass. The actual nutritional factors in phytoplankton determining *Daphnia* growth rates are not known for certain, although ele-

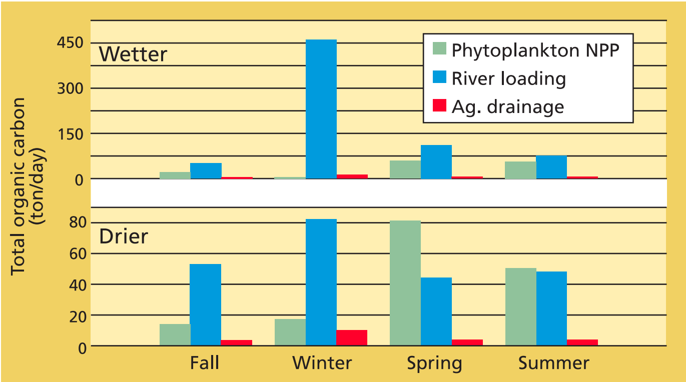


Fig. 4. Phytoplankton net primary productivity (NPP), river loading and agricultural drainage make up most of the bulk organic-matter supply. The values shown here have been corrected for losses due to lack of bioavailability and respiration, and are therefore a more realistic comparison of the food value for consumer organisms than the bulk data of figure 3. Phytoplankton provides a significant source especially in spring and summer, a critical period for populations of many fishes and invertebrates.

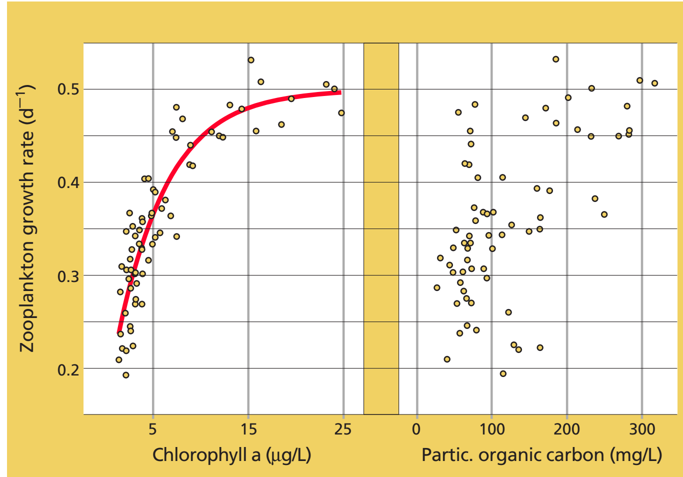


Fig. 5. The growth of the zooplankter *Daphnia magna* in Delta waters is closely related to the supply of phytoplankton, as indexed by chlorophyll *a* concentrations, but not so closely tied to levels of particulate organic carbon in general.

ments such as phosphorus and certain essential fatty acids are candidates.

Supply changes year to year

Phytoplankton are probably the most important portion of the particulate organic matter supply to the Delta's food web on a Delta-wide basis, and growth rates of primary consumers such as *Daphnia* are closely tied to phytoplankton availability below about 10 µg/L. But how often is Delta phytoplankton at levels that can limit zooplankton growth, and is phytoplankton variable enough to induce major changes in zooplankton growth rates? In fact, Delta chlorophyll levels quite commonly fall within the range limiting growth. Thousands of chlorophyll *a* measurements have been made in the Delta since the late 1960s by the CDWR and USBR, and 55% to 93% of them, depending on the year, are below 10 µg/L (Jassby et al. 2002). Moreover, large swings have occurred in Delta-wide chlorophyll from one year to the next, and longer-term changes are evident.

Figure 6 shows the annual average of Delta-wide chlorophyll for each season during a period when analytical methods remained the same and sampling was sufficiently comprehensive to cover the entire Delta. Although the trend is not uniformly downward, there has been an overall tendency toward lower phytoplankton concentrations in later years. In fact, all except spring months (April to June) showed a robust, statistically significant downward movement from 1975 to 1995 (Jassby et al. 2002). Phytoplankton variability could therefore easily lead to a several-fold difference in zooplankton growth rates.

What are the reasons for this variability? In 1986, an Asian clam *(Potamocorbula amurensis)* invaded and established itself in Suisun Bay, presumably after being discharged with ship ballast water. Its establishment and dispersal were aided by the prolonged drought and accompanying low freshwater inflows to the Delta that began in 1987. *Potamocorbula* turned out to be a voracious consumer of phytoplankton and changed phytoplankton dynamics in Suisun Bay (Alpine and Cloern 1992). The effects of *Potamocorbula* probably extend into the western Delta, with a summer downturn after 1986 even in the Delta-wide chlorophyll record (fig. 6); *Potamocorbula* are feeding most actively during summer.

A recent analysis identified the most important driving forces for Delta-wide phytoplankton production: interannual variability of water flow; increased consumption by *Potamocorbula*; and a downward trend in suspended mineral particles over many decades, which improves water transparency and therefore phytoplankton photosynthesis and growth rate (Jassby et al. 2002). The increase in phytoplankton growth rate partially compensates for increased losses due to consumption by clams, but apparently not by enough to prevent a decrease in phytoplankton biomass. The dry weight of suspended mineral particles is much greater than phytoplankton biomass: variations in the latter have relatively little effect on transparency.

Impact of agricultural runoff

Dissolved organic matter in agricultural drainage, although an important issue for drinking-water quality, is not a significant source of energy for the Delta's food web. What effects might other constituents of drainage and runoff, namely pesticides and nutrients, have on phytoplankton productivity?

Pesticide toxicity. Herbicide concentrations may limit phytoplankton growth rates during localized occurrences of elevated concentrations. In 1997, Jody Edmunds and colleagues at the USGS examined 53 water samples collected from May through September at nine Delta sites for six herbicides that inhibit photosynthesis. Only one sample exceeded concentrations (diuron) reported to inhibit primary production in laboratory experiments (Edmunds et al. 1999). Similarly, bioassays showed no relationship between ambient herbicide concentrations and photosynthesis, except for this one sample. The study design might have missed herbicide runoff events during the rainy season.

In fact, Jeff Miller and others from the Central Valley Regional Water Quality Control Board, using an algal indicator species, found toxicity in 22% of samples from the Sacramento–San Joaquin watershed and Delta during 2000 to

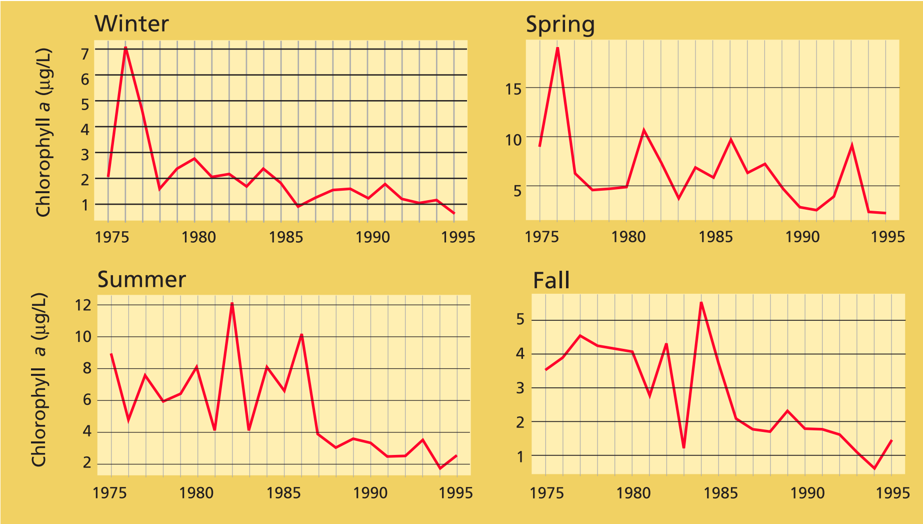


Fig. 6. Average chlorophyll *a*, and therefore phytoplankton biomass, is highly variable from season to season and year to year in the Delta, but in general it has been decreasing since at least the 1970s. Summer chlorophyll, in particular, decreased markedly after the Asian clam, *Potamocorbula amurensis,* invaded in 1986; the clams feed most actively during summer.

2001 (Miller et al. 2002). Again, diuron — an herbicide applied to rights-of-way, alfalfa, vineyards and orchards — was implicated. Most toxicity occurred from January to March when diuron is applied and when it is most likely to rain in California; in contrast, most phytoplankton production takes place in spring and summer. The ecological consequences of this photosynthetic inhibition may therefore be limited.

Pesticides may also affect primary production through indirect effects on the zooplankton community, molluscs and other organisms that feed on phytoplankton. Data collected by the USGS National Water-Quality Assessment program demonstrate that seven pesticides in the San Joaquin River Basin frequently exceed criteria for the protection of aquatic life, and diazinon concentrations sometimes reach acutely toxic levels in the San Joaquin River (Dubrovsky et al. 1998). Similarly, diazinon and chlorpyrifos are linked to toxicity in test zooplankton in the Sacramento River watershed. The Regional Monitoring Program of the San Francisco
Estuary Institute has established that these organophosphate pesticides are also of concern in San Francisco Bay. While there is a growing body of information that pesticides in surface-water runoff can be toxic to invertebrates in the San Francisco Bay and Delta, the ecological significance has not yet been established.

Nutrient levels. Largely because of agricultural drainage, nutrient supplies are well in excess of phytoplankton needs in the Delta. The availability of nitrogen and phosphorus are important determinants of phytoplankton growth and biomass in many aquatic systems. A low nutrient supply can restrict the growth of phytoplankton and, ultimately, fish yield. We found that nutrient concentrations were low enough to limit phytoplankton growth for only about 0.1% of the measurements since the late 1960s, most occurring in the southern Delta during the extremely dry El Niño–Southern Oscillation of 1976 to 1977 (Jassby et al. 2002). Nutrient sources and this nutrient excess are not as pronounced downstream in San Francisco Bay, and nitrogen can become limiting during spring phytoplankton blooms in the South Bay.

Excessive nutrients from agricultural drainage or animal wastewater have promoted huge and harmful phytoplankton blooms in many locations around the world (Anderson et al. 2002). This is not a major problem in the Delta currently because of high concentrations of suspended sediments and accompanying turbidity. High turbidity is in part a legacy of the erosion caused by hydraulic mining in the Sierra Nevada in the 19th century. By decreasing transparency and limiting the penetration of sunlight, turbidity slows phytoplankton photosynthesis and limits its ability to reproduce rapidly to massive levels. However, suspended sediment in the Delta has been decreasing and transparency increasing for decades.

USGS scientists have identified several possible explanations for this phenomenon (Wright and Schoellhamer in press). First, reservoirs have been trapping sediment behind dams similar to the decrease in sediment load over the past 50 years. Second, there are still channel and floodplain deposits of mining-derived sediments that are being eroded and gradually depleted. Third, bank stabilization such as riprap retards meandering, eliminating a sediment source (channel banks) and contributing to decreasing sediment yield. Finally, the depositional nature of the lower Sacramento floodplain has changed in a way that, in principle, could trap additional sediment. The relative importance of these mechanisms is not known precisely. In any case, given the excess of nutrients in the Delta, decreasing turbidity means that large phytoplankton blooms may become a more common phenomenon (Jassby et al. 2002). Moreover, Delta waters are warming, and higher temperatures favor the cyanobacteria (blue-green algae) that constitute nuisance or harmful algal blooms. If such nuisance or harmful blooms become common, control of nitrogen and phosphorus inputs from agricultural drainage will become a much more important issue.

Ecosystem restoration

The research described here highlights the importance of phytoplankton in sustaining the metazoan food web on a Delta-wide basis, despite the presence of many other organic matter sources. Organic matter in agricultural drainage is mostly in dissolved form and not an important nutrient or energy source for the metazoan food web; along with phytoplankton and other sources, however, it reacts with disinfectants during drinking-water treatment to form potentially harmful byproducts. Phytoplankton biomass — and therefore the food supply for higher organisms — has declined over the past few decades, partly because of the Asian clam invasion. Certain herbicides in agricultural drainage may at times inhibit phytoplankton production, especially in winter, but their overall effect on annual production is probably limited. Similarly, certain pesticides can reach toxic levels for primary consumers of phytoplankton, but any ecological significance has not yet been demonstrated.

The phytoplankton decline may represent a reduction in the system's capacity to support higher levels of the food web. Lower phytoplankton levels have been linked to declines in key zooplankton populations in the Delta. Although the evidence for food limitation of fish populations is not as strong as for zooplankton and benthic invertebrates, data from many estuaries and other water bodies also points to an overall correspondence between fish production and primary production (Nixon and Buckley 2002). Unless phytoplankton productivity increases, restoration of fish populations in the Bay-Delta may be limited. Water transparency has increased over the past few decades due to declines in suspended sediments, enhancing phytoplankton photosynthesis and partially offsetting consumption by clams. A continuation of the transparency trend could result in increased phytoplankton production because of the excess nutrients available in the estuary from fertilizer runoff and wastewater treatment effluent. Although this could have positive effects on overall fish production, there is a potential danger from nuisance and harmful phytoplankton species that pose both human and ecological toxicity problems.

As a response to symptoms of gross ecosystem disturbance and the critical role of the Delta as the linkage between San Francisco Bay and its watershed, a consortium of state and federal agencies was established in 1994. The CALFED Bay-Delta Program's mission is to develop a long-term and comprehensive plan to "restore ecological health and improve water management for the beneficial uses of the Bay-Delta system." The program is centered around four objectives, one of which focuses on environmental quality to "improve and increase aquatic and terrestrial habitats and improve ecological functions in the Bay-Delta to support sustainable populations of diverse and valuable plant and animal species" (CALFED 2000). This is one of the largest attempts at ecosystem restoration worldwide, with a multibillion dollar budget and a period of 25 to 30 years for full implementation. Addressing the decline in system productivity is part of one of the key strategic goals of this ecosystem restoration.

Attainment of the CALFED Bay-Delta Program restoration goals requires a solid base of scientific understanding to identify key ecosystem functions within the Delta and to describe how they change in response to human activities, including restoration actions. Restoration actions — including new canals, flow and fish barriers, increased use of floodplains and increased shallow-water habitat — all have significant impacts on phyto-plankton production, some positive and some negative (Jassby and Cloern 2000). Given the significance of phyto-plankton production to the food base in the Delta, as well as other phytoplankton-related functions, these impacts must be defined quantitatively and used to help guide the restoration strategy.

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Biomarkers aid understanding of aquatic organism responses to environmental stressors

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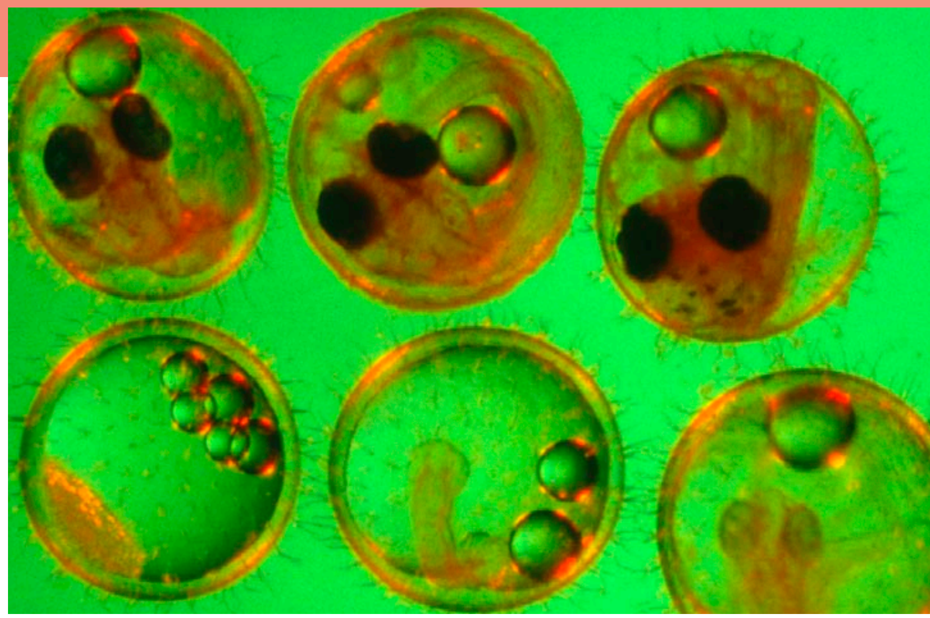
Biomarkers can be useful tools for understanding the complex interactions that govern organism responses to environmental stressors and their sublethal effects on organism health. We conducted studies on two types of biomarkers: stress proteins and tissue alterations. A study on the freshwater fish medaka demonstrates that the ability to increase cellular stress-protein concentrations at specific life stages can be vitally important for normal embryo development. A field study on Asian clam investigates the usefulness of stress proteins and histopathology as indicators of exposure to and sublethal effects of environmental stressors in the northern San Francisco Bay and Delta.



Alex Villalobos

To better understand how stress proteins affect fish, medaka embryos at various stages of development, *above,* were subjected to heat shock. Stress proteins can serve as biomarkers, indicating exposure to environmental stresses such as temperature, pH, chemical pollution or salinity. *Clockwise from upper left:* stages 11, 19, 23, 26, 28 and 35.

Exposure to environmental stressors can result in biochemical, physiological and histological (tissue) alterations in living organisms. The presence of these alterations may serve as "biomarkers," signaling exposure to stressors or adverse effects, which can range from molecular, cellular and tissue damage to genetic alterations. In the aquatic environment, such stressors can constitute changes in physical parameters such as temperature, pH or salinity, as well as toxic concentrations of chemical pollutants or any combination of these.

In the Sacramento–San Joaquin River watershed, populations of finfish are in decline (Bennett and Moyle 1996), and numerous aquatic species are either listed or proposed for listing as threatened or endangered. These include Sacramento splittail *(Pogonichthys macrolepidotus)*, delta smelt *(Hypomesus transpacificus)*, spring- and winter-run chinook salmon *(Oncorhynchus tshawytscha)*, coho salmon *(Oncorhynchus kisutch)* and steelhead trout *(Oncorhynchus mykiss)*. Fisheries experts agree that survival of juvenile fish is a critical factor in maintaining healthy fish populations. Living in an environment that has been altered considerably by human activities, fish are often exposed to a multitude of stressors. Land-use patterns and regulated river flows have changed the temperature, flow and salinity in watersheds (Bennett and Moyle 1996). In addition, toxic contaminants and nutrients enter the water via agricultural and urban runoff, discharges from abandoned mines and point-source dischargers (U.S. Geological Survey 1998; Werner, Deanovic et al. 2000; Roth et al. 2001).

The ability to protect cells at specific life stages can be vitally important for the normal development of organisms. Knowing the course of development, or ontogeny, of biomarkers shown to be important in adult stress responses, and their importance for normal embryo development, can improve understanding of the specific needs of these organisms for successful recruitment. Some biomarkers, such as the activity of enzymes like acetylcholine esterase or the cellular concentrations of metal-binding proteins (such as metallo-thioneins), enable scientists to determine if exposure to particular environmental

Glossary

Biomarkers: Biochemical, physiological or histological indicators of either exposure to or effects of physical stressors or xenobiotic chemicals at the suborganismal or organismal level (Huggett et al. 1992).

Histopathology: The study of lesions (alterations) in certain tissue types, including necrosis, inflammation and degeneration (Huggett et al. 1992).

Stress proteins/heat-shock proteins [hsp]: A family of proteins that protect organisms from environmentally induced cellular damage. Members of the hsp70 protein family are involved in the stabilization of unfolded protein precursors, translocation of proteins across cellular membranes, dissolution of protein aggregates, and repair or degradation of damaged proteins. Several hsp70 proteins are always present in cells, while others are only produced in response to stressful environmental conditions (Feige et al. 1996).

stressors has triggered biochemical and cellular responses in the organism.

Such responses allow preliminary assessments of the impact and bio-availability of a specific type of stressor, but presently cannot provide specific information on higher effects such as survival or reproduction. Other biomarkers, such as cellular stress-protein levels, indicate that potentially harmful effects have occurred inside cells, and that cellular repair mechanisms have been activated. Finally, tissue damage can indicate effects at the organ level and provide insight into the organism's health. These higher-tier biomarkers are often less stressor-specific, but can reflect the combined effects of multiple stressors. On the other hand, they are often difficult to interpret, especially when applied individually in field studies. To reduce variability in field studies, cause-effect relationships between biomarkers and stressors are best examined using sessile organisms, such as shellfish, which do not move around and reflect conditions at a specific location. However, multiple stressor effects in the field can slow attempts to interpret biomarker responses. We conducted several studies in the field and laboratory to further elucidate the use of biomarkers as indicators of exposure to environmental stressors in the northern San Francisco Bay and Delta.

Stress proteins protect medaka

To date, the linkage between the age-dependent sensitivity of aquatic organisms to stressors and cellular stress responses is poorly understood. UC Davis researchers (Marty et al. 1990; Hamm et al. 1998) have determined that the sensitivity of fish embryos to toxic compounds is age-dependent and not related to differences in uptake rate or bioavailability, which determines how much of the chemical is taken up by the organism. Often this sensitivity is a function of the organism's ability to metabolize the chemical or activate cellular stress responses and repair mechanisms. The stress-protein response is among the mechanisms that protect organisms from environmentally induced cellular damage. Presence or absence of these protective proteins at a given developmental stage may influence how the organism is affected by exposure to physical environmental changes and/or toxic chemicals.

To elucidate the protective role of stress proteins in the embryonic development of fish, we characterized the response of the hsp70 protein family to heat-shock in several developmental stages of the freshwater fish medaka *(Oryzias latipes)*(Werner, Koger et al. 2001). Medaka are small, easily cultured fish that produce eggs year-round. Their continuous production and availability of eggs, transparent chorion (eggshell) and relatively small adult size facilitate studies of reproductive and developmental effects.

Embryos were obtained from a medaka colony continuously maintained at UC Davis since 1986. At each of five developmental stages, embryos (n = 100 per stage) were given a 30-minute heat-shock at 104°F and returned to culture conditions. Control embryos were maintained at 77°F. Samples of 10 heat-shocked and 10 control embryos were then taken for hsp analysis at 1, 2, 3, 6, 12 and 24 hours after heat-shock. Proteins were analyzed by gel electrophoresis and immunoblotting using specific antibodies that detect hsp70 (Affinity Bioreagents, Golden, Col.)(fig. 1). Hsp70 proteins were visualized using a chemoluminescent reagent, and subsequently measured by densitometry. For the study of developmental effects and hatching success, 50 embryos per stage were heat-shocked as described, then maintained at culture conditions until hatching. Development and viability were recorded daily.

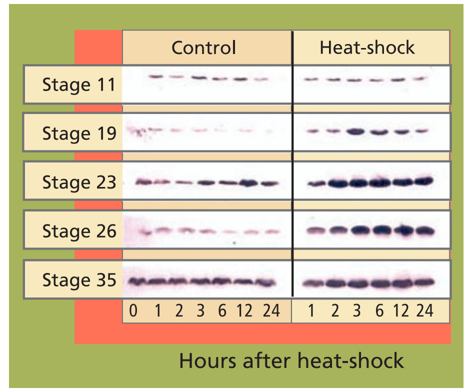


Fig. 1. Western blots of stress protein hsp70 in heat-shocked (30 minutes, 104°F) and control embryos at different stages of development. Each band represents one pooled sample of five embryos. Band intensity reflects cellular concentrations of hsp70 proteins.

In early-stage embryos (stage 11 = early gastrula), stress-protein (hsp70) concentrations did not increase in response to heat-shock (fig. 1), while hsp70 proteins were induced in all other developmental stages. These early-stage embryos were considerably less tolerant to heat stress than embryos at stage 19 and older (table 1). Of stage 11 embryos heat-shocked at 104∞F for 30 minutes, 22% died within 1 day. By day 3 another 22% died. By day 4 another 28% showed retarded development when compared to controls, with the formation of large, clear spaces around the heart and over the yolk sac. In addition, eyes were absent or fragmented. These alterations have also been described in medaka embryos exposed to various toxicants (Marty

TABLE 1. Effects of heat treatment at different stages of development in medaka

Embryonic stage (104°F/30 minutes)	Control/normal development at time of heat-shock	Development/mortality after heat-shock
11	Late blastula/early high gastrula, stage of rapid cell division	28% hatched: 20% normal, 8% curved spines
19	Neuralation, body axis formed (within 2 to 3 days)	100% normal; 52% hatched early
23	Heart begins to beat	94% normal, 6% helmet heads
26	Eyes become pigmented	94% normal, 6% helmet heads
35	Gallbladder and swim bladder are formed, rapid yolk utilization	100% normal
Embryo/control I*		100% normal
Embryo/control II*		100% normal

* No heat treatment

et al. 1990), and represent pericardial edema, yolk sac and peritoneal edema, and microphthalmia (reduced growth of the eyes resulting in small eyes or blindness), respectively. Only 28% developed normally.

Hatching began after 7 days, and by day 14, 93% of normally developed embryos had hatched. Of the hatched larvae, 23% had curved spines. Stage 19 embryos heat-shocked at 104°F for 30 minutes developed normally, but initiated hatching earlier than the embryos heat-shocked at later stages and the control embryos. Eighty percent hatched on day 7 of development whereas hatching had occurred in only 0% to 14% of all control embryo groups. By day 9, all embryos heat-shocked at stages 19 to 35 and control embryos hatched, and showed no sign of developmental lesions. However, a small percentage of stage 23 and stage 26 embryos showed "helmet heads," which occurs when all but the head emerges from the chorion and this structure remains closely attached to the head.

The stress-protein response is one of the most important cellular mechanisms to prevent and repair the adverse effects of thermal stress, some chemical pollutants and disease (Feige et al. 1996). Aquatic organisms respond to temperature stress and toxicant exposure by increasing cellular concentrations of hsp70 and related stress proteins (Sanders 1993; Iwama et al. 1998). Among the chemicals shown to produce this response are dioxin (Soimasuo et al. 2001), heavy metals (Baumann et al. 1993) and pesticides (Werner and Nagel 1997). Cellular stress-protein concentrations also increase in response to bacterial and viral infections (Zuegel and Kaufmann 1999).

The inability of early (stage 11) embryos to increase cellular concentrations of stress proteins may render them more susceptible to a variety of environmental stressors during a critical phase of their life cycle. It is of crucial importance that environmental decision-makers are aware of this when setting water-quality criteria for the protection of aquatic life. Protecting only the juvenile or adult organisms may not guarantee the survival of populations.

Asian clam and environmental stress

The Asian clam, or Amur River corbula *(Potamocorbula amurensis)*, was introduced via ship ballast water into San Francisco Bay in the mid-1980s. The species has since spread prolifically throughout the Bay and Sacramento–San Joaquin River Delta, increasing to a peak population density of more than 12,000 per square yard (Carlton et al. 1990). It has become the dominant species in northern San Francisco Bay (Nichols et al. 1990), where it is implicated as the possible cause of a change in the existing community structure, reducing food supplies for juvenile fish (see p. 104)(Werner and Hollibaugh 1993; Kimmerer and Orsi 1996; Feyrer 2000).

Because of its abundance and wide distribution, UC Davis and the U.S. Geological Survey (USGS) have been studying Asian clam as an indicator species for pollutant effects in San Francisco Bay. Biomarkers of reduced health — including lowered condition indices and energy reserves, and elevated levels of metal-binding proteins — have been observed to increase from San Francisco Bay eastward toward the Sacramento–San Joaquin River Delta. These indicators were partially linked to heavy metals, particularly cadmium, measured in clam tissues (Brown and Luoma 1995; Teh et al. 1999).

In this study, we attempted to link levels of stress proteins and tissue damage in field-collected Asian clam to concentrations of heavy metal in tissues (Werner and Hinton 1999, 2000). From July 1996 to January 1998, clams were sampled monthly (except October 1996, January to March 1997 and October 1997) from each of four stations in northern San Francisco Bay (fig. 2). Average salinities during the collection period ranged from 4.2 ± 4.0 parts per trillion (ppt) at station 4.1 (range: 0.06 to 15 ppt) to 22.3 ± 5.6 ppt at station 12.5 (range: 4.1 to 30 ppt).

Laboratory exposures to dissolved cadmium were conducted to validate results observed in the field and hsp70 proteins were analyzed as described previously. In Asian clam, the antibody

Fig. 2. Asian clam collection sites in northern San Francisco Bay.

used recognized two related proteins, hsp70 and hsp76. For an assessment of histological damage in reproductive organs and gills, clam tissues were scored for severity of pathological alterations as 0 = none, 1 = minimal, 2 = moderate and 3 = severe.

Stress proteins and tissue damage

Data obtained for field-collected clams showed that tissue levels of hsp70 were significantly ($P < 0.001$) higher from stations with the lowest cadmium concentrations and highest salinities (12.5 and 8.1) than from stations with the highest cadmium concentrations and lowest salinities (4.1 and 6.1; fig. 3A). The laboratory results, on the other hand, showed that clams increase their cellular hsp70 levels with increasing cadmium concentrations (fig. 3B). Other heavy metals such as chromium-VI also induced hsp70 proteins. Histopathologic lesions in the testes (chronic inflammation with associated focal necrosis) were relatively common at station 4.1 (high cadmium, low salinity), especially during late spring and early summer (data not shown), and were rare at station 12.5 (low cadmium, high salinity) throughout the year (fig. 4A). Focal necrosis of the ovary and mucus-cell swelling in gills followed a similar pattern. A 14-day laboratory exposure of clams to dissolved cadmium caused increased lesion scores in the gills and ovaries (fig. 4B).

Contrary to our expectations, stress-protein levels, which increased with rising cadmium concentrations in our laboratory experiment, were lowest in

TABLE 2. Hsp70 levels in clams after 3-day laboratory exposure to various salinities*

Salinity	Hsp70
0.1 ppt	16.64 ± 1.79a
10 ppt (ambient)	25.02 ± 6.70a
27 ppt	34.72 ± 3.31b

* Clams were collected from Martinez marina (salinity = 10 ppt). Letters indicate significantly different groups (P < 0.05).

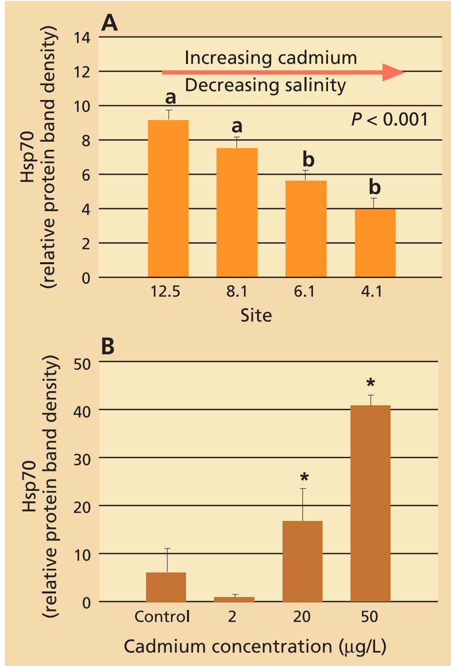


Fig. 3. (A) Average stress protein (hsp70) levels in Asian clam from four stations in northern San Francisco Bay. Six clams per site were collected monthly from July 1996 to January 1998. Group a is significantly (*P* < 0.001) different from group b. (B) Average stress-protein levels in Asian clam (*n* = 6) after exposure to dissolved cadmium in the laboratory. * indicates significant difference (*P* < 0.05) from control and 2 µg/L–exposed clams. Error bars represent standard errors of the mean.

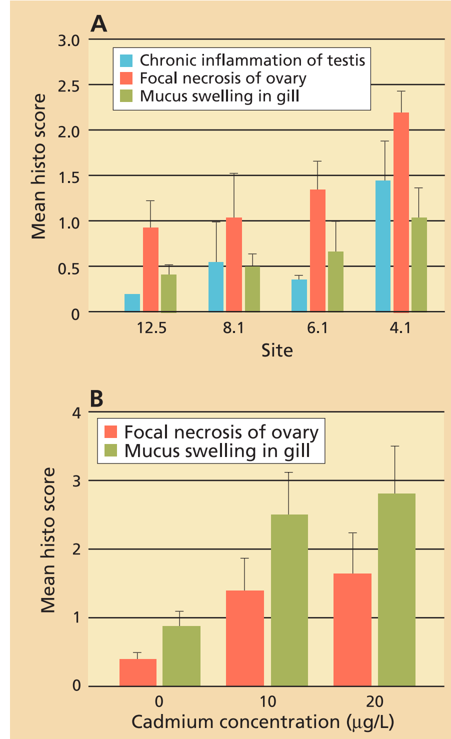


Fig. 4. (A) Results of histopathologic screening in Asian clam from four stations in northern San Francisco Bay. Ten clams per site were collected monthly from July 1996 to June 1997. (B) Average histopathologic screening scores in Asian clam (*n* = 10) after exposure to dissolved cadmium in the laboratory. Error bars represent standard errors of the mean.

clams from station 4.1 (high cadmium, low salinity) and highest at station 12.5 (low cadmium, high salinity), while physiological indicators of reduced health such as condition index (Teh et al. 1999) and the severity of tissue damage (Clark et al. 2000) suggested that the health of clams at station 4.1 was compromised. In addition, cadmium tissue concentrations and levels of metal-binding proteins were highest in clams from this station (Brown and Luoma 1995; R.C. Kaufman, UC Davis, personal communication), and reflected the increased heavy-metal concentrations at station 4.1.

Current hypotheses to explain the apparent discrepancy in the clams' biomarker responses focus on salinity as a stress factor, but do not exclude the possible influence of chemical stressors. While *P. amurensis* can tolerate very low salinities (0.1 ppt), prolonged exposure to freshwater is lethal. At station 4.1, salinity is close to the species' lower tolerance limit, with extended periods of freshwater conditions during winter and spring. Our laboratory experiments suggest that there is a link between cellular stress-protein levels and salinity. For example, clams collected in December 1998 from a low-salinity station (0.1 ppt) were not able to raise stress-protein concentrations in response to heat-shock (fig. 5A), a normal response to temperature stress, whereas clams from stations with higher salinities (5.6 ppt and 14.9 ppt) could (fig. 5B). In addition, clams exposed to low salinity (0.1 ppt) in the laboratory had lower tissue concentrations of stress protein than clams exposed to medium (10 ppt) and high (27 ppt) salinities (table 2).

This is not easily explained. Asian clam is an osmo-conformer, which means they can rapidly (within 48 hours, R.C. Kaufman, UC Davis, personal communication) adapt to changes in salinity by increasing or decreasing intracellular concentrations of certain amino acids (alanine and glycine betaine). Hsp70s perform important cellular functions but there is no indication that they are involved in osmo-regulation, the process animals use to adapt to changes in salinity, or that their concentrations are diluted selectively during osmo-adaptation.

A possible explanation could lie in the energetic cost of osmo-regulation, and the effect of energy depletion on the clam's ability to maintain proper cellular function. Osmo-regulation is very costly in terms of energy consumption. In clams from stations with the lowest salinities, concentrations of glycogen (a carbohydrate used by animals to store energy) were significantly reduced, and gradually increased toward stations with the highest salinities (C. Brown, USGS, Menlo Park, personal communication). Such a reduction in cellular energy reserves could compromise the clam's ability to increase cellular stress-protein

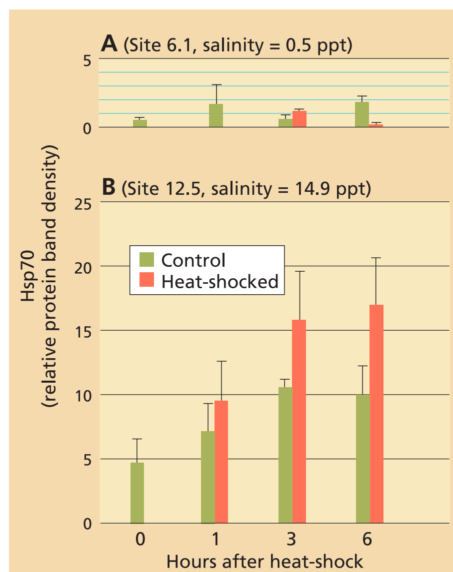


Fig. 5. Results of stress-protein (hsp70) analyses in Asian clam collected from northern San Francisco Bay stations in December 1998 and exposed to brief heat-shock (15 min., 98°F) in the laboratory. Salinities at collection sites were (A) 0.5 ppt (site 6.1) and (B) 14.9 ppt (site 12.5). Clams from site 6.1 were unable to respond to heat-shock by increasing their cellular hsp70 concentrations.

The nonnative Asian clam was introduced into San Francisco Bay in the mid-1980s. Clams were collected from various sites in the Delta and tested for stress proteins and tissue damage. Tissue damage was common at sites where heavy metal concentrations were highest and stress proteins lowest, potentially signaling an impairment of reproductive capacity and cellular protective responses.

concentrations in an effort to adapt to stress. This, in turn, may lead to higher susceptibility to other environmental stressors and reduced organism health. Protein synthesis and repair are energy-intensive processes. Roberts et al. (1997) estimated that the total cost of protein synthesis under nonstressful conditions constitutes 20% to 25% of the energy budget of the bay mussel *(Mytilus edulis)* and repair of one damaged protein molecule, which is what stress proteins do, requires as much as 100 ATP (the energy "currency" of cells) molecules. Research shows that energy-deprived cells are more heat-sensitive than controls, indicating that their normal heat-shock response may be disrupted, and establishing a link between reduced ATP levels and compromised stress-protein function (Feige et al. 1996).

Consequences for organisms

Despite these complex interactions, which we are still striving to understand, our results to date show that biomarkers can be useful indicators of sublethal effects or responses to environmental stressors, and that the failure to raise cellular stress responses can have severe consequences for the survival and health of organisms. Our medaka study demonstrated that early-stage fish embryos are more sensitive to certain environmental stressors because they lack the ability to raise cellular concentrations of certain stress proteins. Our study on clams showed that histopathology is a sensitive indicator of compromised organism health. We also learned that the ability to raise cellular stress responses can be compromised when organisms experience prolonged exposure to environmentally stressful conditions such as low salinity. It is possible that the high degree of osmo-regulation required at very low salinities depleted energy reserves and, in turn, rendered clams more susceptible to additional stressors such as heavy metals.

If this concept can be transferred to other species and stressors, these kinds of studies will improve our understanding about the mechanisms underlying the effects of multiple stressors on organisms. However, there is still a paucity of information on the complex interactions and mechanisms that govern biomarker responses. This lack of thorough functional databases can render the interpretation of results from field studies difficult, especially where results need to be linked to organism or population health. Nevertheless, biomarkers offer valuable mechanistic insights into sublethal physiological processes that will eventually elucidate the complex links between environmental conditions, stress responses, and organism and population health.

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RESEARCH ARTICLE

Landscape changes in Nevada County reflect social and ecological transitions

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About an hour's drive east of Sacramento in the Sierra Nevada, Nevada County typifies expansion of the "exurbs," which have experienced dramatic population growth in recent years. Grass Valley (Brunswick basin) is a small but growing city in the primarily rural, agricultural and residential county.

Large-scale migration of urban people seeking a better quality of life in rural places has generated considerable concern about "rural sprawl." In a multimethod, fine-scale, longitudinal study of land ownership and use in Nevada County, we found that this quintessential "exurban" community reveals a complex story of interacting social and ecological change with some reasons for concern, but also optimism. Land-use data from 1957 to 2001 shows dramatic fragmentation of the county's landscape as a result of increased residential use. The full scale of this transition is not visible because many parcels that are already zoned for further subdivision and residential use remain undeveloped. The related ecological changes have been mixed so far, with tree cover and riparian areas recovering from historic mining, ranching and timber harvesting. These changes are not incidental: many residential owners expressed a strong conservation ethic. However, ecologically harmful effects of increased residential use are present as well. In surveys and interviews, rural-residential owners revealed conflicting feelings about their changing landscape: most are concerned about preserving their quality of life and preventing the ecological impacts of further growth, but also do not want additional government regulations. Research on a fine scale into the cultural basis of ecologically beneficial and harmful rural-residential land-use practices can assist policymakers in crafting innovative and effective growth-management institutions.

During the 1990s some of the nation's fastest-growing counties were "exurbs," encompassing small towns that receive migrants from expanding metropolitan areas; the populations of some nearly tripled during the 1990s alone and continued to increase more than 10% annually (Pollard 2003; Johnson 1999). The ecological and social effects of the resulting growth or "sprawl" rapidly emerged as the focus of major public policy debates. This study addresses the effects of massive population growth in Nevada County, Calif., during the second half of the 20th century.

It differs from other studies on the effects of exurban growth in two significant ways. First, the ecological data was collected on private land, which not only is underrepresented in studies of conservation and biodiversity, but also tends to have greater habitat amenities than public land (Hilty and Merenlender 2003; Hansen and Rotella 2002). Second, we analyzed the interrelations between cultural attitudes, land use and landscape change in exurban landscapes (regions outside a city and usually beyond its suburbs, typically inhabited by well-to-do residential households [Spectorsky 1955]). Much exurban migration has been motivated specifically by a desire to live in a relatively natural setting (Jones et al. 2003). Nonetheless, until recently (Nelson 2002; Walker and Fortmann 2003) little attention was paid to the role that cultural views play in shaping environmental change and management in rural-residential or exurban landscapes (Nassauer 1995).

The story of change in Nevada County's landscape illustrates the interaction of ecological, social and cultural processes. We have framed it in terms of three transitions: the rural-residential transition; an invisible transition as spaces that appear open today have been subdivided and zoned for future development; and visible transitions on the land. It is not a story encompassed by the metaphor of a coin with two sides, one ecological and the other social/cultural. Rather, it resembles a Mobius strip with ecology and culture intertwined on its only side. One cannot be understood without the other.

Sierra Gold Country

Located northwest of Lake Tahoe in the oak woodlands and conifer forests of the Sierra Nevada, Nevada County is in the heart of California's historic Gold Country and includes the small cities of Grass Valley, Nevada City and Truckee. Since the Gold Rush of 1849, the region has experienced dramatic transformations of its society and landscape (SNEP 1996). Following the Gold Rush, open-range cattle grazing, orchards, timber production and deep, hard-rock gold mining became the economic mainstays. By the mid-1950s, however, the last major commercial mines closed and the traditional natural resource–based economy went into steady decline. By 1998, employment in agriculture, forestry and mining (together) in Nevada County dwindled to about 2% of local jobs (SEDD 2001). Currently the county's economy is based primarily on income from non-wage-related sources such as dividends and pensions; its salary base is mostly local service-sector employment and businesses (SEDD 2001).

By the late 1960s a "second Gold Rush" (Duane 1996) arrived, in the form of land speculation and development for waves of residential migrants moving to the county in search of investments in cheap land and a better quality of life. Located only an hour drive from Sacramento and a 2.5-hour drive to the San Francisco Bay Area, Nevada County's open spaces and scenic qualities became a magnet for these exurban migrants. Between 1965 and 2001, the county's population nearly quadrupled, from 25,100 to 94,361, almost exclusively through in-migration (Berliner 1970; U.S. Census Bureau 2003). This in-migration fundamentally changed the county's economy, culture and landscape.

Nevada County is an ideal place to study the effects of exurban in-migration that is transforming many rural areas. The Sierra Nevada is a harbinger of changes occurring throughout rural America, and Nevada County has been among the Sierra region's fast-growing counties.

Over the past half-century, the authors found that many of Nevada County's private landowners have allowed their property to be revegetated and reforested following decades of clearing for logging, mining and ranching.

Transects and interviews

In 1957, Teeguarden et al. (1960) drew north-south sampling transects at 2- and 3-mile intervals on vegetation maps of Nevada, Placer and El Dorado counties and recorded land ownership and use among owners whose parcels intersected the transects. We conducted a restudy of the Nevada County transects, documenting changes in ownership, use and land cover between 1957 and the present. Mail surveys on the histories of parcel ownership, use and management as well as attitudes about the environment and government regulation were completed by the current owners of 358 parcels that lie on the original 1957 transects.

We also conducted 26 follow-up interviews with survey participants, as well as 93 interviews with landowners who did not participate in the survey and 49 interviews with county officials, activists and long-time residents. We compared ownership and land-use data with Teeguarden's 1957 baseline data and tracked changes in land cover on the sample parcels at two spatial and temporal scales. Vegetation changes on 140 parcels were tracked for each decade using fine-scale aerial photographs covering 1952 to 2000. Coarse-scale vegetation changes were tracked on 549 parcels at two time periods, 1948 through 1950 and 1996 through 2000, using vegetation stand maps prepared by the California Department of Fire and Forest Protection (CDF) and the U.S. Forest Service (USFS). The base period of 1948 to 1950 consisted of USFS-CDF timber stand maps interpreted from aerial photography (USDA 1949) and the 2000 CDF CALVEG map for Nevada County interpreted from Thematic Mapper satellite data (CDF 2000).

The county's rural landscape is at risk, with 40% of privately owned parcels slated for development. A golf course, 2,000 homes, business park and shopping center are proposed for this 760-acre Northstar property.

Rural-residential transition

Most rural landowners in Nevada County come from someplace else. Just over 3% of 736 adults residing in the households that returned our mail survey were born in Nevada County, and 85% first acquired land in the county since 1968. In-migration brought dramatic changes in land use. In 1957, private, rural, land use in Nevada County was roughly evenly divided among agriculture, timber and residential/recreational use — with small amounts of mining and other commercial uses. By 2001, private land under rural-residential and recreational use had increased from 30% to 70%. Mining and other commercial uses dropped to 2% and timber from 31% to 18%. Agricultural land (used for farming as a full- or nearly full-time occupation) decreased from 33% to 10%. We defined land used for part-time, small-scale agricultural activities (hobby farming) as primarily residential. The California Department of Conservation (2000) indicates that if very small-scale farming is included in the definition, agricultural land has increased slightly in recent years, although not reversing the longer-term downward trend.

The increase in rural-residential land use is associated with a decrease in the size of landholdings (the total acres in all parcels held by a single owner). The median size of landholdings in Nevada County decreased from 550 acres in 1957 to 9 acres in 2001, reflecting a shift from large ranches and timber operations to single-family residential units on parcels typically ranging from 3 acres to 15, 20 or occasionally 40 acres or more. The 1957 landscape of a few large parcels has been almost completely replaced countywide by a fragmented landscape of many small parcels.

Rural-residential landowners use their land in a variety of ways that challenge a simplistic understanding of a rural-residential landscape as synonymous with suburban sprawl. In Nevada County, many primarily residential owners engage in small-scale farming, ranching and/or timber production. Of the mail survey landowners, 83% primarily used their land for residential purposes, 10% for commercial agriculture, ranching or timber production, and 4% for recreation. A few said they keep the land simply to preserve open spaces. Thirty-five percent of primarily residential landowners (typically with larger parcels) practice small-scale farming, ranching, timber production and other small-scale commercial uses such as home-based businesses and crafts workshops. Therefore, some land that has been converted from large ranches and timber operations to residential use retains a degree of rural or agricultural use.

The invisible transition

The view seen by residents and visitors to Nevada County does not reveal the full extent of the transition to an increasingly fragmented landscape. Nothing in the landscape reveals, for example, the precarious financial position of most remaining large farms and ranches, which give Nevada County a rural feel. In our research, ranch owners expressed doubts that their children or grandchildren would be able to continue to farm the land and keep these remaining open spaces undivided. More important, much of the county's open space is already zoned and intended for future residential development. Much of the open space in Nevada County today is composed of parcels zoned for agricultural or rural-agricultural uses that, under current General Plan designations (most recently revised in 1995) and zoning rules (implemented in 1997), may be subdivided into 3-acre parcels with a single dwelling unit. Other undeveloped parcels were subdivided under earlier zoning rules that were implemented during the 1960s and 1970s at even higher densities, and some planned-unit developments may allow 15 units or more per acre. More restrictive zoning policies, driven by fears among many in-migrants of an eroding quality of life due to explosive growth, began in earnest only in the 1980s, but by that time much of the landscape had already been zoned at higher densities. Thus, in their current undeveloped condition these areas give a misleading sense of open space that masks the large amount of land already planned, zoned and intended for future development.

Public records from the Nevada County Tax Assessor's office for 2001 indicate that 15,064 (40%) of the county's private rural parcels can be developed for residential or commercial uses according to existing zoning designations. More than 3.5 times as much private rural land (281,689 acres) remains available for future development as all the private rural land already developed in the county (76,145 acres)(fig. 1). The "checkerboard" pattern in the county's central and eastern areas was created when 19th-century surveyors created a grid of 1-mile-square sections for federal land grants; alternating sections were retained as public land (now the Tahoe National Forest). Our criteria for identifying parcels that remain available for development included: a) privately owned; b) current zoning rules allowing development or subdivision; and c) current improvement value less than $20,000, indicating that no residential unit is present, making the parcel eligible for further development. Figure 1 includes parcels designated as a Timber Preserve Zone and current timber-producing parcels that can be developed under existing zoning rules.

Nevada County's landscape is deceptive in its feeling of openness. Viewed through the lens of parcel maps and zoning rules, we see a landscape that has already been carved into many parcels owned largely by those who are waiting for the right time to build. In our research, both absentee and resident owners of undeveloped parcels almost universally indicated that they intend to develop these properties for retirement or plan to sell to others for development. The population implications of

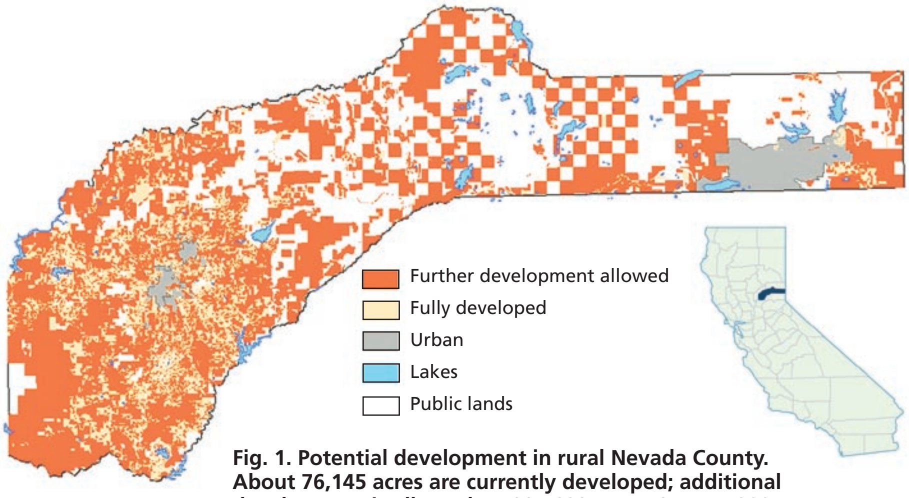


Fig. 1. Potential development in rural Nevada County. About 76,145 acres are currently developed; additional development is allowed on 281,689 acres. Source: 2001 County Assessor's parcel data.

this potential development are dramatic. The county's estimated 2001 population is 94,361 (US Census 2003). By multiplying the number of parcels available for residential development by the number of dwelling units allowed by zoning rules on each parcel, and multiplying again by the average number of persons per dwelling unit (2.47 per unit in Nevada County, according to the U.S. Census), we find that the "build-out" population that can be reached under current zoning rules is 233,522 people — 2.5 times the current population. The visible landscape conceals a future that has already to a large extent been determined, unless policies are put in place that further limit development.

Visible transitions on the land

Data from the Nevada County Tax Assessor's office for 2001 shows that while suburban-style parcels of 1 acre or less account for 31% of all private rural parcels, they represent only 1.5% of the total private rural acreage (0.9% of the total area). As such, highly visible suburban-style developments have relatively little spatial impact on the landscape. Much more of the rural landscape is dominated by low-density residential development on parcels typically ranging from 5 to 40 acres. Most research on the Sierra landscape has been conducted using satellite imagery at a geographic scale of analysis of 40 acres or more (considerably larger than the majority of parcels), which is unable to reveal complex changes in areas composed of a mosaic of residential uses. Rural-residential development in areas formerly dominated by ranching and timber production is often portrayed as an unmitigated environmental detriment (Maestas et al. 2001; Hansen et al. 2002). Our preliminary analysis suggests that the overall impact of the residential transition is mixed and should not invariably be considered ecologically harmful.

The most notable vegetation transition found on our sample parcels was increased canopy closure across all forest types, including conifer, hardwood and mixed hardwood-conifer forests. This pattern was consistent across almost all sample parcels, and is strongly consistent with findings of increasing tree cover in neighboring Placer and El Dorado counties (Saah 2001; Wacker 2002). Most of Nevada County's historic forest cover — conifer, mixed conifer-hardwood forests and oak woodlands — was logged or cut during the Gold Rush. Cut-over land was later heavily ranched, leaving a sparsely vegetated landscape by the 1950s. The greatest transition observed from the early 1950s to late 1990s (using our two-time-period analysis of 549 parcels) was from small woody growth (the CDF timber stand maps did not distinguish between shrubs and small hardwoods) to dense hardwood forest. In the early 1950s, this shrub-statured woody growth was the most common vegetation type on all parcels in our study area. The second greatest transition was from sparse conifer forest with shrub-statured vegetation to mixed hardwood-conifer forest, also reflecting the change from small to mature hardwoods. This forest regrowth appears to have been accelerated by many residential owners choosing for cultural reasons not to harvest timber, graze cattle or clear trees.

Exceptions to the pattern of forest regeneration are: areas of recent wildfires; portions of land logged by residential owners; and areas immediately surrounding residential structures, often cleared of conifers for fire prevention. With the expansion of conifer and hardwood forests, the diversity of other vegetation types decreases as forest encroaches or replaces annual grassland and short-statured woody vegetation. In Nevada County, we observed the expansion of improved road networks that fragment the landscape and a simultaneous disappearance of older networks of logging and ranching roads. While new residential buildings are going up, many previous agricultural structures have also been removed. Moreover, the type of land use associated with the presence of human-made structures is generally more ecologically important than the structures themselves. The types of land use associated with residential homes today — such as simply leaving the land "natural" for aesthetic or recreational purposes, or small-scale recreational farming (what long-time local farmers call "hobby farming") — are very different from those associated with the agricultural structures and farmhouses that dominated in the 1950s. The appearance of new houses on large, rural-residential parcels may be less significant than the fact that these houses signal a new regime of land use.

The rural-residential transition is having significant impacts on vegetation and forest density in many areas of Nevada County. Figure 2 shows a typical 40-acre parcel near Nevada City occupied by one single-family residence, which has been used exclusively for residential purposes for more than 25 years. The black-and-white maps illustrate a dramatic increase in overall tree canopy between 1952 and 2000 (fig. 2A). The color maps illustrate a more subtle transition, with an overall trend from a landscape of mixed hardwoods and conifer patches with moderate cover of shrubs or grass to a landscape increasingly dominated by conifer forest (fig. 2B).

It is widely accepted that the presence of more houses is associated with increased disturbance of wildlife (due to fence construction, and harassment and predation by domestic cats and dogs) and decreased biodiversity (Hansen et al. 2002; Hansen and Rotella 2002). These findings do not differentiate among different land-use practices, especially on large parcels with a greater diversity of land uses. Our study shows that there are many relatively large (10 to 60 acres) residential parcels in Nevada County where the impact of domestic activities may be relatively minor and whose owners practice active management of forests and vegetation to reduce fire hazards. Particularly on larger parcels, the ecological impacts of residential use in comparison to uses such as ranching and logging appear less clear than the literature portraying residential development as ecologically harmful suggests. For example, our study suggests that many rural-residential owners in Nevada County allow riparian vegetation to regrow, resulting in significantly improved conditions compared to ranching and agricultural use, in which cattle and erosion, and pesticide and fertilizer runoff often harm stream conditions.

What rural landowners want . . .

Nevada County's growth is primarily driven by quality-of-life values rather than economic opportunities. For 71% of mail survey landowners, the most important reasons for coming to Nevada County were landscape quality (scenery, environmental qualities and open spaces — 54%); recreational values (8%); and opportunities for farming and other resource uses (9%). With inclusion of the 24% who wanted to "get out of the city" (a push factor closely intertwined with the pull of the rural landscape), 95% of respondents considered the quality of the landscape, directly or indirectly, the major attraction. Other important attractions included "sense of community" (6%) and a desire to be near relatives or friends who live in the county (3%). Only 6% cited a job as their most important reason. (Many in-migrants are retired or do not work: 32.9% of Nevada County households receive Social Security income, and 40.8% of adults are not in the labor force [US Census 2003]).

While Nevada County land-use debates have been framed as the agricultural and timber economy versus environmentalists, 78% of landowners in our mail survey saw both as important to the county's future. They also tended to agree that a common enemy — runaway growth — threatens these desirable landscape features. When 93 rural landowners were asked in interviews whether they favor more growth, controlled growth, no growth or had no opinion, 68% favored controlled growth, which most respondents interpreted as strict zoning and minimum parcel sizes.

Rural landowners tended to support agriculture because it provides open spaces and scenic qualities, helps to preserve a sense of rural community and a "slower pace of life," and is an important part of the county's history. Some respondents viewed agriculture as generally compatible with responsible environmental management. Others expressed concerns, such as the effects of grazing and fertilizer runoff. Many stated that they believe there is a future for timber production in Nevada County, even while expressing concerns about specific timber practices, especially clear-cutting. Even those expressing strongest support for the natural resource–based economy had serious misgivings about the environmental effects of mining.

Respondents in the mail survey and personal interviews often observed that growth is inevitable but emphasized that they would hate for the county to end up looking like the urban and suburban places they left behind. Many said they accept growth because they feel it is unfair to close the door behind them, but often feel strongly that growth should be regulated. The reasons for controlling growth were diverse. Some saw advantages in growth such as easier access to shopping and lower prices, and believed that it would enhance their property values. These same landowners tended to express deep reservations about the capacity of the county to handle growth, especially impacts on local infrastructure such as excessive traffic on rural highways and overburdened water supplies. Others perceived growth as inevitable, but wanted to protect the county's wild and rural feel.

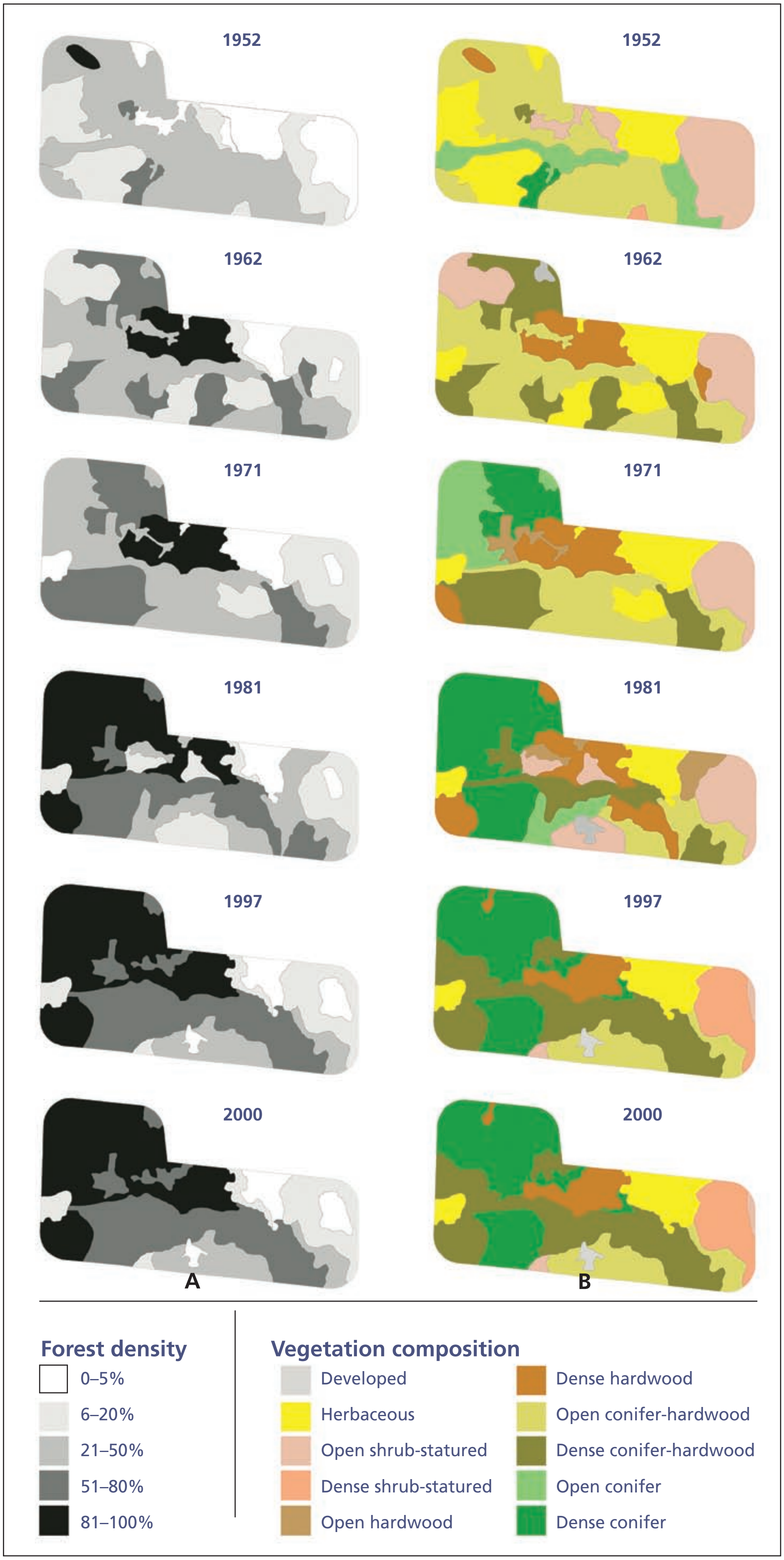
Many cited personal experiences witnessing the overdevelopment of their old hometowns in what are now major urban areas. Fourteen percent in the mail survey and interviews declared that they were in favor of stopping all growth in the county. One declared, for example, that the county is being destroyed for the "almighty buck," and another said she "doesn't care what happens to land values . . . the county needs open spaces, not more ticky-tacky."

Twelve percent of the mail survey said that growth is good for jobs and generally brings conveniences to the county. Those who saw a positive side to growth were often among the most concerned about possible infringements on property rights under policies of growth control. Supporters of growth also included long-time residents who observed that the county was boring and kids had nothing to do before the county grew. In sum, the great majority of rural landowners who participated in our study appeared to recognize that growth will happen and wanted its effects to be controlled. Minorities of roughly equal size either advocated or opposed growth in any form. And there were mixed feelings. One respondent observed, "We bought the land [in the 1980s] because we liked the wildness and the remoteness. However . . . every development that brings civilization and population closer also raises the value [of our property], so we consider the investment factor but do not intend to sell — so there goes that argument! Clear as mud? That's how we feel, too."

. . . and what they will do to get it

While 68% of our interview respondents reported that they want to see growth controlled, feelings about land-use controls in general tended to be highly negative. Fifty-nine percent disagreed with the statement that the county needs strong controls on land use. Only 34% agreed with this statement.

Consistent with the generally negative view of government controls, 81% of mail survey landowners agreed that "Nevada County needs strong protection of private property rights." Only 11% disagreed. These negative views of government control and strong support for property rights are consistent with the strongly conservative bent of the



◀ **Fig. 2. Changes in (A) forest density and (B) vegetation composition from 1952 to 2000, on a 40-acre parcel in Nevada County, Calif.**

county. Most respondents, when asked in the abstract where they stand on these issues, tended to take conservative positions. However, when respondents were asked more specific questions pertaining to particular types of government controls or specific issues relating to property rights, their views took a more conservationist position. Seventy-one percent agreed that the county needs strong environmental protection, while 23% disagreed. Notably, 62% who strongly agreed that Nevada County needs strong protection of property rights also agreed that it needs strong environmental protections. Similarly, 46% who strongly disagreed with the need for strong government control of land use on private property agreed that Nevada County needs strong environmental protection.

While a few argued that environmental protection can be achieved without government involvement, more recognized the contradiction in their opinions. Many respondents who strongly supported property rights and rejected government controls in the abstract nevertheless acknowledged strong support for specific government interventions to protect the landscape. Support tended to be very strong for minimum parcel sizes and zoning restrictions even among otherwise steadfast conservatives. When it comes to protecting the landscape, conservatives in Nevada County often seemed to be conservationists. For example, in the November 2002 county supervisor elections in the Third District, which is 43% Republican and 35% Democrat, a slow-growth candidate depicted by opponents as an environmental extremist lost by a razor-thin 19 votes. More broadly, rural landowners appeared to agree on the importance of protecting environmental and rural qualities. This view transcends party affiliations or ideologies and has become an enduring feature of the cultural and political landscape of the county.

Under current zoning, Nevada County's population could more than double as private lands are sold for development. About two-thirds of those surveyed wanted to see growth controlled, but almost as many did not support government controls on private land use.

Land-use realities, contradictions

Our data revealed contradictory tensions in Nevada County. Based on our ecological data, we could argue that certain types of residential development and land use may be less harmful to the landscape than extractive uses. Others could also argue that low-density residential development is inherently inefficient and wasteful, resulting in fragmentation of the landscape, more public-sector costs and creation of sprawl by spreading population over a wider area. Similarly, there are tensions between the strong desire and willingness to protect the environment and ideological opposition to the most common ways of doing so.

Our research suggests that certain questions about the interrelationship between social and environmental change in exurban landscapes need to be reexamined at a finer scale. It also suggests that in some exurban landscapes the questions that have drawn the greatest research interest may no longer be relevant. In places like Nevada County, the time for the "cows versus condos" debate (Knight et al. 1995) is past. The condos won. The questions that need to be asked now concern how to make this rural-residential transition work better — and these are questions that require fine-scale, integrated, social and ecological research.

Property owners, planners and government regulators must recognize that ecological changes in the landscape are not the coincidental outcomes of solely natural processes. Rather, they reflect cultures and images of landscape brought by in-migrants who literally recreated the landscape through their own practices and influence on land-use policies, in their image of what was rural and natural (that is, forested).

In Nevada County, creating and sustaining healthy ecosystems requires the ability to base policy on cultural and ecological interconnections. By studying at a fine-scale which rural-residential practices are harmful and beneficial to a healthy and livable landscape, the basis for encouraging or discouraging particular land practices can be developed. By understanding the cultural basis of rural-residential land-use practices, policies can reflect the desired images of landscapes. And finally, by understanding the cultural bases of responses to policy, innovative policy institutions can be crafted that are culturally acceptable and ecologically effective.

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RESEARCH ARTICLE

Olive fruit fly populations measured in Central and Southern California

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Long a pest in the Mediterranean region, the nonnative olive fruit fly was first detected in California in 1998. Although extensive research has been conducted abroad, California-specific trapping data was needed on the fly's seasonal occurrence and geographic distribution. *Above*, A female olive fly on a yellow sticky trap.

The olive fruit fly was detected in Southern California in October 1998. This nonnative pest, which can render fruit unmarketable, has since moved throughout California and is now believed to be present wherever olives are grown in the state. Seasonlong trapping of adult flies in the San Joaquin Valley, and Ventura and Santa Barbara counties in 2001 and 2002 showed similarities in seasonal phenology, but also differences primarily due to varying temperatures and fruit availability. In the San Joaquin Valley, fly activity declined as maximum daily temperatures rose above 90°F, but increased when temperatures were between 70°F and 85°F. On the Southern California coast, the combination of available, susceptible fruit and moderate climate throughout the year may allow continuous reproduction of OLF with six or perhaps even seven generations per year.

The olive fruit fly (OLF or olive fly) is considered the most serious insect pest of olive fruit in the world. Historically, it infested Mediterranean areas of southern Europe, North Africa and the Middle East, where olives have been cultivated for thousands of years (Economopoulos 2002). It is also found on the Indian subcontinent, Mexico, South Africa and other regions of Africa where wild olives grow.

A feral olive fruit fly, *Bactrocera oleae* (Gmelin), was first detected in North America on Oct. 19, 1998, in an orange tree in west Los Angeles. This fly was caught in a McPhail bait (food lure) trap, which is commonly used by regulatory agencies for detecting insects such as Mexican fruit fly that do not respond to specific lures or attractant chemicals. Subsequent delimitation (detection and distribution) trapping found that the coastal counties from Santa Barbara south to San Diego, and the inland counties of Riverside and San Bernardino were generally infested with olive fly.

On Sept. 14, 1999, a male olive fly was trapped in a commercial olive grove in southern Tulare County in the San Joaquin Valley, the major production area for table olives in California. California produces 99% of commercial olives grown in the United States, with 134,000 tons of olives on 36,000 acres in 2001, for a total value of $90 million (CDFA 2002). Intensive trapping in 1999 failed to detect any additional flies in the surrounding area. The apparent absence of additional flies was reassuring to olive growers and led to speculation that perhaps the olive fly could not move from Southern California into the central and northern areas of the state, or would be severely restricted in its establishment due to the hot, dry climate of the interior.

In May 2000, however, additional flies were trapped in Tulare County, and in adjacent Kern and Fresno counties. New OLF detections were also reported along the coast north of Santa Barbara County, in San Luis Obispo County and eventually Monterey County. Following these spring collections in the San Joaquin Valley and Central Coast, fly populations and detections increased rapidly in these areas through 2000 (Rice 2000). Detection trapping by state and county agricultural officials was terminated by mid-2000 due to the high numbers of flies being collected. An initial trapping study in Ventura and Santa Barbara counties showed low early-season collections followed by higher summer and fall populations (Phillips and Rice 2001).

With the long history and pest status of olive fly in Mediterranean countries, extensive research on its biology, ecology and control are available in the European literature. In order to use this large database effectively, however, California olive growers wanted to obtain state-specific information on the fly's seasonal occurrence and geographic distribution. Consequently, the California Olive Committee (COC), representing table olive growers, initiated a 2-year trapping program in commercial groves in the San Joaquin Valley and provided partial support for a regional trapping

Researchers trapped for olive fruit fly in the San Joaquin Valley, and Santa Barbara and Ventura counties, using yellow sticky traps, *above.* In each replicate, traps were baited with ammonium bicarbonate food attractant lures plus an olive fly spiroketal pheromone lure, *left.*

project in coastal Santa Barbara and Ventura counties. We conducted less extensive OLF trapping in urban and noncommercial sites in Tulare and Fresno counties to supplement the COC-funded data.

Our study objectives were to expand on preliminary information about seasonal and geographic distribution of OLF in Central and Southern California (Phillips and Rice 2001; Rice 2000), evaluate and compare fly collections with different types of lures, and help develop possible control strategies in commercial production areas based on fly phenology and crop development.

Olive fly trapping projects

The commercial trapping project — directed by Pest Management Associates (PMA) in Exeter, Calif. — was established in 10 olive groves on the east side of the San Joaquin Valley from northern Kern County to Madera County, over approximately 110 miles. Several of these groves were located in rolling foothills at the western base of the Sierra Nevada; others were on the flat valley floor.

In nine groves, 10 yellow-panel “ChamP” sticky traps were placed within the perimeter of each grove in five equidistant paired-trap replicates. Traps in each replicate were placed three trees apart, four to seven trees inside the orchard, 8 to 10 feet high in open shade. (Open shade refers to trap placement in constant shade within the tree canopy, but with clear or unrestricted access to the trap by responding insects and no nearby leaves or limbs for the insect to land on instead of the trap.) Traps were placed on the north side of trees during hot weather (June to September) and on the south side in cooler weather.

In each replicate, one trap was baited with an ammonium bicarbonate food attractant lure (Suterra LLC [Consep], Bend, Ore.) plus an olive fly spiroketal pheromone lure (Vioryl S.A., Athens, Greece). The second trap in each replicate was baited only with the ammonium bicarbonate food lure. The 10th commercial grove in the COC/PMA project was a small organic planting with enough area for only six traps (three reps). A total of 96 traps were included in this study.

Trap sites remained the same during the 2-year study. All commercial olive groves except the organic grove were treated in 2001 and 2002 with spinosad bait sprays (GF-120, Dow AgroSciences) at recommended rates to control OLF. Upon recommendations from European researchers, bait spray treatments were initiated at the beginning of olive “pit-hardening,” which is presently determined by periodically slicing carefully through small, developing olives with a sharp blade until resistance or hardening of the olive seed (pit) is detected. At this stage, olives are considered susceptible to infestation by OLF. Using this method, pit-hardening in the southern San Joaquin Valley was identified in Manzanillo fruit on June 13, June 18 and June 19 in 2001, 2002 and 2003, respectively. Treatments were applied at 2-week intervals through harvest in September or October. In addition to the 10 commercial groves (PMA data), we monitored 15 noncommercial, untreated urban and rural sites in Tulare County with single traps having both lure types (Tulare), as well as three untreated urban and rural sites Fresno County with two traps per site and both lure types (Fresno).

Traps in all three San Joaquin Valley studies were initially placed in the field in March 2001 and inspected for OLF at weekly intervals through November 2001. Trapping continued during winter 2001 and through 2002, although traps were serviced at only 2-week intervals from December 2001 through mid-February 2002 due to cold weather and low fly collections. Collected flies were sexed and comparisons made between traps with both lure types and only the ammonium bicarbonate food lures in the PMA commercial groves.
The food lures were replaced at 2-week intervals in hot weather, and every 3 weeks in cool weather; spiroketal lures were replaced at 4-month intervals throughout the year. Trap bodies were replaced as needed to minimize contamination by nontarget insects, especially muscoid flies responding to the ammonium bicarbonate lures, and other insects responding to the yellow trap color.

Along with trapping in the San Joaquin Valley, we maintained a similar project in Ventura and Santa Barbara counties in noncommercial urban and rural sites throughout 2001 and 2002. We wanted to compare OLF phenology

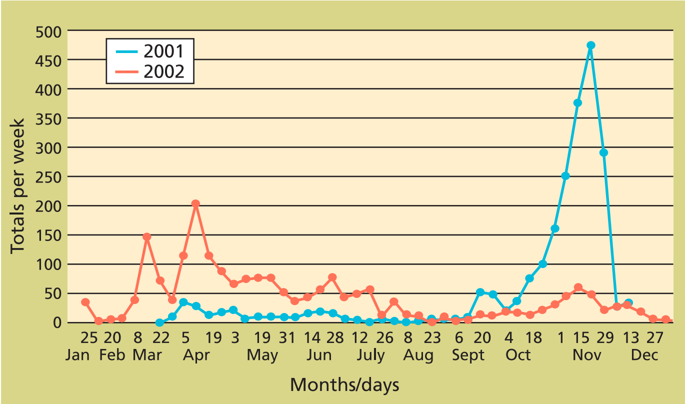

Fig. 1. Olive fly trapping in the San Joaquin Valley; all traps (117) combined, 2001 and 2002.

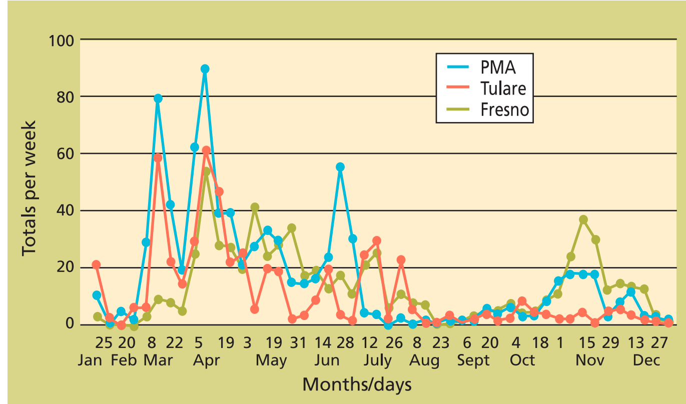

Fig. 2. Olive fly collections in commercial olives (PMA, 96 traps) and urban/rural traps (Tulare County, 15 traps; Fresno County, six traps) in the San Joaquin Valley, 2002.

and collection data between the two regions because of expected differences in fly bionomics between coastal and interior valley climates (Michelakis 1990; Todd 1929). In Ventura County, eight trap sites (replicates) were monitored with two yellow-panel (ChamP) sticky traps, one with only the ammonium bicarbonate lure and one with both ammonia and pheromone lures, for a total of 16 traps. In Santa Barbara County two traps with lures as described for Ventura were maintained at each of seven sites for a total of 14 traps. Trapping protocols as previously described were used in this study, except traps were serviced and flies counted every week rather than
biweekly through the winter months.

San Joaquin Valley trap data

In general, the observed seasonal activity of OLF based on their attraction to yellow-panel sticky traps with food and pheromone lures in California was similar to reports of olive fly phenology in Mediterranean areas (Economopoulos et al. 1982; Longo and Benfatto 1982; Ramos et al. 1982; Kapatos and Fletcher 1984; Haniotakis 1986; Montiel-Bueno 1986). In the San Joaquin Valley, the data showed relatively high adult fly activity in late winter/early spring with a decline in April and May. This was followed by a smaller OLF flight in June, and then a decline to very low, sometimes almost nondetectable levels during the hot summer months (July to early September)(figs. 1, 2). Beginning in September, fly populations again began to increase and reached very high levels in 2001, but not in 2002, before the onset of cool weather in November. Although relatively few flies were caught from December 2001 to February 2002, at least one fly was trapped somewhere in the San Joaquin Valley every week during this period.

In early March 2002, OLF numbers began to increase again, representing continuing activity of overwintered adult flies. Another peak in April, possibly representing flies emerging from overwintered pupae, was followed by a small flight in May, representing the first generation of flies that developed in fruit remaining on trees from the previous crop year (Economopolous et al. 1982; Tzanakakis and Koveos 1986). A sustained period of adult activity in June and July probably represents emergence of the second generation of adult OLF. From late July through early September, adult fly activity was very low in the San Joaquin Valley, a phenomenon considered a facultative or summer diapause and described by several European researchers (Fletcher et al. 1978; Kapatos and Fletcher 1984; Tzanakakis 1986; Tzanakakis and Koveos 1986). In September, a third emergence of flies was detected, followed in October through November by a sustained increase in adult flies, representing the fourth, and perhaps a fifth generation of OLF. Up to five generations of OLF have been reported in southern Europe (Tzanakakis 1986; Tzanakakis and Koveos 1986).

The much lower level of total fly collections in fall 2002 (fig. 1) was due primarily to the reduced numbers of flies found in the 15-trap Tulare County project, although the other two projects (PMA and Fresno County) also recorded fewer flies in fall 2002 compared with 2001. Comparisons of the three San Joaquin Valley trapping projects in 2002 (fig. 2) showed similar trends in fly collections through the year, but with some variations from week to week.

The PMA trapping data from commercial groves showed the most consistent pattern of OLF phenology over 2 years, and closely tracked the combined totals shown in figure 1. This data also showed the relatively greater increase of flies collected in 2002 in the five northern locations (Madera to Exeter) compared with five southern groves (Lindsay to Bakersfield)(fig. 3). These collections demonstrate the continuing increase and expanding distribution of OLF populations from the southern San Joaquin Valley to the north, even in groves treated from mid-June to harvest with spinosad bait sprays. The bait applications, however, appeared to be effective in preventing economic damage to fruit, at least at the relatively low population levels experienced to date. No infestations were found in olives delivered to table olive canners in 2001 and 2002.

Trap data on the number of OLF generations per year in the San Joaquin Valley indicates that flies trapped from February to early March may represent adults overwintered from the previous fall. The increase in collections in late March and April could be new adults emerging from overwintered pupae. The short, sharp increase in May would then represent first-generation adults emerging from old crop olives infested by adults from February through April, and adult flights in June and July could be a second generation from eggs laid in

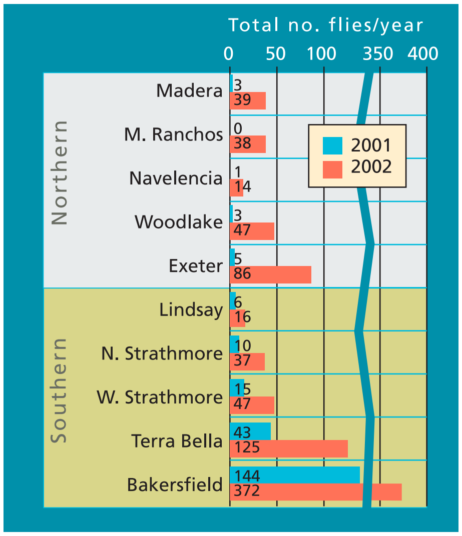

Fig. 3. Olive fly population distribution (numbers) and relative densities in San Joaquin Valley commercial olive groves, northern (Madera–Exeter) and southern (Lindsay–Bakersfield) trapping regions.

California Olive Committee

◀ Olive flies were found year-round in southern and interior-central California, with varying levels of seasonal activity. So far, growers have been able to prevent economic damage to fruit by using spinosad bait sprays, integrated pest management and organic growing methods.

old crop fruit in April and May. These second-generation adults then lay eggs in new crop olives that become susceptible to oviposition beginning in mid- to late June; adults representing the third generation emerge in September. A fourth, and probably a fifth, generation then developed in October and November in the Central Valley. However, this hypothesis is speculative, and must be confirmed and validated by detailed studies on egg and larval development throughout the year in different climatic areas of interior California.

Trap lure comparisons

Equal numbers of traps with ammonium bicarbonate lures, and ammonia lures plus spiroketal pheromone lures, were placed in the 10 commercial San Joaquin Valley groves, allowing for comparisons of relative fly collections with the different lures. In traps baited only with ammonium bicarbonate lures, more male than female flies were collected, at a ratio of almost 2:1 (table 1). Whether this represents the actual sex ratio in the OLF population could not be determined without rearing flies from pupae, but a 1:1 ratio would be normal (Moore 1962). However, Longo and Benfatto (1982) also noted more males than females in traps baited with ammonia attractants. As expected, the addition of spiroketal pheromone lures (a male sex attractant) to the ammonia lures increased collections of male flies approximately twofold, with little increase in female fly collections (table 1). Traps with only spiroketal pheromone lures were not included in this study, so comparisons of male response to the pheromone alone and to the other lures were not made.

Southern California trapping

In the coastal areas of Ventura and Santa Barbara counties, adult OLF collections were generally similar to patterns observed in the San Joaquin Valley (fig. 4). However, individual sites, primarily in Ventura County, differed in numbers of flies collected between the cool, immediate coastal areas and warmer, drier areas only a few miles inland. These interior areas tended to have more flies than the coastal sites, perhaps due to temperatures warmer for optimum flight and fly activity during much of the day. Also, the midsummer (hot weather) depression of fly captures occurred earlier (May and June) and resumed earlier (August) in Ventura County than in the San Joaquin Valley; this event was not observed in Santa Barbara County in 2002. Adult flies were trapped in Ventura and Santa Barbara counties in all 12 months of the year, similar to adult OLF captures reported from northern Greece (McFadden et al. 1977). Coastal population fluctuations were also similar to northern Greece, with high populations in the spring from overwintered adults or immature stages, lower populations in midsummer and increasing populations from late July into the winter.

While OLF population trends on the coast generally were similar to the San Joaquin Valley, it was more difficult to distinguish discrete generations in the coastal climates. More flies were trapped in the winter on the coast than in the San Joaquin Valley, an expected result due to more moderate winter temperatures. It is also not unusual to find mature fruit from the previous year on trees along the coast until new crop fruit becomes susceptible to infestation in the late spring or early summer. The

TABLE 1. Number of male and female olive flies attracted to different lures in yellow-panel sticky traps

Sex	Lure type	2001*	2002†	Total
Male	Ammonia	54	199	253
Female	Ammonia	28	113	141
Male	Ammonia plus pheromone	118	384	502
Female	Ammonia plus pheromone	39	116	155

* March 23–Dec. 31, 2001.
† Jan. 1–Dec. 27, 2002.

TABLE 2. Number of olive fly females with or without eggs, San Joaquin Valley, 2002

Month	With eggs (%)	Without eggs
February	3 (21.4%)	11
March	27 (35.5%)	49
April	23 (27.7%)	60
May	15 (15.6%)	81
June	13 (22.0%)	46

combination of available, susceptible fruit and moderate climate throughout the year could allow continuous reproduction of OLF on the Southern California coast, with six or perhaps even seven generations per year.

Summer collections decline

Reports from Europe suggest that a summer reproductive diapause in OLF is due to high temperatures, low humidity and absence of fruit (Fletcher et al. 1978), which may cause a decline in fly response to trap lures. A similar correlation of hot weather and fly response to the traps was seen in the three San Joaquin Valley projects in 2001 and 2002, with fly activity declining as maximum daily temperatures rose above 90°F, but increasing whenever temperatures fell into the 70°F to 85°F range.

Mating status of female flies

The maturity and mating status of female flies was determined at various times during this study. The sexual maturity of collected flies, defined as females with eggs, was never high (table 2), but at least some of the trapped females were still immature. However, we expected many unmated females would eventually mate because of the number of male flies present. Females mated in the late winter to early spring infest old crop fruit to produce a new generation of flies in late spring and early summer.

Dissections and examination of female flies trapped in the San Joaquin Valley from June through September 2001 and the spring months of 2002 showed female flies with eggs present in every month from June through November 2001 and February through

TABLE 3. Number of mated and unmated OLF females in San Joaquin Valley, 2001–2002*

Date	Mated	Unmated
June 2001	6	3
July	4	2
August	1	3
September	8	6
October	11	5
November	1	1
June 2002	7	6

* Sexually mature, with eggs.

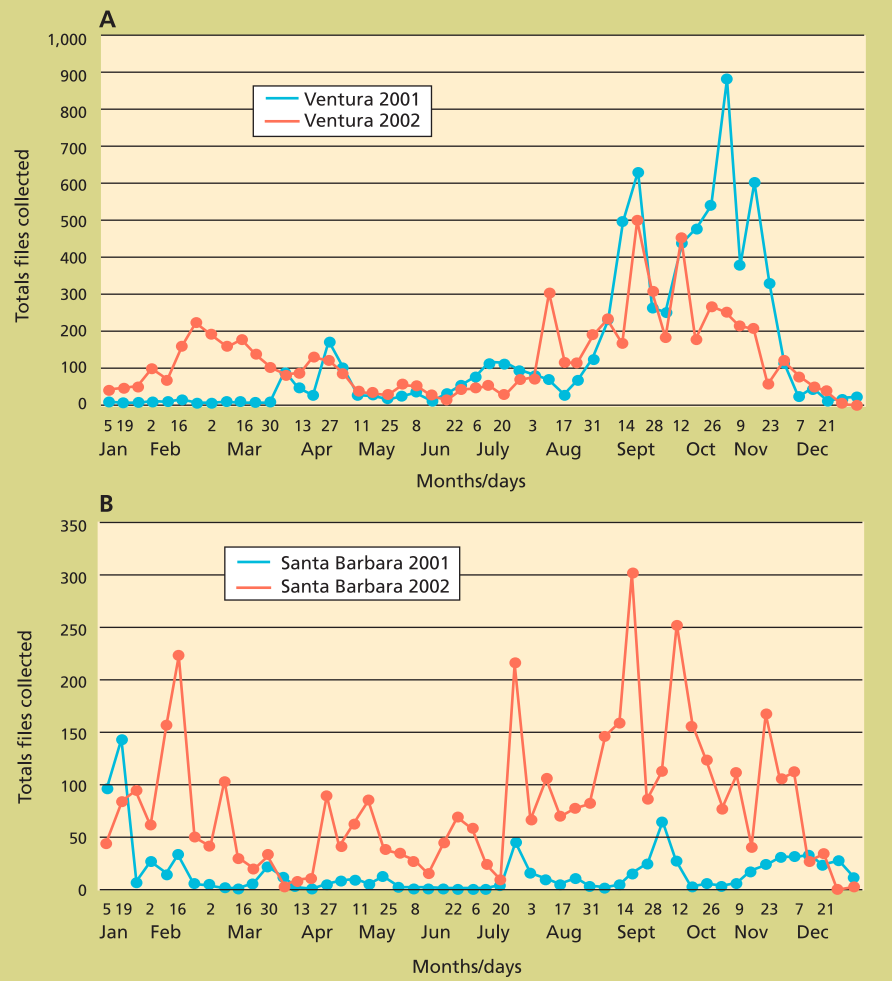

Fig. 4. Total olive flies trapped per week in (A) urban and rural Ventura County (16 traps) and (B) urban Santa Barbara County (14 traps), 2001–2002.

June 2002 (table 2). Michelakis (1986) reported a decline in mature female flies (with eggs) during hot weather, but noted that some portion of the female OLF population was always mature. Tzanakakis and Koveos (1986) observed a similar effect in conjunction with long day length. Observations from the San Joaquin Valley indicate that olives, even in hot weather, can become infested as soon as the fruit becomes susceptible to oviposition, usually in mid- to late June. In cooler coastal climates, OLF could infest either old or new crop fruit as soon as the females are mated, at any time of the year.

To determine the mating status of mature female flies, Eric Fisher of the California Department of Food and Agriculture dissected subsamples of female flies and examined them for sperm in their spermathecae. These examinations showed a relatively high percentage of mated females in June of both years and fall 2001, but a low mating percentage during hot weather in August (table 3). The presence of mature, mated females in June coincided in 2001 and 2002 with pit-hardening and initial susceptibility of new crop fruit to oviposition and larval development.

Population dynamics of OLF

The trapping data from coastal southern and interior central California showed that olive fly adults are present and active throughout the year, although populations were, as expected, low in the cold winter and hot summer months in the San Joaquin Valley. In the more moderate coastal climates, olive fly activity varied throughout the year, allowing for continuous breeding and reproduction in warmer, more protected areas, depending on the availability of host fruit on trees or the ground.

Reasons for the significant differences in fly collections between September and October in 2001 and 2002 in the San Joaquin Valley are not readily apparent. Even with low populations in late 2002, continued spring trapping in the 10 commercial groves in 2003 showed, as in 2001, much higher fly collections than in early 2002 (PMA, unpublished data). Continued research should provide valid explanations for these year-to-year and seasonal fluctuations. There were distinct differences in fly densities and activity in the coastal areas (fig. 4) by year and area; monitoring of olive fly phenology and behavior is needed in microclimates as well as regions to select and optimize management strategies.

We still have much to learn about control and management of olive fly in California. While our data is to a certain degree preliminary, it provides the foundation for continued research on the relationships between macro- and microclimates, fly behavior and phenology, fruit development and susceptibility of table and oil cultivars to infestation, and a better understanding of when and how to apply various integrated pest management (IPM) strategies such as bait spray applications, trapping options, parasite releases and harvest timing. An olive fly phenology model based on trapping and temperature, for example, could be used to determine optimum harvest timing, or the release of parasites in urban trees or organic olive production; such studies are under way.

California Olive Committee

California supplies 99% of the commercial olives grown in the United States, with 134,000 tons harvested on about 36,000 acres in 2001. Trapping data will aid in the development of pest-control strategies to manage the olive fruit fly.

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Insecticide treatments disinfest nursery citrus of glassy-winged sharpshooter

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To protect uninfested areas of California from glassy-winged sharpshooter (GWSS), the disinfestation of citrus nursery stock prior to shipment is essential. A nonnative insect, GWSS transmits the bacterium that causes Pierce's disease in grapevines. In our study, GWSS adults were especially sensitive to two categories of insecticides, the pyrethroids and systemically applied neonicotinoids. Several insecticides, including the carbamate carbaryl and a few of the foliar neonicotinoids were highly effective in preventing GWSS nymphs from successfully emerging from egg masses. While no pesticide treatment will perfectly protect nursery citrus, a treatment plan that includes a combination of insecticides that are effective against adults and emerging nymphs will minimize the chance of transporting GWSS throughout California.

The glassy-winged sharpshooter (GWSS) was recognized as a serious insect pest in California in the mid-1990s. Subject to quarantine restrictions, nursery citrus is usually treated with insecticides to prevent the transport of GWSS throughout the state.
***Above*, A GWSS adult rests on a citrus stem.**

Glassy-winged sharpshooter (GWSS), a nonnative insect, arrived in Southern California prior to 1990 (Sorenson and Gill 1996). However, it was not until the late 1990s that the serious nature of its potential as a vector of *Xyllela fastidiosa,* the bacterium that causes Pierce's disease in grapes, was recognized in California. From 1997 to 2000, the number of grapevines infected with Pierce's disease in Temecula, Calif., rapidly escalated from a small number to thousands (Blua et al. 1999). This epidemic pointed out to the grape industry the seriousness of GWSS as a vector of Pierce's disease.

Glassy-winged sharpshooter *(Homalodisca coagulata)* entered the southern San Joaquin Valley in the mid-1990s and has been gradually spreading northward along the citrus belt. It now infests citrus in most of Kern County and portions of southern Tulare County. Citrus is a preferred oviposition (egg-laying) host of GWSS; grapes located near citrus are at greater risk for Pierce's disease (Perring et al. 2001).

The bacterium that causes Pierce's disease blocks the water-conducting cells of the grapevine, causing leaves to become scorched, fruit to shrivel and canes to grow poorly. Currently there are no resistant rootstocks or treatments for Pierce's disease once a vine is infected, so the only control measures available to growers are roguing out infected vines and reducing the sharpshooter vectors with insecticide treatments. Since GWSS has numerous hosts, eradication with insecticides is impossible. Preventing GWSS from being artificially transported into uninfested regions is critical, to buy time for research and regulatory programs to develop additional control strategies.

A series of quarantine laws went into effect between 2000 and 2002 to prevent the movement of GWSS nymphs, adults and eggs on landscape ornamentals, bulk grapes, bulk citrus and nursery citrus to uninfested areas of California. Citrus nurserymen accomplish disinfestation of their trees by insecticide treatments, and careful visual inspection and hand removal of GWSS egg masses prior to shipment. These measures have greatly reduced the number of nursery shipments rejected at destination due to GWSS infestation. However, citrus nurserymen need better information about which insecticides are most effective and how long they last. Many have treated their nurseries at frequent intervals and rotated through various insecticides without full knowledge of their efficacy. Since nursery operators often do not know exactly when plants will be shipped, they must be confident that insecticides will be toxic to GWSS for at least several weeks. Our experiments were conducted to determine the residual effect of various pesticides on adult GWSS survival, their ability to deposit eggs and the ability of nymphs to emerge from egg masses.

Adult GWSS tests

In 2001, we tested commercial applications of several insecticides at an Arvin nusery, using 66 'Eureka' lemon on volkameriana rootstock and 66 'Newhall' navel oranges on Schaub rough lemon rootstock (15-gallon potted plants)(table 1). Foliar insecticides were mixed using field rates in 750 gallons of water and trees were sprayed to runoff using a Hudson-type pump sprayer. Systemic insecticides were diluted in 500 milliliters (ml) water per pot and applied to moistened soil. About 1 liter of water was added to each pot immediately after treatment. The soil of all trees was hand-watered every 2 to 3 days. Half of the trees were additionally irrigated using overhead sprinklers for 30 minutes, three times per week. Trees were kept in a commercial greenhouse where the temperature fluctuated between 60ºF and 85ºF.

GWSS adults were collected at weekly intervals in an untreated Bakersfield citrus orchard from August to October 2001, using sweep nets. Each week, freshly collected adults were caged on six trees per treatment (five adults per cage, six cages per treatment, one cage per tree) using polyester paint-strainer bags. The number of live adults after 24 hours and number of egg masses deposited after 7 days were recorded each week for 11 weeks after treatments. During the first week, the mortality of adults was not measured after the first 24 hours. When GWSS adults survived 24 hours of an insecticide treatment and deposited eggs over the 7-day exposure period, that treatment was no longer tested. At the end of each 7-day interval, living adults were removed and destroyed, and freshly captured adults were caged on new branches.

TABLE 1. Insecticides and rates tested for efficacy against GWSS

Insecticide	Trade name	Class	Formulated rate applied	lb AI/acre or cubic ft soil*
Acetamiprid	Assail 70 WP	Neonicotinoid foliar	0.36 lb	0.25
Bifenthrin	Talstar F	Pyrethroid foliar	187.5 oz	0.98
Buprofezin	Applaud 70 WP	Insect growth regulator foliar	2.86 lb	2.0
Carbaryl	Sevin XLR Plus	Carbamate foliar	8 pt	4.0
Chlorpyrifos	Lorsban 4 E	Organophosphate foliar	12 pt	6.0
Dinotefuran	V-10112 20 SG	Neonicotinoid foliar	0.66 lb	0.13
Dinotefuran	V-10112 20 SG	Neonicotinoid foliar	1.65 lb	0.33
Fenpropathrin	Tame 2.4 EC	Pyrethroid foliar	60 oz	1.125
Imidacloprid	Marathon II	Neonicotinoid foliar	12.68 oz	0.20
Imidacloprid	Provado 1.6 F	Neonicotinoid foliar	15.83 oz	0.20
Imidacloprid	Admire 2 F	Neonicotinoid systemic	0.025 oz/ft^3 soil†	0.0004/ft^3
Thiomethoxam	Platinum 2 SC	Neonicotinoid systemic	11 oz/acre	0.17
Thiomethoxam	Actara 25 WG	Neonicotinoid foliar	0.09 lb	0.023

* All entries are lb AI/acre, except for Admire.

† Soil volume of test pots approximately 1.25 cubic feet.

Adult mortality. Residues began to break down — as evidenced by more than one adult surviving a 24-hour period — 2 weeks after treatments were applied for the organophosphate chlorpyrifos (Lorsban), 3 weeks for the carbamate carbaryl (Sevin), and 2 and 4 weeks for the foliar neonicotinoids imidacloprid (Marathon) and acetamiprid (Assail)(table 2). We do not have adult mortality data for the first week after treatment, so the chlorpyrifos treatment may have had an even shorter residual effect. The systemic neonicotinoid imidacloprid (Admire) allowed only an occasional adult to survive for 8 weeks following treatment, and the systemic neonicotinoid thiomethoxam (Platinum, unregistered) caused complete mortality of adults for 11 weeks. The pyrethroids fenpro-pathrin (Tame) and bifenthrin (Talstar) were highly effective; bifenthrin allowed only one adult to survive 24 hours and fenpropathrin allowed no adults to survive over the 11-week test period. Combining foliar imidacloprid and fenpropathrin seemed to reduce efficacy compared to fenpropathrin alone. We saw no effect of the host plant (lemons or oranges) on the mortality of adult GWSS.

TABLE 2. Number of live GWSS adults 24 hours after exposure to insecticide residues-number of egg masses deposited during 7-day exposure period*

Treatment	Weeks after treatment 1	2	3	4	5	6	7	8†	9	10	11
Untreated	-2	26-0	22-5	28-3	25-12	21-4	22-7	28-0	27-	17-	22-
Chlorpyrifos	-2	26-11									
Carbaryl	-0	0-2	14-1								
Neonicotinoids:											
Acetamiprid	-0	0-0	1-0	6-1							
Imidacloprid (foliar)	-2	11-0	6-0	6-0	5-3						
Imidacloprid (systemic)	-0	1-0	0-0	0-0	0-0	1-0	0-0	1-0	17-		
Thiomethoxam (systemic)	-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-	0-	0-
Pyrethroids:											
Fenpropathrin	-0	0-0	0-0	0-1	0-0	0-0	0-0	0-0	0-	0-	0-
Bifenthrin	-0	1-0	0-0	0-0	0-0	0-0	0-0	0-0	0-	0-	0-
Fenpropathrin + imidacloprid (foliar)	-0	0-0	0-0	0-0	0-0	1-0	2-0	3-0	3-		

* Treatments applied Aug. 17, 2001; 30 individuals tested per treatment.

† Oviposition stopped Oct. 11, 2001.

Egg masses deposited. In this same experiment, we evaluated the number of eggs that GWSS were able to deposit during the 7 days after placement of adults on the insecticide residues (table 2). Egg masses were found 1 week after application in the chlorpyrifos and foliar imidacloprid treatments, and during week 2 in the carbaryl treatment. These insecticides had a short residual effect on egg deposition. The foliar neonicotinoid acetamiprid prevented egg-laying for 3 weeks. The fenpropathrin treatment allowed one egg mass to be deposited during week 4. The other treatments (systemic imidacloprid, systemic thiomethoxam and bifenthrin) did not allow a single egg to be deposited during the 8-week experiment. On Oct. 11, 2001, the field-collected GWSS adults halted oviposition, so this portion of the experiment could not be continued. We saw no effect of the host plant (lemons or oranges) on egg production of GWSS.

Overhead irrigation. We compared GWSS adult survival during 24 hours on treated trees with overhead irrigation (applied for 30 minutes, three times per week), and without overhead watering (table 3). There was a significant reduc-

Various insecticides were tested on citrus for their effectiveness in controlling GWSS nymphs and adults. Laboratory assistant Becky Striggow placed GWSS adults in cloth cages on treated citrus trees to test their response.

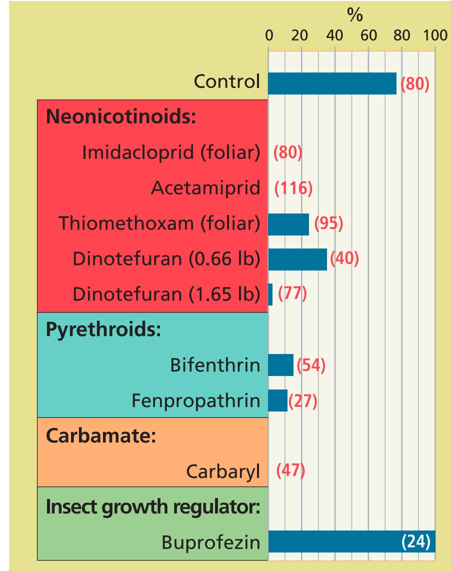

Fig. 1. Percentage of nymphs that successfully emerged from egg masses treated with various insecticides (and total number of eggs tested).

tion in toxicity of the insecticides due to overhead watering during week 4 for carbaryl, weeks 2 through 4 for acetamiprid, weeks 4 and 5 for foliar imidacloprid, weeks 6, 8 and 9 for fenpropathrin, and during weeks 5 to 9 for fenpropathrin and the fenpro-pathrin plus foliar imidacloprid combination. We found that overhead watering reduces the toxicity of foliar insecticides and should be avoided. The exception was bifenthrin, which was highly effective under all application conditions. The systemic neonicotinoids (imidacloprid and thiomethoxam) did not appear to be significantly affected by overhead watering during the first 9 weeks of the experiment.

Emergence from egg masses

In the second experiment, GWSS adults were collected weekly from an unsprayed citrus orchard in Kern County during September 2002 and caged for 1 week on nursery citrus (15-gallon potted lemons and oranges of the same varieties as the 2001 test). After egg masses were deposited, the adults were removed and the trees were treated using a 1-liter hand-pump sprayer with commercial rates of various insecticides to determine if nymphs could successfully emerge from the egg masses. This process was repeated three times to obtain results for eight different insecticides. At the time of treatment, eggs ranged in age from 1 to 6 days. Successful emergence was defined as nymphs that completely emerged from the egg cell and fully developed their nymphal form (legs and dark body color).

Foliar imidacloprid (Provado), acetamiprid and carbaryl did not allow any nymphs to successfully emerge from the egg masses (fig. 1). The nymphs either died inside the egg cell or as they began to emerge from the egg cell. The foliar neonicotinoids thiomethoxam (Actara) and dino-tefuran, and the pyrethroids fenpropathrin and bifenthrin, allowed 5% to 40% of nymphs to successfully emerge. Some foliar neonicotinoids are more effective than others, and in the case of dinotefuran, the insecticide application rate is important. Buprofezin (Applaud), an insect growth regulator, did not have any effect on nymphal emergence, an unsurprising result since this insecticide affects GWSS when it is molting. The significance of preventing nymphs from successfully emerging is to prevent them from moving to untreated surfaces and surviving transportation to uninfested regions of California. Insecticides that show complete mortality of emerging nymphs are the most suitable for citrus nursery treatments.

GWSS adults and nymphs emerging from egg masses differed in their responses to the insecticides tested. The pyrethroids and systemically applied

TABLE 3. Number of surviving GWSS adults 24 hours after placement on insecticide residues without overhead watering-with overhead watering*

Treatment	Weeks after treatment: 2	3	4	5	6	7	8	9	10	11
Untreated	26-29	22-20	28-25	25-23	21-27	22-25	28-26	27-27	17-27	22-27
Chlorpyrifos	26-28									
Carbaryl	0-10	14-13	4-27							
Neonicotinoids:										
Acetamiprid	0-12	1-4	6-16							
Imidacloprid (foliar)	11-10	6-2	6-15	5-8						
Imidacloprid (systemic)	1-3	0-0	0-2	0-0	1-2	0-0	1-3	17-10		
Thiomethoxam (systemic)	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-5	
Pyrethroids:										
Fenpropathrin	0-0	0-0	0-0	0-1	0-3	0-0	0-12	0-12		
Bifenthrin	1-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0
Fenpropathrin + imidacloprid (foliar)	0-0	0-0	0-1	0-7	1-5	2-18	3-17	3-18		

* Treatments applied Aug. 17, 2001; 30 individuals tested per treatment.

GWSS nymphs as they emerge from the egg case.

The nymphs turn a dark color and develop legs soon after emergence.

Imidacloprid kills GWSS nymphs as they try to emerge from the egg case.

neonicotinoids were the most effective against the adult stage, limiting their survival and ability to deposit eggs. These insecticides should be used as the first line of defense. Any insecticide that eliminates adults is likely to also eliminate emerged nymphs, because of their smaller size. Sometimes, GWSS adults are able to deposit eggs before the insecticides kill them (table 2). The carbamate carbaryl and the foliar neonicotinoids imidacloprid (Provado) and acetamiprid were highly effective in preventing nymphs from successfully emerging from egg masses.

Advice for citrus nurseries

Based on these experiments, we advise citrus nursery operators to apply a systemic neonicotinoid 1 to 8 weeks before shipment is expected. Systemic imidacloprid (Bayer CropScience) is the only one currently registered for nursery citrus. Treatment with systemic imida-cloprid at least 1 week prior to shipment is needed to ensure uptake into the tree. The foliage should be visually inspected at the time of shipment and any sharpshooter egg masses found should be removed and destroyed.

Just prior to shipment, a pyrethroid such as fenpropathrin or bifenthrin should be applied to ensure that the foliage is disinfested of nymphs and adults. This is especially important if the trees were not treated with systemic imidacloprid within the 1- to 8-week time frame. This treatment is effective for up to 8 weeks, so no additional adulticide is needed if shipments are delayed within that time period. In addition, carbaryl, acetamiprid or foliar imidacloprid (Provado) should be applied just prior to shipment (1 to 3 days) to prevent nymphs from emerging from egg masses that were not found during the visual search.

Our results confirm previous research on controlling GWSS. Bethke and Redak (2001, 2002a, 2002b) and Bethke et al. (2001) demonstrated similar efficacy of systemic neonicotinoids and pyrethroids against adult GWSS and efficacy of carbaryl against emerging nymphs for nursery ornamentals. Akey et al. (2001) and Grafton-Cardwell et al. (2001) demonstrated the efficacy of pyrethroids and neonicotinoids for GWSS in commercial grapes and citrus. These recommendations should reduce insecticide use in nurseries because operators will be able to apply the most effective insecticides at the right time. In addition, they will have confidence that the pyrethroid and systemic neonicotinoid residues will remain effective for a number of weeks if shipment is delayed.

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Drip irrigation increases tomato yields in salt-affected soil of San Joaquin Valley

Blaine Hanson
Don May

This study evaluated the potential for subsurface drip irrigation in processing tomato to reduce subsurface drainage, control soil salinity and increase farm profits in areas affected by saline, shallow groundwater. Subsurface drip irrigation systems were installed in three fields of fine-textured, salt-affected soil along the West Side of the San Joaquin Valley. No subsurface drainage systems were installed in these fields. Yield and quality of processing tomato were compared with sprinkler irrigation systems. Yields increased 5.4 tons per acre to 10.1 tons per acre in the drip systems with similar amounts of applied water. The solids content of drip-irrigated processing tomato was acceptable. Water-table levels showed that properly managed drip systems could reduce percolation below the root zone, reducing subsurface drainage. Yields of the drip systems were also similar over a range of soil salinity levels.

Subsurface drip irrigation was tested in processing tomatoes grown in the fine-textured, salt-affected soils of the West Side of the San Joaquin Valley. *Left,* Wetting at the soil surface above a buried drip line. Yields were significantly better in fields irrigated with the drip system, *right,* than with sprinklers.

AN economically, technically and environmentally feasible drain-water disposal method does not exist for the San Joaquin Valley. Therefore, the drainage problem must be addressed through options such as better management of irrigation water to reduce percolation below the root zone, increased use by crops of the shallow groundwater without any yield reductions, and reuse of drainage water for irrigation. One option for improving irrigation water management is to convert from furrow or sprinkler irrigation to drip irrigation.

Drip irrigation can apply water more precisely and uniformly, potentially reducing subsurface drainage, controlling soil salinity and increasing yields. The main disadvantage is installation costs up to about $1,000 per acre. For drip irrigation to be at least as profitable as other irrigation methods, growers must receive more revenue from higher yields and lower irrigation and cultivation costs. Yet, several large-scale comparisons of furrow and drip irrigation in cotton revealed uncertainty as to the economic benefits of drip irrigation (Hanson and Trout 2001). As a result, growers converting to drip irrigation face uncertainty about the economic risks involved.

From 1999 to 2001, we evaluated subsurface drip irrigation in processing tomato to determine its effect on crop yield and quality, soil salinity and water-table depth in salt-affected, fine-textured soil underlain by saline, shallow groundwater on the West Side of the San Joaquin Valley. Processing tomato is a major crop on the valley's west side; acreage in the Westlands Water District is about 90,000 acres, about 16% of the district's irrigated acreage (Westlands Water District 2002). Because processing tomato is a high cash-value crop, the need for increased profitability with drip irrigation is greater than in cotton. However, tomato is much more sensitive to soil salinity, raising concerns about possible reductions in crop yields in salt-affected soil.

Subsurface drip irrigation

Subsurface drip irrigation systems were installed in three fields (about 160 acres each) of processing tomatoes located in the Westlands Water District. Sites DI (80 acres of drip irrigation) and BR (40 acres) were installed in 1999, while DE (40 acres) was installed in 2000. (DI, BR and DE are site identifications.) Sprinkler irrigation was used for the rest of each field, the normal irrigation method of tomatoes in these soils. Westlands irrigation water was used at DI and BR, and well water at DE. Measurements made at all sites were field-wide red fruit yield (machine harvested), yield quality, depth to the water table, irrigation water salinity, groundwater salinity and applied water.

The irrigator determined irrigation scheduling at each site using appropriate crop coefficients and reference crop evapotranspiration from the California Irrigation Management Information System (CIMIS). There were no subsurface drainage systems at the drip-irrigated sites. Low-flow drip tape (0.2 gallons per minute [gpm]/100 feet), 7/8-inch diameter, was buried about 8 inches deep with one drip line per bed, although two drip lines per bed were used for BR2001 (site/year). Emitter spacing ranged from 12 inches to 18 inches depending on the type of tape. Drip-line lengths were about 1,300 feet at all sites. Irrigations were twice per week during the period of maximum canopy size.

Small plot experiment

In addition, a second experiment consisted of applying different amounts of irrigation water to small plots in the drip-irrigated area of each site to determine the minimum amount of water that can be applied under saline, shallow groundwater conditions without reducing crop yield. The DI1999 experiment used processing tomato varieties H9557, H9665 and H8892, while the DE2000 experiment used the varieties Halley 3155, H9665 and H8892. Otherwise, the growers' variety was used (table 1).

Data collected in the small-scale, drip-irrigated plots included: total red fruit yield (machine harvested), soluble solids and color; percent red, green and nonmarketable fruit; applied water; weekly measurements of canopy coverage; and soil moisture content and salinity. Sampling locations for soil moisture content and soil salinity were 10 inches from the drip line at 6-inch depth intervals down to 30 inches to 36 inches deep at the head, middle and end of the field. A digital infrared camera and appropriate software were used to measure canopy coverage. A neutron moisture meter was used for soil moisture measurements. In addition to the these measurements, patterns of soil moisture content and soil salinity around the drip line were determined by a one-time sampling with depth at various distances from the drip line.

Left, **A set of filters prevents irrigation water from clogging the drip lines.** ***Right,*** **Pressure-regulating valves allow growers to control the pressure of the irrigation water flowing into the drip line.**

Seasonal crop evapotranspiration (ET) was estimated using a computer model (Hsiao and Henderson 1985) and reference crop (grass) evapotranspiration. The model was calibrated for processing tomato with data from an unrelated project. Differences between measured seasonal ET and that estimated by the model were 5% or less.

Fieldwide yield characteristics

At each site, only 1 year of comparing drip-versus-sprinkler irrigation was possible (1999 for DI and BR; 2000 for DE). After the first year at each site, the rest of the BR and DE fields were converted to drip irrigation, while at DI a different crop was planted. Yields of the drip-irrigated fields were monitored for several additional years.

Fieldwide yields under drip irrigation were 5.4 tons per acre to 10.1 tons per acre greater than under sprinkler irrigation, an increase of about 15% to 35% (table 1). Average yields were 41.8 tons per acre and 33.4 tons per acre for drip and sprinkler irrigation, respectively. The average yield difference was statistically significant using the *t*-test with a 5% significance level. Drip yields were considered high for these fine-textured, salt-affected soils. After the first year, yields at DI and DE continued to be high (table 1). Yields at BR for 2000 and 2001 were relatively low, albeit higher than normally experienced for late plantings. However, a high yield occurred at BR in 2002.

Soluble solids, a measure of the solid material of tomatoes, were acceptable for all years, averaging 5.3% and 5.5% for sprinkler and drip irrigation, respectively. Soluble solids increased with increasing soil salinity, averaging 4.9%, 5.3% and 5.4% for DI (lowest salinity level), BR and DE (highest salinity level), respectively. The average color — determined by commercial graders — was 24.3 and 22.5 for sprinkler and drip irrigation, respectively. (Lower color numbers indicate better quality.) Differences in soluble solids and color between drip and sprinkler irrigation were not statistically significant.

Applied water at BR1999 was similar for drip and sprinkler irrigation. About 6 inches more water was applied to the drip field compared with the sprinkler field for DE2000, partly because the drip field was irrigated for about 2 weeks longer. Applied water data for the sprinkler field at DI was not available.

TABLE 1. Fieldwide applied water and yield characteristics for processing tomato, all sites and years

Irrigation system	Variety	Applied water	Yield	Soluble solids	Color*
		inches	*ton/acre*	*%*	
BR					
Sprinkler (1999)†	H8892	16.8	36.5	5.3	24.2
Drip (1999)†	H8892	16.0	46.3	6.0	21.1
Drip (2000)	Halley 3551	16.8	35.0	5.4	23.4
Drip (2001)	H9665	20.5	31.9	4.6	25.3
Drip (2002)	Peto303	‡	48.9	4.8	24.1
DI					
Sprinkler (1999)†	H9557	‡	35.2	5.2	24.8
Drip (1999)†	H9557	22.2	40.6	5.0	22.8
Drip (2000)	H9492	29.0	46.4	4.8	21.0
Drip (2001)	H9492	22.9	51.7	4.9	24.1
DE					
Sprinkler (2000)†	H9557	22.8	28.5	5.5	23.9
Drip (2000)†	H9557	28.0	38.6	5.6	23.7
Drip (2001)	H8892	22.1	45.8	5.2	23.6

* Color determined by commercial grade. Lower numbers indicate better quality.
† Comparison year.
‡ Data not available.

Differential irrigation results

Results of the differential irrigation experiments showed that plot yield decreased with decreasing irrigation water applications for all sites and all

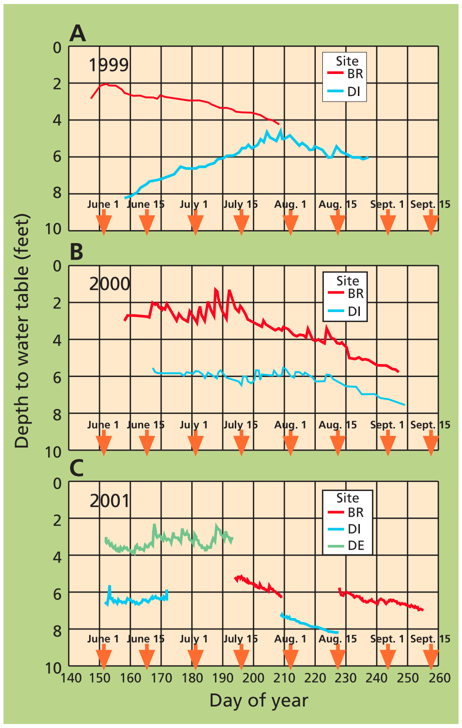

Fig. 1. Depth to water table for (A) 1999, (B) 2000 and (C) 2001.

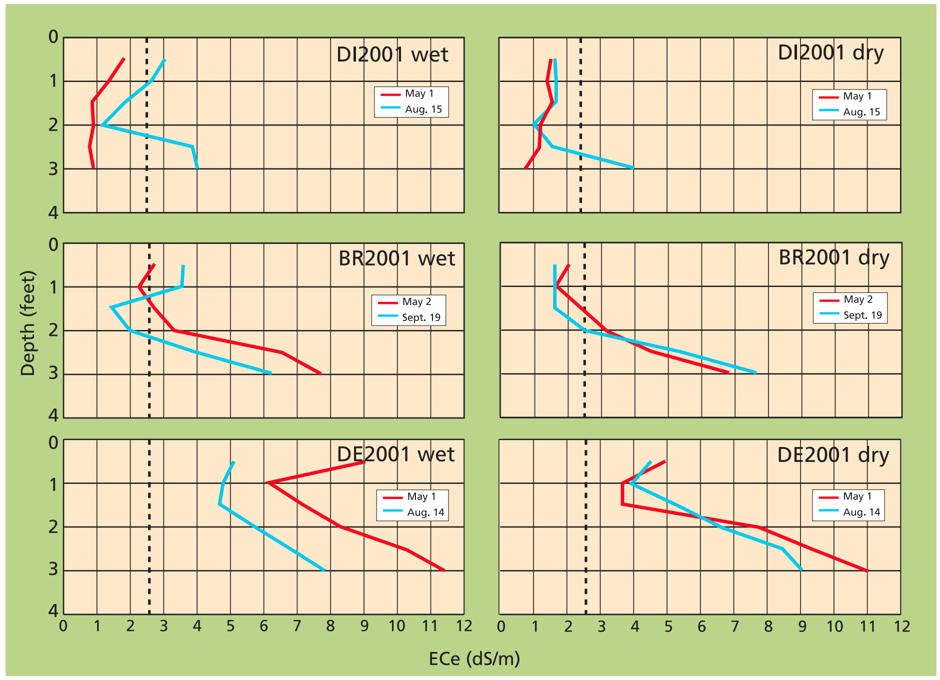

Fig. 2. Electrical conductivity of saturated extracts (ECe) with depth for wet (receiving the most irrigation water) and dry (receiving the least irrigation water) differential drip-irrigated treatment in 2001. Dashed line is the reference salinity threshold value for tomato.

years, although differences in behavior occurred among the sites and years. For example, at DI the overall average yield for all tomato varieties (no yield differences between varieties) decreased from 47 tons per acre to 42 tons per acre as applied water decreased from 23.0 inches to 14.8 inches in 1999; and in 2001, it decreased from 50.5 tons per acre to 46.4 tons per acre as applied water decreased from 20.0 inches to 13.5 inches.

Soluble solids increased with decreasing applied water for all sites and all years, but different magnitudes of changes occurred each year. For example, the overall average soluble solids at DI1999 increased from 4.6% to 5.0% as applied water decreased from 20.0 inches to 16.4 inches. Applied water had little effect on color and percent red fruit (data not shown).

Linear regression equations relating yield characteristics with applied water were tested for their statistical significance and for statistical similarity among the sites. Results of the statistical tests were mixed, preventing any conclusions from being developed about differences between sites and years. There were no statistical differences in yield, solids and color between varieties at DI in 1999 and DE in 2000.

Water quality and levels

The irrigation water and groundwater quality was assessed using measurements of electrical conductivity (EC). Higher ECs reflect higher salt content of the water and lower quality. The EC of the Westlands Water District irrigation water at BR and DI normally was about 0.34 deciSiemens/meter (dS/m) (data not shown). At DE, the electrical conductivity of the well water was about 1.06 (dS/m) to 1.2 dS/m. The EC of the shallow groundwater at BR1999 ranged from 4.7 dS/m to 7.4 dS/m. The groundwater EC at DI ranged from 7.9 dS/m to 11.1 dS/m for 1999 and 2000, but was 4.0 dS/m to 4.7 dS/m in 2001. Reasons for the small 2001 values are unknown even though sampling locations were within 30 feet of each other. EC values at DE were 13.6 dS/m to 16.4 dS/m in 2000 and 9.0 dS/m to 9.5 dS/m in 2001. These differences may reflect different sampling locations due to using different areas of the field each year.

Measurements of water-table depth were used as an indicator of subsurface drainage (or lack of) below the root zone. The water-table depth at DI1999 decreased with time until about July 20 and then increased to about 6 feet deep, while the water table at DI remained below 6 feet deep in 2000 and 2002 (fig. 1). No response of water-table depth to drip irrigation was evident. At BR1999, the water-table depth increased from about 2 feet to 4.3 feet. But in 2000, drip irrigations caused it to rise to nearly 1.6 feet deep before July 15, the result of applying about 10% more water than the estimated crop evapotranspiration. After mid-July, the water-table depth increased to 5 feet to 6 feet deep due to reduced water applications. Water-table levels were not measured at DE in 2000 because of problems with installing observation wells. In 2001, water-table depth at DE fluctuated between about 2 feet and 4 feet with a definite response to drip irrigation. The gaps in the 2001 data were caused by the water level in the observation wells dropping below the pressure transducers.

Soil salinity

Soil salinity, as measured by the electrical conductivity of the saturated extract (ECe), differed considerably among the three sites (fig. 2 for 2001

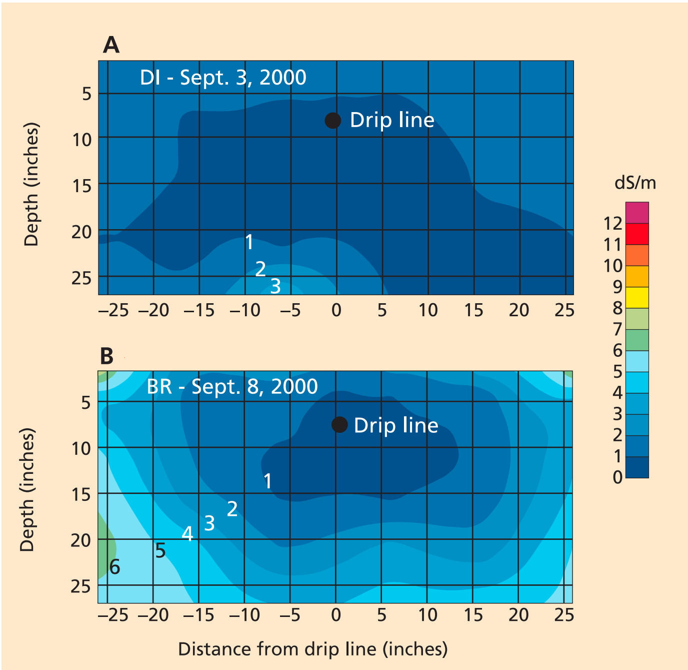

Fig. 3. Patterns of electrical conductivity of saturated extracts (ECe) around the drip line for (A) DI2000 and (B) BR2000.

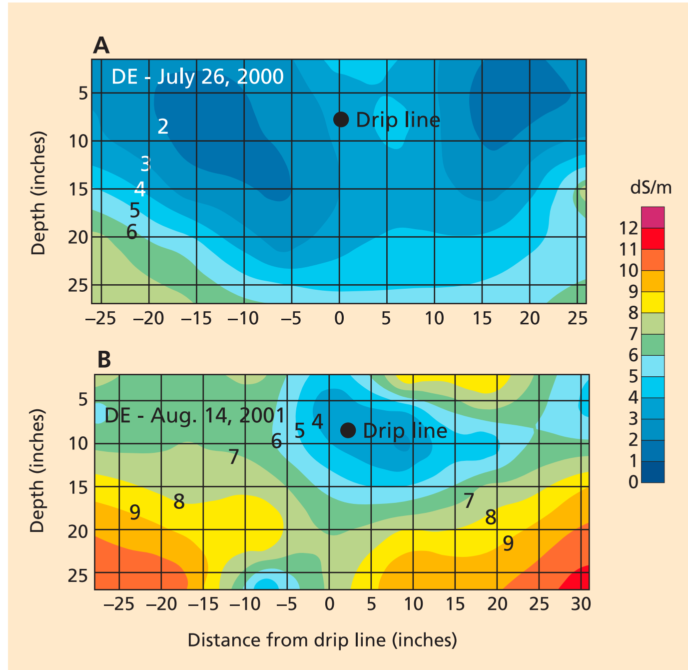

Fig. 4. Patterns of electrical conductivity of saturated extracts (ECe) around the drip line for (A) DE2000 and (B) DE2001.

data). (In the differential drip-irrigated experiment, the "wet" treatment received the most and the "dry" treatment received the least irrigation water.) ECe values at DI were generally less than 2.5 dS/m, the threshold value for tomato. The threshold ECe value is the maximum average root-zone ECe at which no yield reduction should occur (Maas 1990). The actual root-zone salinity under drip irrigation is unknown because of spatially varying patterns of soil salinity, soil moisture and root density around drip lines. The threshold value is provided as a reference only to indicate a potential for yield reduction. At BR2001, ECe increased considerably with depth and exceeded the threshold value except for depths less than about 1.5 feet. ECe values at DE2001 increased with depth, with values exceeding the threshold value throughout the soil profile. At all sites, differences between wet and dry irrigation treatments were slight.

The pattern of ECe around the drip line showed values less than the threshold value of about 2.5 dS/m throughout the soil profile at DI (fig. 3A). At BR2000, salinity was least near the drip line with values less than about 1 dS/m, but increased with horizontal distance from the drip line and depth to values of about 7 dS/m (fig. 3B). The zone of ECe values less than the threshold value extended about 16 inches horizontally from the drip line and 8 inches deep below. Salt accumulated above the drip line. While the actual root distribution around the drip line is unknown at these sites, it is likely that most of the roots are near the drip line. Therefore, the soil salinity near the drip line will affect crop yield more than the salinity elsewhere in the soil profile. These results show that the levels of soil salinity near the drip line should not adversely affect crop yield.

At DE2000, ECe was highest near the drip line with values of 3 dS/m to 4 dS/m and decreased with horizontal distance to values less than 2.5 dS/m beyond about 8 inches to 16 inches (fig. 4A). The high salinity near the drip line reflected the well water EC. The low levels of salinity near the edge of the pattern probably reflected leaching of salts due to ponding from a severe late spring rain. The next year, ECe levels ranged between 5 dS/m and 7 dS/m throughout most of the soil profile except near the drip line, where ECe values were between 3 dS/m and

TABLE 2. Applied water, cumulative crop evapotranspiration (ET) and irrigation efficiency (IE) for processing tomato*

Site/ year	Applied water	Seasonal change in soil moisture	Cumulative crop ET	IE
	. . . .	*inches*	. . . .	%
BR				
1999	16.0	3.4	20.3	105
2000	16.8	2.7	21.4	110
2001	20.5	2.7	22.9	99
DI				
1999	22.2	1.5	25.1	106
2000	29.0	3.4	25.2	78
2001	22.9	3.0	26.6	103
DE				
2000	28.0	1.3	24.2	83
2001	22.1	3.2	23.1	91

* Irrigation efficiency is the ratio of the cumulative crop ET to the sum of applied water and seasonal soil moisture change.

4 dS/m (fig. 4B). For both years, soil salinity near the drip line exceeded the threshold salinity value, suggesting a potential for yield reductions. However, crop yield data (table 1) indicates that these levels of salinity had little effect on crop yield.

The main source of salt in these fields is the upward flow of saline groundwater into the root zone. However, we found a weak correlation between soil salinity near the bottom of the sampled soil profile and groundwater salinity. At DI, soil salinity at the deeper depths was generally less than 2 dS/m, but groundwater salinity was much higher. At BR, soil salinity levels at the deeper sampled depths were similar to groundwater salinity; however, at DE, soil salinity was less than groundwater salinity. The reasons for the behavior at DI and DE are not clear, but the deeper water-table depth at DI (generally 6 feet or deeper) may have contributed to the smaller soil salinity values, whereas at the other sites much smaller water-table depths occurred. The deeper depth at DI may have greatly reduced the upward flow of shallow groundwater.

Soil moisture, evapotranspiration

Soil moisture was monitored over time to determine the adequacy of irrigation. Soil moisture content decreased slightly with time throughout the irrigation season for all treatments (data not shown). Average moisture contents of the wet differential-drip treatments were slightly higher than those of the dry. Wetting patterns around the drip line showed water moving laterally to about 16 inches from the drip line at DI (fig. 5) and BR (not shown) for both irrigation treatments. At about that distance, soil moisture content was the least for a given depth. Soil moisture content increased with depth, but such changes were small below the drip line. At about 20 inches from the drip line (in the furrow), slightly higher soil moisture occurred compared to 16 inches for both irrigation treatments, suggesting less moisture extraction near the furrow. Soil moisture contents above about 15 inches to 20 inches deep were less for the dry treatment (fig. 5B) compared with the wet treatment (fig. 5A). Similar behavior occurred at BR. Wetting patterns at DE were not measured, but based on the salinity pattern in figure 4A, lateral flow was between 8 inches and 16 inches from the drip line. At BR2001, where two drip lines per bed were used, wetting across the bed was more uniform compared to the single drip-line configuration (not shown).

Seasonal cumulative ET for all years (calculated using the computer model and canopy growth curves) showed ET values ranging from 20.3 inches to 26.6 inches (table 2). Seasonal irrigation efficiency, defined as the ratio of cumulative ET to the sum of cumulative applied water and seasonal change in soil moisture, ranged from 78% to 110%. Values near or exceeding 100% indicate deficit irrigation and possible use of the shallow groundwater, both of which may be undesirable in processing tomato. The seasonal change in soil moisture content was estimated from measurements taken 10 inches from the drip line. The actual seasonal change may vary because of the spatially varying soil moisture content around the drip line.

Economics of processing tomato

The economics of converting to subsurface drip irrigation from sprinkler irrigation were determined using cost data provided by one of the grower participants. Assumptions used in this analysis were:

- The existing sprinkler irrigation system was used elsewhere on the farm.
- The economic life of the drip system was 20 years.
- Replacement of the drip tape occurred every 5 years.
- Filters and pumps were replaced every 10 years.
- Yield increases ranged from 5.4 tons per acre to 10.1 tons per acre (table 1).
- Equivalent annual capital cost of the drip irrigation system was determined for interest rates of 5% and 10%.
- The same amount of irrigation water was applied by both irrigation methods.
- Area irrigated was 80 acres.

The benefits of converting to drip irrigation were increased revenue from higher yields and annual savings in cultural costs and energy. The conversion costs were the equivalent annualized capital cost of the drip system and its annual cultivation and energy costs. Annual net return ranged from $369 per

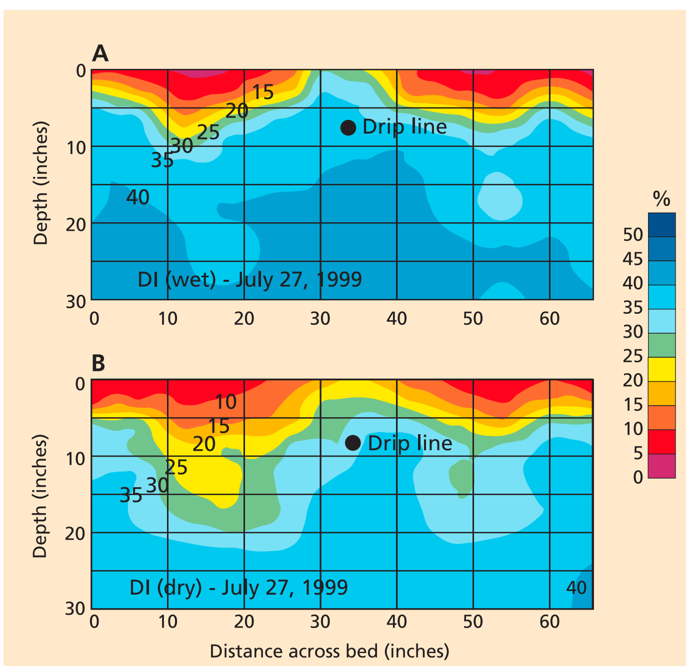

Fig. 5. Patterns of volumetric soil moisture content (%) around drip lines for (A) wet and (B) dry differential drip-irrigation treatments in DI1999.

acre to $604 per acre for a 5% interest rate and from $334 per acre to $569 per acre for a 10% rate (table 3). Returns to land, farm management costs, taxes and insurance costs were not available. The capital cost of the drip system was $809 per acre. The equivalent annual capital cost of the drip system was $120 per acre and $155 per acre for the 5% and 10% interest rates, respectively.

Irrigation and water management

Subsurface drip irrigation in the fine-textured, salt-affected soils on the West Side of the San Joaquin Valley can increase the yield and profitability of processing tomato compared to sprinkler irrigation, with acceptable levels of soluble solids (mainly due to the soil salinity at these locations). Properly managed drip irrigation can also control subsurface drainage to the shallow groundwater, as indicated by the water table data, potentially reducing problems caused by excessive subsurface drainage. Little correlation was found between soil salinity and crop yield, even though ECe values higher than the threshold ECe were found around the drip line at one site, suggesting that soil salinity under drip irrigation may affect crop yield less than other irrigation methods. Subsurface drip irrigation also provided better water management late in the growing season, when careful management is needed to prevent excessive deficit irrigation and phytophthora due to overly wet soil.

Little, if any, water savings on a per acre basis are likely when converting to drip irrigation from sprinkler irrigation for processing tomato. The higher yields with drip irrigation suggest that percolation and evaporation losses under sprinkler irrigation became transpiration losses under subsurface drip irrigation. However, because of higher yields the same total tons can be grown on fewer acres, saving water.

Subsurface drip irrigation must be carefully managed to prevent yield reductions and excessive percolation to the groundwater. Recommended irrigation amounts are about 100% of the potential crop ET in processing tomato as a compromise between reducing drainage and leaching of salts in the root zone. Crops should be irrigated two to three times per week.

In summary, the long-term sustainability of processing tomato yield under subsurface drip irrigation in these salt-affected soils will require:

- Sufficient leaching to maintain acceptable levels of soil salinity near the drip lines, where root density is probably the greatest.
- Periodic leaching of salt accumulated above the buried drip lines with sprinklers for stand establishment, if winter and spring rainfall is insufficient to leach the salts.
- Careful management of irrigation water to apply sufficient water for crop evapotranspiration and leaching yet prevent excessive subsurface drainage.
- Periodic system maintenance to prevent clogging of drip lines. Clogging due to root intrusion was a severe problem at one site where little or no chlorination occurred. Clogging will not only reduce the applied water needed for crop ET, but also reduce the leaching.

Subsurface drip irrigation in the marginal soils we tested was very profitable, which has encouraged growers to convert additional acreage in this area. However, where high tomato yields are obtained under furrow and sprinkler irrigation, converting to drip irrigation may not be as profitable because the potential for large yield increases may be reduced; any increase in revenue under drip irrigation may be insufficient to offset the capital, energy, maintenance and management costs of subsurface drip irrigation. Also, using drip irrigation on lower-valued crops may be unprofitable even if yields increase.

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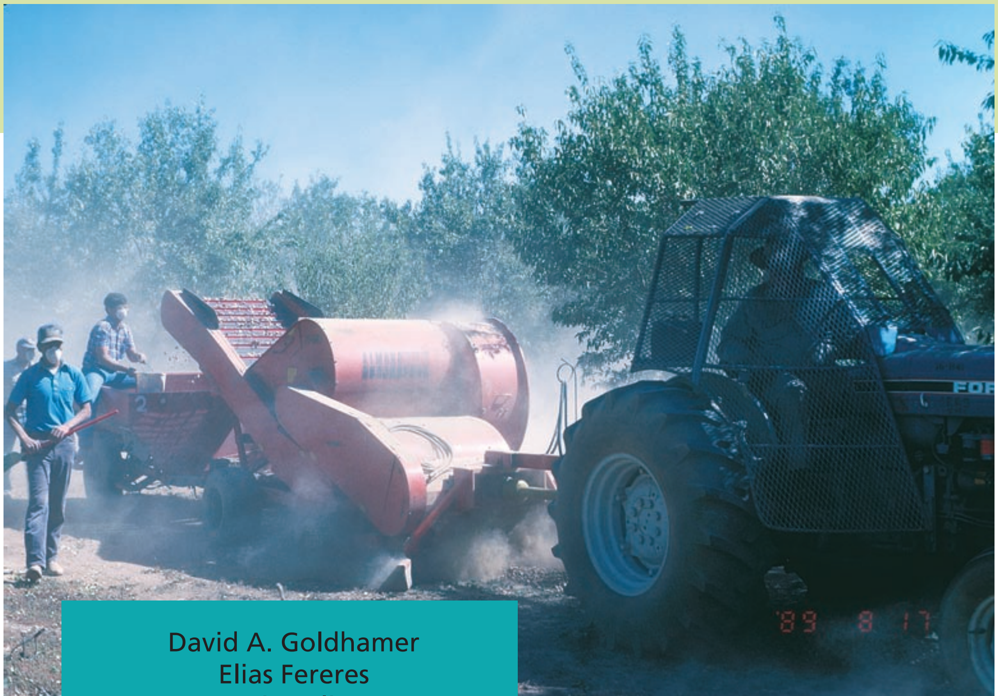
TABLE 3. Economic analysis of benefits and cost of converting from existing sprinkler to subsurface drip system for interest rates of 5% and 10%*

Benefits	5%	10%
	$/acre	
Revenue increase	270†–505‡	270†–505‡
Sprinkler energy costs	57	57
Sprinkler cultural costs	635	635
Subtotal	*962†–1192‡*	
962†–1197‡		
Costs		
Equivalent annual capital cost of drip system	120	155
Drip energy costs	28	28
Drip cultural costs	445	445
Subtotal	*593*	*628*
Net returns	**369†–604‡**	**334†–569‡**

* Crop price was $50/ton.
† Yield increase of 5.4 ton/acre.
‡ Yield increase of 10.1 ton/acre.

Can almond trees directly dictate their irrigation needs?



◀ **In addition to saving water, regulated deficit irrigation (RDI) — aided by measurements of minute fluctuations in tree trunk diameters — can provide benefits to almond growers such as accelerated hull-split and consequently, an earlier harvest. Additionally, it may be possible to replace the current method of ground drying with on-the-tree drying. Windrowing nuts on the ground and mechanical pickup, *left*, can create dust, which is considered a health risk.**

David A. Goldhamer
Elias Fereres
Mario Salinas

Many of California's fruit and nut growers have already embraced more efficient irrigation systems (drip and microsprinkler) and adopted scientific irrigation-scheduling methods that closely match net applied water to evapotranspiration (ETc). Further improvements in irrigation efficiency may be possible by using regulated deficit irrigation (RDI) to purposely stress trees at specific times of the season. Tree-based RDI triggers for irrigation scheduling, such as stem water potential (SWP) and maximum daily trunk shrinkage (MDS), as opposed to soil and atmospheric measurements, have the major advantage of being directly linked to crop productivity. The current state of the art in plant-based scheduling is SWP and MDS, but adoption is hampered by the lack of field studies validating its effectiveness. We conducted an experiment in a commercial almond orchard to evaluate the suitability of MDS measurements as indicators for RDI management. Small, electronic sensors affixed to the tree trunks continuously recorded diameters from which MDS values were gleaned and used to schedule two RDI treatments. We found that with the less severe RDI regime, less water was applied relative to the cooperator's nearly fully irrigated trees with no significant reduction in kernel size or other important almond parameters. In fact, the RDI regimes accelerated hull-split, decreased kernel water content and increased the nut-kernel percentage at harvest — all desirable almond results. We have demonstrated, for the first time in California, that RDI can be successfully scheduled based entirely on continuously recorded, tree-based electronic data. We believe that MDS measurements have some operational advantages over SWP, including lower labor costs and the ability to be directly incorporated into remotely operated, electronic controllers.

As its population grows and environmental concerns increase, California is likely to be 2 million acre-feet (650 billion gallons) short of water annually in the immediate future for an average rainfall year (DWR 1998). For drought years, the gap between supply and demand will be even greater. Given the economic and environmental constraints to developing new water supplies and that agriculture uses 75% to 80% of the state's developed water, agriculture is currently perceived as a water source for the municipal and environmental sectors. Subsequently, growers face increasing pressure to reduce water use. We believe that this will drive the adoption of improved and innovative water-management practices.

California growers seeking higher profits have been converting from low-value field crops to high-value permanent crops, especially almonds, pistachios and high-quality wine grapes. While the former were irrigated with conventional systems such as flood, furrow and border strip, much of the permanent crop acreage is now irrigated

Glossary

ETc: crop evapotranspiration

LVDT: linear variable differential transformer

MDS: maximum daily trunk shrinkage

RDI: regulated deficit irrigation

SWP: stem water potential

VDP: atmospheric vapor pressure deficit

Mario Salinas assesses tree water status manually with midday pressure-chamber readings. This method, while yielding state-of-the-art data, is labor intensive, must be conducted during a midday time window, and cannot be directly linked with irrigation controllers.

Linear variable differential transformers (LVDTs) continuously recorded the diameter of primary tree scaffolds. Maximum daily trunk shrinkage (MDS) data was used as a water-stress indicator to schedule regulated deficit irrigation (RDI).

with drip and microsprinkler systems. The traditional on-farm approaches for minimizing water losses associated with irrigation — deep percolation below the root zone and end-of-field runoff — involve both irrigation systems and irrigation scheduling. If properly designed, maintained and managed, water losses should be very low with drip and microsprinkler systems. Improved irrigation scheduling means better matching irrigation amounts to crop evapotranspiration (ETc). The development of the CIMIS (California Irrigation Management Information System) network of automated weather stations and the availability of other irrigation management information on the Internet has made developing accurate irrigation schedules much easier for California orchardists. As a result, opportunities for tree growers to save water in the traditional areas of reducing application waste and more closely matching net applied water to ETc are becoming more limited.

Tree water status indicates stress

It has long been recognized that the tree itself is the best indicator of its water status (energy level). Since water status directly controls many physiological processes, such as vegetative and reproductive growth, this information can be highly useful in irrigation scheduling. On the other hand, both ETc and soil water measurements are only indirectly related to tree water status. Research over the last 2 decades has shown that careful management of water deficits (referred to as stress) in trees can have beneficial effects on crop production, such as lower hydration with prunes (Lampinen et al. 1995), reduced hull rot in almonds (Teviotdale et al. 2001) and better peel quality in citrus (Goldhamer and Salinas 2000). This type of water management is now termed regulated deficit irrigation (RDI).

By definition, RDI reduces ETc below potential levels leading to water savings, ideally without a negative impact on orchard profits. Reducing ETc below potential levels has the added advantage of decreasing agricultural consumptive use, although water saved by reducing irrigation-system losses does not necessarily result in net water savings because of reuse. Plant-based stress indicators for use in RDI are superior to those that use ETc or soil-based measurements simply because they are more directly coupled to plant performance. What is needed is an accurate, convenient and inexpensive measurement of tree water status.

Shackel et al. (1997) demonstrated that midday stem water potential (SWP), a direct measure of tree water status, can be used for tree-based irrigation scheduling. However, measuring SWP is done manually with a pressure chamber, requiring trips to the field and significant labor if frequent readings are needed. Since SWP measurements must be taken during about a 2-hour period midday, the number of fields that can be monitored is limited. Operator error of the chamber can also introduce some uncertainty.

Goldhamer et al. (1999) showed that continuous recordings of trunk diameter with electronic sensors can be used to calculate maximum daily trunk shrinkage (MDS; fig. 1) and demonstrated that this indirect indicator of stress is well correlated with SWP in peach trees. In addition to being automated with consequent low labor requirements, electronic measurements can be directly incorporated into remotely operated electronic irrigation controllers. Recently, we proposed a set of protocols to schedule irrigation in orchards using trunk diameter measurements (Gold-

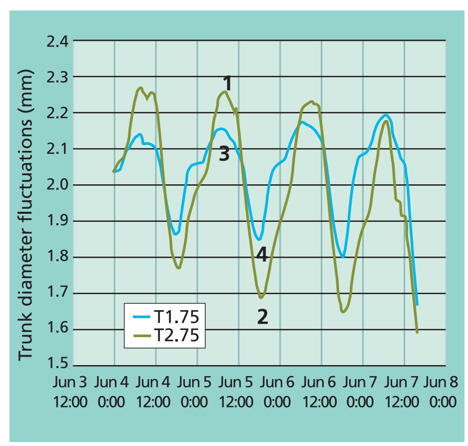


Fig. 1. Continuous recording of trunk-diameter fluctuations over a 4-day period for two sensor-based irrigation treatments. Values are means of four sensors, one each on four trees per treatment. Maximum daily trunk shrinkage (MDS) is calculated as the difference between maximum trunk diameter in early morning and minimum trunk size in late afternoon. For June 5, this would be the difference between 1 and 2 for T2.75, and 3 and 4 for T1.75.

An added benefit of the RDI regime is an accelerated rate of hull-split compared with the more fully regulated trees. This results in drier kernels at harvest and potentially allows for drying nuts on the tree rather than the orchard floor. Harvesting directly from the tree, as is done with pistachios, would eliminate problems associated with ground drying.

hamer and Fereres 2001a). This paper reports on an experiment conducted in a commercial almond orchard to test these protocols and compare MDS performance as a stress indicator with SWP.

San Joaquin Valley research. This work took place in a mature almond orchard in western Kern County. The trees (Fritz cultivar) were 6 years old and grown in a well-drained, clay loam soil with a root zone extending to about 6 feet. A buried-drip irrigation system was used with 18-inch-deep lateral lines located 5 feet on either side of the tree row (21-feet-by-24-feet spacing). This resulted in 20 1-gallon-per-hour emitters per tree and an application rate of 0.06 inches per hour. The system was operated two or three times per day. The orchard contained three blocks, each about 10 acres, and the irrigation for each block could be operated independently.

Weather effects. In addition to reflecting tree water status, both SWP and MDS are influenced by weather conditions. The hotter and drier the atmosphere, the greater the SWP and MDS value under conditions found in most irrigated orchards. Some reference or baseline number that reflects the water status response of a fully irrigated tree to weather conditions is required to interpret SWP and MDS measurements for irrigation scheduling. Both SWP and MDS of fully irrigated trees correlate well with atmospheric vapor pressure deficit (VPD; Shackel et al. 1997; Fereres and Goldhamer 2003). It is therefore possible to develop a baseline relationship between air VPD and the MDS or SWP values of fully irrigated trees. Armed with this information, one can calculate "signals" for MDS or SWP as the measured value divided by the baseline value calculated for the VPD at the time the measurement was taken. The MDS and SWP signals should reflect only tree water status; a signal of 1.0 indicates no irrigation-related stress while progressively higher signal values denote escalating stress levels.

Trunk diameter fluctuations

Our irrigation protocols require manually adjusting irrigation rates based on how the MDS signals change over time. We proposed that if the MDS signal does not reach a target value (referred to as a threshold) for 3 consecutive days, the irrigation rates are lowered by 10%. Similarly, if the MDS signal exceeds the threshold for 3 consecutive days, irrigation rates are raised by 10%. The MDS signals ideally oscillate around the target threshold values over the season.

We evaluated two MDS signal thresholds. The first had a value of 1.75, which we believed would result in mild stress that presumably would have little effect on production, while the second had a more severe stress threshold level of 2.75. Each of these treatments (T1.75 and T2.75) was established in respective irrigation blocks. Within each block, four trees were instrumented with linear variable differential transformers (LVDTs; Model 2.5 DF Solartron Metrology, Bagnor Regis, U.K.) installed on the southwest primary scaffold; these sensors measure minute changes in trunk diameter. The LVDTs were mounted on holders built

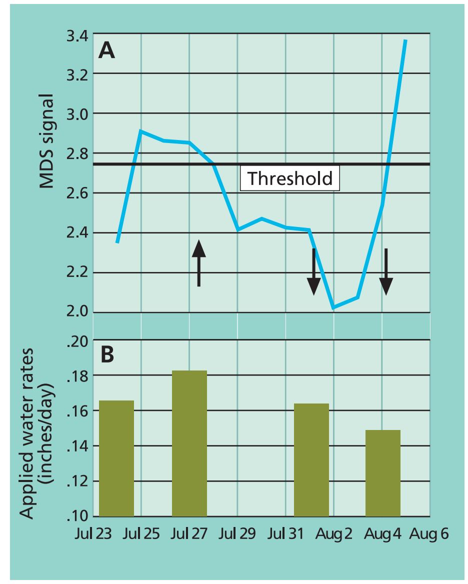


Fig. 2. Example of the interactive nature of irrigation schedule protocols where (A) MDS signals consistently above or below the target threshold triggered increases (up arrows) or decreases (down arrows) in (B) rates of applied water.

of aluminum and INVAR — an alloy comprised of 64% iron and 35% nickel that has minimal thermal expansion. The sensors were covered with silver foil to provide constant shade. Trunk diameter measurements were recorded every 30 seconds by a data logger that was programmed to report 20-minute means. These values were automatically downloaded daily to a desktop computer in our laboratory with a cellular phone and modem located at the field site. If the MDS signals indicated that a change in the irrigation rate was required, a phone call was made to the grower/cooperator. In-line water meters were used to measure water applied to the experimental trees.

We developed a relationship between MDS and mean daily VPD using MDS values from fully irrigated trees in the T1.75 block collected in April and May, prior to the onset of the irrigation treatments in early June. Mean daily vapor pressure and relative humidity were taken from a CIMIS automated weather station located 6 miles from the experimental site to calculate VPD. The linear regression between MDS and VPD during this period (MDS = 0.0744VPD + 0.0148; $R^2 = 0.77$) was used to determine the reference or baseline MDS value required in the MDS signal calculation for the two irrigation regimes.

SWP measurements. Midday shaded leaf water potential (1 p.m. to 2 p.m.) was monitored every weekday with a pressure chamber (Model 3005 Soil Moisture Equipment, Santa Barbara). Two single leaves close to the trunk on each of the four instrumented trees per treatment were covered with a moist cloth just prior to excision. We have previously shown that measurements taken in this manner are nearly identical to SWP (Goldhamer and Fereres 2001b). Similar to the relationship developed between MDS and VPD, we calculated the linear regression between the SWP of fully irrigated trees early in the season and atmospheric VPD at the 2 p.m. measurement time (SWP = –0.0554VPD – 0.448; R^2 = 0.76). The SWP signal was calculated by dividing the actual SWP measurement by the reference SWP value determined with this equation.

Harvest data. On Sept. 30, the four instrumented and monitored trees plus six trees of the same size randomly located within each block were mechanically shaken, and on Oct. 9 they were individually harvested to estimate yield. Ten trees in a third 10-acre block (the Ranch) adjacent to the two experimental blocks, which had been irrigated by the grower/cooperator based primarily on SWP, were also harvested. A 5-pound nut sample was collected from each tree. The percentage of nuts that had fully split hulls (more than 50% of the suture line separated) was determined. The kernels were separated from the shells and hulls to determine the kernel percentages on a fresh and oven-dry weight basis. Nut loads were determined by multiplying the fresh nut yields per tree by the percentage of kernels in the corresponding 5-pound sample. Prior to tree shaking, 50-nut samples were randomly collected from the four instrumented trees in T1.75 and T2.75 on Sept. 14, 19 and 27. Four Ranch trees were also sampled on these dates. These samples were composited and analyzed for hull-split and kernel hydration.

Interactive MDS scheduling. Figure 2 shows a representative example of how applied water was managed via the MDS signals and its impact on subsequent signals for T2.75 from late July to early August. Following 3 days where the MDS signal was above the 2.75 threshold (July 25 through July 27), applied water was increased by 10%. This resulted in the MDS signal decreasing to about 2.45 from July 29 through July 31, triggering a 10% decrease in the rate of applied water to 0.18 inch per day from 0.16 inch per day (fig. 2). This did not achieve the desired increase in MDS and the applied water rate was again decreased 10% on Aug. 4. This resulted in a sharp increase in the MDS signal to 3.36 by Aug. 5, well above the 2.75 signal threshold.

Prior to harvest, machines shake nuts to the ground where they dry for 7 to 10 days before being picked up. While on the ground, nuts are subject to ant damage as well as contamination by soil-borne pathogens.

Trunk vs. stem water signals

Observed MDS ranged from 0.1 to 0.9 millimeters (mm) depending on evaporative demand and treatment, but the T2.75 MDS was always greater than that of T1.75, except for a few days at the beginning and end of the study period (data not shown). The evolution of the MDS signal demonstrates that the signals of the two treatments went above their respective thresholds between 12 and 15 times during the period and every time, a 10% upward adjustment of the irrigation application rate was made (fig. 3A). This increase in applied water in T1.75 sometimes alleviated all stress, as evidenced by the MDS signal approaching a value of 1.0. In fact, the T1.75 signal dipped slightly below 1.0 for a few days in both mid-July and late August. We attribute this to the uncertainty that results from the scatter in the experimental points that we used in determining the baseline MDS equation.

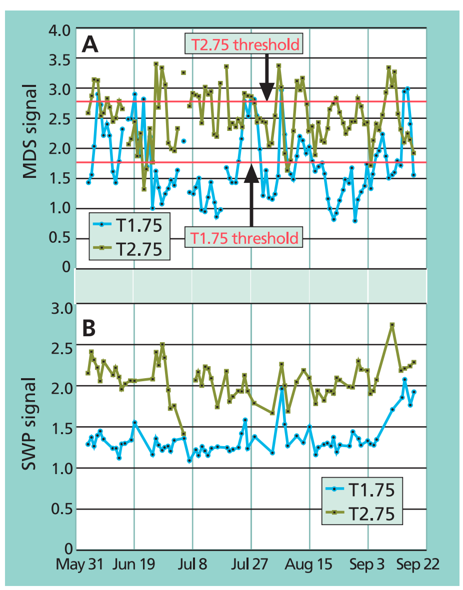


Fig. 3. Signal values over time for (A) maximum daily trunk shrinkage (MDS), and (B) stem water potential (SWP).

Measurements of SWP ranged from -0.7 to -1.4 megaPascal (MPa) in T1.75, varied between -1.3 and -1.5 MPa for T2.75 on most days, but reached -1.7 MPa just prior to tree shaking (data not shown). The SWP signal pattern with time (fig. 3B) is similar to the companion MDS signal pattern (fig. 3A) with two important differences. First, T1.75 and T2.75 oscillated around 1.2 and 2.0, respectively, much lower than the mean MDS signal oscillations. This is consistent with our previous finding that the MDS response to stress is more sensitive than the corresponding SWP response (Goldhamer et al. 1999). Second, there was much less variation in the SWP signal over time for both irrigation treatments as compared with MDS signal values.

The differences in variability around the mean values for the season can be quantified by calculating the coefficient

TABLE 1. Applied water, yield and yield component values

Irrigation regime	Applied water thru Sept. 18	Fresh gross nut yield	Fresh kernel yield	Fresh nut unit weight	Dry nut unit weight	Fresh kernel weight	Dry kernel weight	Harvest dry kernel/nut	Full hull-split nuts
	inches	*. . . . . . . lb/acre . . . . . .*		*. . . . . gm . . . .*				*% by weight*	*% harvested nuts*
T1.75	33.8	7,558	2,256	3.57b*	3.35b	1.12b	1.04b	31.1b	89.8b
T2.75	20.7	6,720	1,982	3.25a	2.99a	1.01a	0.92a	30.8b	95.2c
Ranch	35.4	7,719	2,176	3.70b	3.47b	1.08ab	1.02b	29.5a	82.2a
		NS†	NS						

* Numbers followed by different letters are significantly different using Fisher's least significant difference method ($P = 0.05$).

† NS = no statistically significant differences between irrigation regimes using Fisher's least significant difference method ($P = 0.05$).

of variation for the MDS and SWP signals from June 4 to Sept. 18. The mean coefficients of variation for T1.75 and T2.75 were 0.255 and 0.127 for the MDS and SWP signals, respectively, clearly showing less SWP variability. Again, this is primarily due to the more sensitive stress response of MDS compared with SWP. Nevertheless, the MDS signal deviations both above and below the target thresholds were greater than desired. Our protocols were designed to be interactive and triggered by the MDS signals. Scheduling adjustments were made manually, and the only management variable was a fixed 10% change in irrigation duration. We believe that a more detailed, mathematical analysis of how the MDS signals change over time should produce algorithms that would allow an electronic controller to better detect trends and react accordingly. This would likely involve changing irrigation timing and durations by a variable percentage. The development of this type of software should result in MDS signals that oscillate more closely around the target threshold.

We chose the term "signal" to refer to plant water-status indicators in irrigation management rather than "relative SWP" or "relative MDS," in order to teach this concept. We equate the analysis of the water-status indicators to how radio performance is quantified. With a radio, the waves are transmitted from a tower and picked up by the radio as a signal, and background interference is considered noise. Overall performance is indicated by the signal-to-noise ratio; the higher, the better. Sensitivity is defined as the ability of the radio to detect the waves (resolution).

In this analogy, the SWP and MDS measurements are transmitted from the tree. Dividing this data by reference values gives the signal strength, while the noise is the variability in tree-to-tree measurements, and sensitivity is defined as the ability of MDS and SWP to detect stress. As with the radio, the signal-to-noise ratio is the best indicator of how well the water-status indicator is performing. While the MDS signals are higher than those of SWP, MDS noise (tree-to-tree variability) is also higher. This is, in part, because the LVDT measurement is taken on a very small part of the trunk (about 1 square millimeter) where anatomical differences in the configuration of bark and phloem tissue can influence readings. On the other hand, SWP is taken from nontranspiring leaves, presumably giving a representative measure of the entire tree canopy. Nevertheless, the signal-to-noise ratio for almond trees has been shown to be higher for MDS (Goldhamer and Fereres 2001a). Increasing the number of sensors could reduce noise but also increase costs.

Water, crop quality and yield

Applied water. Applied water in T1.75 and T2.75 differed markedly over the entire experimental period (fig. 4). Maximum water application rates were 0.31 inches per day for T1.75 in early July and 0.19 inches per day for T2.75 in late July. Applied water rates in T1.75 were similar to ETc, with the exception of early in the experimental period and in late July. At the end of the experimental period (Sept. 18), a total of 33.8 inches and 20.7 inches of water was applied to T1.75 and T2.75, respectively, for a difference of 13.1 inches or 38.8% (table 1). Estimated cumulative ETc at this time was 40.9 inches.

Hull-splitting, kernel hydration. The water stress induced by the scheduling treatments hastened fruit maturation, as shown by the hull-splitting data generated by the 200-nut composite sample collected from the four trees in each irrigation regime. By Sept. 14, only 44.5% of the Ranch nut hulls had fully split as compared to 84.5% and 100% for T1.75 and T2.75, respectively (fig. 5A). The accelerated hull-splitting allowed the kernels to dry more rapidly in the irrigation treatments. This lowered the kernel hydration of T1.75 and T2.75 in the last half of September versus the Ranch (fig. 5B). Just prior to tree shaking, kernel hydration was 8.0% in T2.75 and 17.3% in T1.75, while it was 27.3% in the Ranch.

The accelerated hull-splitting in the irrigation treatments allowed more in-tree kernel drying as compared with the on-the-ground kernel drying required at the Ranch. This lessens the time required between shaking and nut pickup, reducing potential fire ant damage (Zalom and Bentley 1985). Besides ant damage, the windrowing of nuts on the ground and pickup operations create dust, which is considered a health risk. By allowing for more effective on-the-tree kernel drying, accelerated hull-splitting makes it more feasible to harvest nuts without first drying them on the orchard floor (as is done with pistachios). Additionally, on-the-tree drying eliminates potential food safety concerns associated with ground drying, including salmonella contamination caused by contact with manure fertilizers and aflatoxin resulting from fungal diseases. (The California almond industry is well aware of these potential health-related concerns and has taken action to prevent their occurrence.)

Yield. Mean nut loads in the 10 harvested trees varied by up to 11.9% for the two irrigation treatments and the Ranch (data not shown). Fruit load is determined by the stress history of trees rather than current-year irrigation treatments. We wanted to minimize the effects of fruit load in comparing the impact of this single season of stress on the size of fruit components (kernels, shells). We therefore chose five trees each in our irrigation treatments and the Ranch that gave us mean fruit loads varying by less than 1%. Individual fresh and dry nut (hull, shell and kernel) weights for T2.75 were 9.0% and 10.7% lower, respectively, than T1.75, which was not significantly different from the Ranch (table 1). Similarly, individual fresh and dry kernel weights of T2.75 were lower than T1.75 by 9.8% and 11.5%, respectively. Again, there were no significant differences between T1.75 and the Ranch. At harvest, T2.75 and T1.75 had significantly more fully hull-split nuts compared with the Ranch; 95.2%, 89.8% and 82.2%, respectively. Both irrigation treatments resulted in nuts with a significantly higher dry-kernel percentage than the Ranch (table 1). We previously observed lower kernel percentages in response to preharvest water stress (Teviotdale et al. 2001). We cannot explain at this time why the kernel percentage response to preharvest stress was different in these experiments.

Tree-based stress monitoring

In this study, we showed that an indirect measure of tree water status (MDS), which is highly correlated to the directly measured SWP (and, in turn, important physiological processes), and gleaned from trunk-diameter monitoring, could be used to schedule irrigations in a mature almond orchard. The MDS signal thresholds for the irrigation regimes were chosen to produce constant stress levels throughout the season, rather than to maximize yields. While significant water savings (40%) were achieved with T2.75, the impact of a single year's water deficits on almond production may not be indicative of the long-term response of the orchard. Previous research (Goldhamer and Smith 1995; Goldhamer and Viveros 2000; Esparza at al. 2001) showed that water stress at harvest or immediately after can reduce the subsequent season's fruit load, which was not the case with preharvest water deficits similar to those found in the current study.

Numerous RDI studies in a variety of tree crops where target stress levels are varied over the season have shown that seasonal ETc can be reduced without reducing fruit yield or quality (Goodwin and Jerie 1992; Caspari et al. 1994) and in some cases, actually improves yield components (Lampinen et al. 1995; Goldhamer and Salinas 2000). Indeed, Teviotdale et al. (2001) showed that mild water stress imposed about a month prior to almond harvest can significantly reduce almond hull rot, a fungal disease that can cause shoot dieback, but lamented the fact that monitoring tree stress with a pressure chamber was cumbersome for most growers. At that time, target values were based on predawn leaf-water-potential measurements, which have now been replaced by the more convenient SWP. We believe that MDS monitoring has the potential to be even more expedient. While this study used a scheduling protocol designed for high-frequency drip irrigation, we have developed similar protocols for lower frequency systems, such as micro-sprinklers, that are also based on signals and thresholds (Goldhamer and Fereres 2001a).

As water scarcity increases, irrigators will seek more advanced, sophisticated means of managing water, including new techniques that can be automated and adjusted to individual needs. Tree-based RDI triggers for irrigation scheduling, such as SWP and MDS, as opposed to soil and atmospheric measurements, have the major advantage of being directly linked to crop productivity and may also be tailored to specific orchard needs. The MDS signal is a more sensitive stress indicator than SWP and has numerous operational advantages, including lower labor costs and the capacity to be directly incorporated into remotely operated electronic controllers. Therefore, it may be a superior indicator for use where RDI and/or precise irrigation scheduling is needed. We envision an MDS-controlled irrigation regime where signal thresholds vary over the season to take advantage of the beneficial aspects of stress in almonds, such as the control of hull rot, accelerated fruit maturation and on-the-tree drying, in addition to water savings.

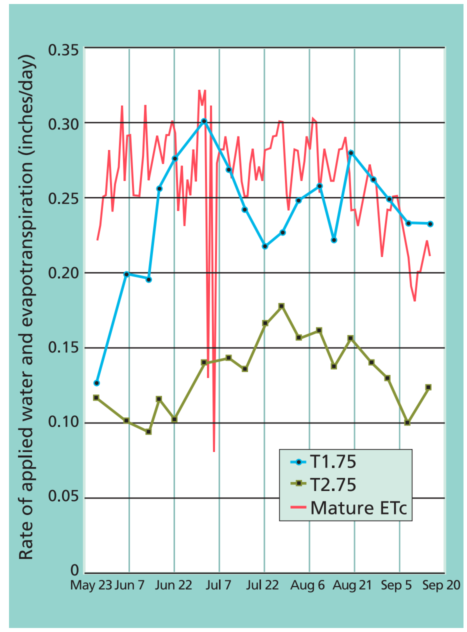


Fig. 4. Applied water rates for both irrigation treatments compared with mature orchard evapotranspiration (ETc).

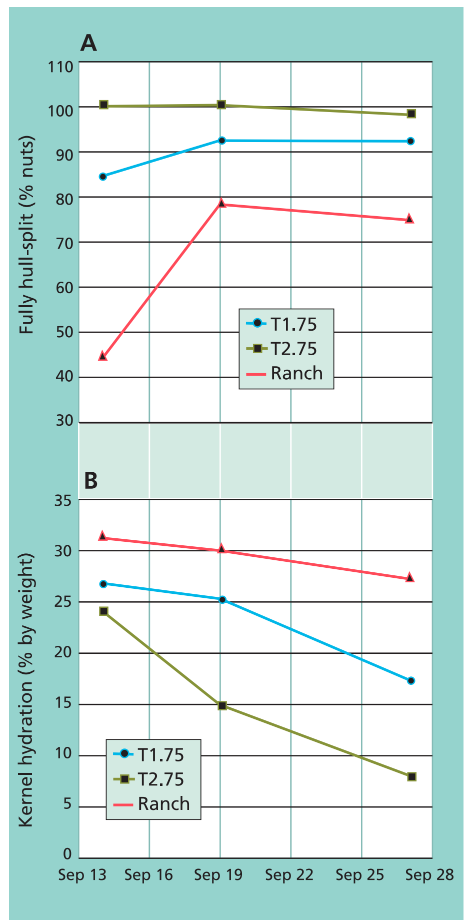


Fig. 5. (A) Hull-splitting and (B) kernel hydration during 2-week period prior to tree shaking for two sensor-based irrigation regimes and grower/cooperator's irrigation schedule (Ranch).

COMINGUP

IRRIGATION— continued from page 143

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Food security, nutrition and obesity

How can Californians be overweight and hungry at the same time? Paradoxically, obesity is reaching epidemic proportions among children and adults, yet many overweight people are often hungry or "food insecure" (lacking access to food at some time each month). In the next issue of *California Agriculture,* researchers examine the complex interrelationships among food security, nutrition and weight.

New studies of low-income Latino households in California found that more than 60% were food insecure, and demonstrated important associations between food security and overweight status in mothers and their children.

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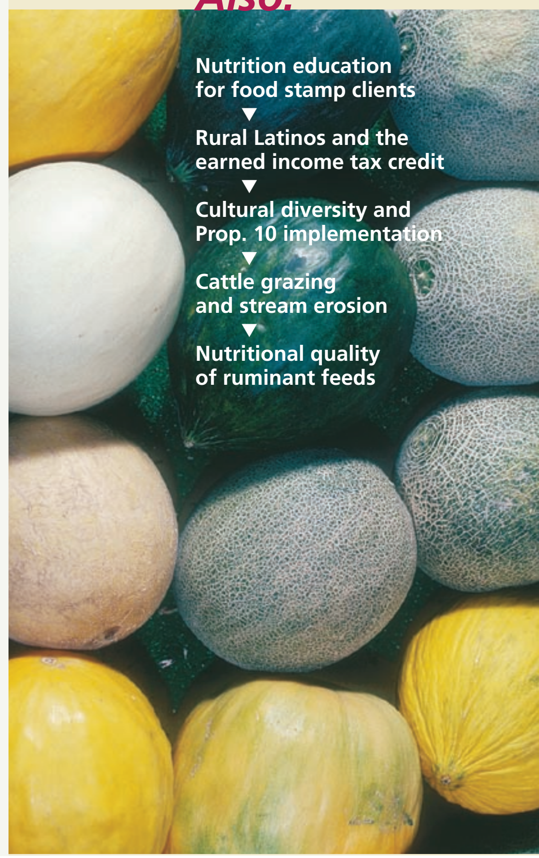

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