OCTOBER–DECEMBER 2013 • VOLUME 67 NUMBER 4

California Agriculture

Cultivating urban agriculture

Also:
Methyl bromide alternatives, part two

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

Urban agriculture is a gateway to healthy foods

Assembly Speaker John A. Pérez
(D-Los Angeles)

As we often boast, California is home to 81,000 farms and ranches that produce more than 400 different varieties of fruits, vegetables, nuts and other products, making "California grown" synonymous with the best-grown commodities in the nation. Farming occurs in some form in each of the state's 58 counties, but each day too many Californians go without access to fresh and healthy food. Many of these people, living in both rural and urban communities scattered around the state, suffer from poor health and diet-related illnesses and experience an overall lower quality of life because they do not have access to affordable healthy foods.

For more than 50 years, California has led the nation in agricultural production, yet nearly 1 million of our residents live in areas known as "food deserts." Found mostly in urban settings, these areas do not provide affordable, fresh and nutritious fruits, vegetables and dairy products. As a result, those living in food deserts suffer from higher rates of obesity, diabetes, heart disease and cancer, and they experience higher instances of premature death. These ailments and premature deaths can be reduced with access to healthy foods.

Research from the University of California shows that small-level farming in cities is not an unreasonable enterprise.

Many urban residents have taken the initiative to start growing their own vegetables. In the last 3 years, the number of community gardens in Los Angeles has risen by 30%. According to the U.S. Department of Agriculture, from 2011 to 2012 the number of farmers markets increased from 580 to 729 locations statewide, sparked by a desire from urban residents to have greater access to healthy produce.

Genevieve Hernandez

I have firsthand knowledge of the economic benefits that occur in communities that combat food deserts. I worked for nearly a decade to bring a full-service grocery store to the Downtown Los Angeles neighborhood I now represent. The community—which was previously considered a food desert—is now home to one of the most profitable stores in the entire chain. Bringing that grocery store to this neighborhood not only improved public health but also benefitted the local economy.

Every Californian has the right to healthy and affordable food. That's why I created the California Healthy Food Financing Initiative in 2011, which will work to increase access to healthy food items in underserved urban and rural communities. I furthered this action in 2012 with my legislation AB 2246, which helps facilitate financing to support projects that increase access to healthy foods.

Planting community gardens in vacant lots, growing vegetables in backyards and on rooftops, and increasing the number of farmers markets are just some of the activities that will improve the quality of life for residents in underserved urban areas. Research from the University of California shows that small-level farming in cities is not an unreasonable enterprise, and more people are realizing this. Working with UC Cooperative Extension, UCLA researchers identified almost 1,300 urban agriculture sites in Los Angeles County's 88 cities and unincorporated areas.

There are many creative ways Californians can help their neighborhoods—whether it's lobbying to site a grocery store with fresh produce near their homes, creating a mobile food bank to reach those in the community without transportation or establishing a community garden today so that people can eat healthy tomorrow.

Every Californian has the right to healthy and affordable food.

Urban agriculture has multiple benefits because when communities eat healthier, children can focus better in school, workers can be more productive and the people living in the area can lower their rates of obesity-related ailments, which in turn, decreases medical bills and helps families save money. By providing better access to healthy foods, communities plant the seeds for a better California.

Assembly Speaker John A. Pérez (D-Los Angeles) represents urban neighborhoods such as Boyle Heights, Downtown Los Angeles and Westlake.

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COVER: Urban agriculture is growing statewide, as California cities increasingly allow food plants in front yards and under power lines, and bee hives and chicken coops in backyards. To help city dwellers produce food proficiently and safely, UC Cooperative Extension is developing research-based best practices for urban agriculture (page 199). In addition, the California Animal Health and Food Safety laboratory system offers free post-mortems for backyard poultry through the Backyard Flock program (page 203). This diagnostic service enables researchers to collect data on disease trends and can help amateur poultry producers keep their flocks healthy. *Photo by Peter Bennett, greenstockphotos.com.*

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Now in print

This article was published online (July–September) on the *California Agriculture* website; it now appears in print after page 227.

E-Edition

This article can be found in full on the *California Agriculture* website; for a summary and link, see page 229.

About California Agriculture

University *of* **California**
Agriculture and Natural Resources

California Agriculture is a quarterly, peer-reviewed journal reporting research and reviews, published by the University of California Agriculture and Natural Resources (ANR). The first issue appeared in 1946, making *California Agriculture* one of the oldest, continuously published, land-grant university research journals in the country. There are about 15,000 print subscribers, and the electronic journal logs about 5 million page views annually.

Mission and audience. *California Agriculture* publishes refereed original research in a form accessible to a well-educated audience. In the last readership survey, 33% worked in agriculture, 31% were university faculty or research scientists, and 19% worked in government agencies or were elected office holders.

Electronic version of record. In July 2011, the electronic journal became the version of record; it includes printed and electronic-only articles. When citing or indexing articles, use the electronic publication date.

Indexing. The journal is indexed by AGRICOLA, Current Contents (Thomson ISI's Agriculture, Biology and Environmental Sciences and the SCIE databases), Commonwealth Agricultural Bureau (CAB), EBSCO (Academic Search Complete), Gale (Academic OneFile), Proquest and others, including open-access databases. It has high visibility on Google and Google Scholar searches. All peer-reviewed articles are posted to the ANR and California Digital Library eScholarship repositories.

Authors and reviewers. Authors are primarily but not exclusively from ANR; in 2010 and 2011, 23% were based at other UC campuses, or other universities and research institutions. In 2010 and 2011, 33% and 40% (respectively) of reviewers came from universities, research institutions or agencies outside ANR.

Rejection rate. The rejection rate has averaged 34% in the last 3 years. In addition, associate editors and staff may send back manuscripts for revision prior to peer review.

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

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

Submissions. *California Agriculture* manages the peer review of manuscripts online. Please read our Writing Guidelines before submitting an article; go to: http://californiaagriculture.ucanr.edu/submit.cfm.

Letters. The editorial staff welcomes your letters, comments and suggestions. Please write to us at the address below. Include your full name and address. Letters may be edited for space and clarity.

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WHAT DO YOU THINK?

The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at: 2801 Second Street, Davis, CA 95618-7774, or calag@ucdavis.edu. Include your full name and address. Letters may be edited for space and clarity.

California Agriculture *staffing changes*

Janet White has retired after 23 years as *California Agriculture*'s executive editor. When she arrived in 1991, the journal's submission reviews were photocopied and mailed by hand. Slides were pulled from plastic sleeves and scanned. There was no academic associate editor panel and no double-blind peer review. Journal issues had no news section; few carried a thematic focus, and none included interpretive glossaries, citations or references.


Michael S. Clark

Janet White

White oversaw the journal's transition to electronic peer review of research articles, and she augmented its electronic presence, including the full-text digitization of all articles back to 1946. She coordinated the journal website's redesign in 2009 in which e-journal content became searchable and discoverable. In addition, she pursued indexing on open access and proprietary databases — of value to faculty authors as well as readers and browsers worldwide. And she established systems of metrics that documented the journal's diversity of reviewers and authors, rejection rate and readership statistics.

"Janet brought the magazine to journal status, improving its format, scientific quality and utility; she ushered it into the high technology era, significantly increasing its accessibility and value as a resource. These were major, major accomplishments," said Carol Lovatt, associate editor in plant sciences and UC Riverside plant physiologist.

http://californiaagriculture.ucanr.edu

Today the journal's website includes linked references for every article and serves lay readers with a news section and links to related material. It offers wide dissemination, including to policymakers and decision makers, for faculty authors.

"Content drives readership, and faculty research drives content," White said. "We owe a debt to UC scientists, many of whom are committed to translating their findings and putting them in the hands of people who can apply them."

Under White's guidance, the journal won numerous awards from the Association of Communication Excellence (ACE) for such special editions such as Biotech: Risk and Benefit, Wine Grapes Go Green, Unequivocal – How Climate Change Will Transform California, and Food as Medicine. In 2013, White and her team received the ACE Gold Award for the editing of the article "Analysis reveals potential rangeland impacts if Williamson Act eliminated," which appeared in October 2012.

July-September 2011

"These awards recognize the combined skill and effort of an outstanding team," White said. "I've had the privilege to work with highly talented editors, writers, web developers, IT analysts and artists."

In recent years White began the digitization of *Hilgardia*, UC ANR's primary technical publication for 70 years, from 1925 to 1995. The associated fund-raising is approaching the $30,000 goal, and the digitization of all monographs is under way through Aptara, Inc.

"I am happy to be leaving at a time when *California Agriculture* is thriving. We have a flow of excellent submissions in the pipeline, and faculty have proposed and begun submitting articles for four special collections," she said. "Understanding new scientific findings gains importance daily — whether it be medical, environmental, agricultural or other science."

White plans to gain further training in information science, and search and discovery on the web.

Ann Senuta, UC ANR Communication Services and Information Technology publications manager and former managing editor of scientific publications at the California Academy of Sciences and of *California Farmer* magazine, is serving as interim executive editor of *California Agriculture* and managing recruitment for White's replacement.

In late May, **Debbie Thompson** became the new managing editor of *California Agriculture*. Previously, she worked as a production editor at Public Library of Science (PLOS), where she served as the lead copy editor and production editor for magazine-type articles across six different biomedical journals (*PLOS Medicine*, *PLOS Biology*, *PLOS Computational Biology*, *PLOS Genetics*, *PLOS Pathogens* and *PLOS Neglected Tropical Diseases*). She grew up in Pleasanton, Calif., and attended University of Washington in Seattle, and later Boston University for a master's degree in international relations.

Debbie Thompson

—*Editors*

Correction

On page 147 of the July–September 2013 issue, the name of the last author in the research article by Ajwa et al. was spelled incorrectly. The correct spelling is Ruijun Qin.

Immigration reform and California agriculture

Philip Martin
Professor, Department of Agricultural and Resource Economics
University of California, Davis

Over half of the workers employed on U.S. and California farms are unauthorized. Congress is debating reforms that would increase enforcement against illegal migration, allow unauthorized immigrants in the United States to become legal immigrants and create new guest worker programs. The status quo means uncertainty for farmers worried about labor shortages, uncertainty for workers fearful of removal from the United States and uncertainty for communities with large numbers of mixed families (unauthorized parents with U.S. citizen children). This article summarizes the data and assesses the implications of the major reform proposals for California agriculture.

Immigration reform

There were almost 42 million foreign-born U.S. residents in 2012, including almost 12 million (28%) who were not authorized to be in the United States. The number of immigrants born outside the United States continues to increase, but the number of unauthorized residents peaked at over 12 million in 2007 and fell to 11.4 million in 2010 before rising in 2012 (fig. 1).

The United States has been debating what to do about unauthorized immigrants for decades. In June 2013, the Senate approved the Border Security, Economic Opportunity, and Immigration Modernization Act (S 744) on a 68–32 vote, and President Obama endorsed S 744 as "largely consistent with the principles of common-sense reform I have proposed." However, the House of Representatives has refused to consider S 744, opting instead for a piecemeal or step-by-step approach to immigration reform. The House Judiciary Committee approved four bills in June 2013, two dealing with the enforcement of immigration laws and two with new guest worker programs.

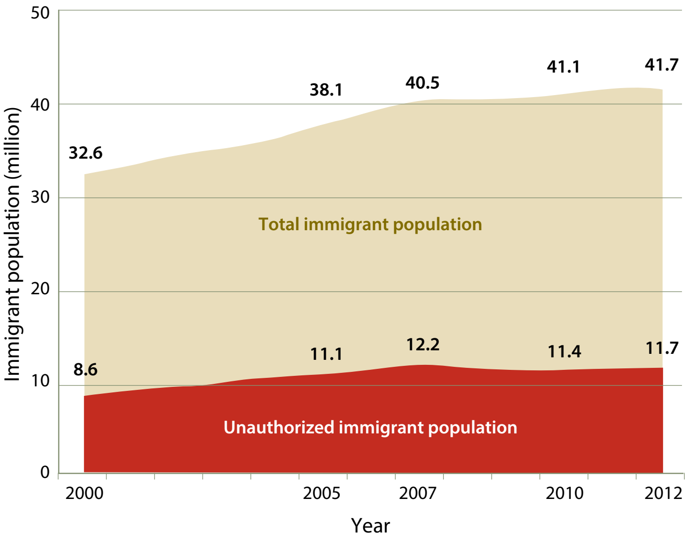

Fig. 1. Total and unauthorized immigrants, 2000–2012. Source: Pew Hispanic Center.

Senate: Enforcement and legalization

S 744 calls for more border and interior enforcement to deter illegal migration, legalization for most unauthorized immigrants in the United States and new guest programs to make it easier for employers to hire legal foreign workers temporarily. S 744 authorizes up to $46 billion in additional spending for a "border surge" to secure the 2,000-mile Mexico–United States border to prevent further illegal migration.

Currently, employers in some states and those with federal contracts must use E-Verify, the Internet-based system to which employers submit data on newly hired workers to determine if they are legally authorized to work in the United States. S 744 assumes that immigrants will be discouraged from coming to the United States if employers will not hire them, so it requires all employers to check new hires using the E-Verify system within 4 years. When hired, non–U.S. citizens would have to show employers a "biometric work authorization card" or immigrant visa that includes a photo stored in the E-Verify system, which makes it more difficult for unauthorized workers to borrow documents from legal workers.

After the Department of Homeland Security (DHS) submits a plan to secure the Mexico–United States border, unauthorized immigrants who were in the United States before December 31, 2011 could pay $500, any back taxes owed and application fees to obtain Registered Provisional Immigrant (RPI) status for 6 years, and this probationary status could be renewed after 6 years for another $500 fee. After a decade of RPI status, probationary immigrants could apply for normal legal immigrant status by showing they have worked (or were enrolled in school) and lived in the United States since registering. After 3 years as regular immigrants they could apply for U.S. citizenship.

Unauthorized farm workers would have a faster path to immigrant status under S 744. Those who performed at least 100 days or 575 hours of U.S. farm work in the 24 months ending December 31, 2012 could become RPIs with "blue cards" by paying an application fee and a $100 fine. Agricultural RPIs could become regular legal immigrants by doing at least 150 days of farm work a year for 3 years or 100 days of farm work a year in 5 years. The family members of RPIs could apply for immigrant visas when the farm worker does.

The United States now has three major guest worker programs. The H-1B program admits about 100,000 foreign workers a year with a college degree; about half of H-1B visa holders are Indians employed in information technology (IT) services. The H-2A program admits 60,000 foreign farm workers to fill seasonal farm jobs after the U.S. Department of Labor certifies farm employers as needing foreign workers; a sixth of these are in North Carolina. The H-2B program admits up to 66,000 foreign workers a year to fill seasonal nonfarm jobs in landscaping, resorts, hotels and reforestry; a sixth are in Texas.

Under S 744, the number of H-1B visas would double and there would be new guest worker programs for farm and nonfarm workers. There are several types of H-1B visas, and the number of the largest type would increase from the current 65,000 a year to 110,000, while the number for foreign workers who have earned advanced degrees from U.S. universities would increase from 20,000 to 25,000.

The current H-2A program for farm workers would be replaced by new W-3 and W-4 guest worker programs administered by the U.S. Department of Agriculture (USDA). The W-3 program would be like the current H-2A program and tie a foreign farm worker to a particular U.S. farm employer and job for up to 3 years. However, W-3 farm workers could work for another grower, known as a designated agricultural employer (DAE), after they completed their initial contracts if their visas allowed continued time in the United States. W-4 visa holders would need an initial job offer from a DAE to enter the United States, but could "float" from one DAE to another during the 3 years that their W-4 visas are valid.

The number of W-3 and W-4 visas would initially be capped at 112,333 a year, so that a maximum of 337,000 new guest workers could be in the United States at any one time. The minimum hourly wage for W-3 and W-4 crop workers would be $9.64 an hour across the United States in 2016, and this wage could be raised each year by 1.5% to 2.5%. S 744 requires farm employers to provide housing or a housing allowance of $1 to $2 an hour in most counties to both W-3 and W-4 visa holders, but not to U.S.-born farm workers.

A new W-2 visa program would admit more low-skilled nonfarm workers: up to 20,000 in the first year; 35,000 in the second year; 55,000 in the third year and 75,000 in the fourth year. No more than a third of W-2 visa holders could be employed in construction.

Where will U.S. employers get low-skilled W-visa workers? Mexico–United States migration has been declining, and more Mexicans returned to Mexico than were admitted in recent years. A century ago, many farm workers in western states were Chinese and Japanese. A combination of longer periods of U.S. employment permitted by S 744 and the opportunity for guest workers to bring family members with them to the United States may re-introduce more Asians to U.S. agriculture.

House: Enforcement and guest workers

The House Judiciary Committee approved four bills in June 2013 to increase enforcement against illegal migration and to modify guest worker programs for agriculture and IT. The Legal Workforce Act (HR 1772) would require all employers to use E-Verify to check the immigration status of employees within 2 years, sooner than the 4 years allowed by the Senate bill.

The Strengthen and Fortify Enforcement Act, or SAFE Act (HR 2278), would criminalize more activities by unauthorized immigrants to expedite their removal from the United States; increase the number of interior DHS immigration and customs enforcement agents by 5,000; and allow states and localities to enact and enforce immigration laws as long as penalties do not exceed federal penalties for the same offense. Unauthorized immigrants convicted of criminal gang membership, drunk driving, manslaughter, rape and failure to register as a sex offender could be removed more easily.

The Agricultural Guestworker Act, or AG Act (HR 1773), would replace the current H-2A program with a new H-2C program administered by USDA. Any farm employer, including dairy and food processing employers, could register with USDA to be designated as a registered agricultural employer (RAE) and petition to hire H-2C guest workers, including unauthorized workers currently in the country. However, H-2C visas would be issued only outside the United States, where workers would receive 18-month visas if they filled seasonal farm jobs and 36-month visas if they filled non-seasonal jobs. If their visas were still valid when the first job ended, H-2C workers could switch to another RAE, provided they were not unemployed in the United States more than 30 days. Employers would not have to pay the in-bound transportation expenses of H-2C workers or provide them with housing.

The status quo means uncertainty for farmers worried about labor shortages and uncertainty for workers fearful of removal from the United States.

H-2C workers would have to be out of the United States at least a sixth of the time they were in the country, that is, for at least 3 months after being in the United States 18 months. To encourage guest workers to depart, 10% of the wages paid to H-2C workers would be held in an escrow account and paid with interest if claimed by returned workers at a U.S. embassy or consulate in their home countries.

The Supplying Knowledge-based Immigrants and Lifting Levels of STEM Visas (SKILLS) Act (HR 2131) would shift the 55,000 diversity immigrant visas currently available to citizens of countries that send few immigrants to the United States and make them available to foreign workers who earn advanced degrees from U.S. universities in STEM fields (science, technology, engineering and mathematics). SKILLS would raise the number of regular H-1B visas from 65,000 a year to 155,000 and double the number of H-1B visas for foreign workers with advanced degrees from U.S. universities to 40,000.

Implications for California

About 98% of the crop workers on California farms, and 58% of crop workers on farms outside California, were born abroad. Table 1 shows that the share of foreign-born crop workers who are unauthorized, 68%, is similar in California and the rest of the United States; however, since 98% of California's crop workers are foreign-born, California has a higher-than-average share of unauthorized workers than most other states.

There are no reliable data on the number of hired farm workers. The average employment of hired workers or the number of year-round equivalent jobs in U.S. agriculture is 1.2 million, including 400,000 in California. However, agricultural employment is seasonal, and there are an estimated two workers for each year-round equivalent job, suggesting 2.4 million U.S. farm workers and 800,000 in California.

Table 1. Crop workers in California and the rest of the United States, 2007–2009

	California			U.S. excluding California		
	All	U.S.-born	Foreign-born	All	U.S.-born	Foreign-born
Share of workers (%)	33	2	98	67	42	58
Authorized (%)	33	100	32	61	100	32
Farm work						
Age first farm job (yrs)	23	18	23	23	22	23
Average years of farm work	12	17	12	13	14	94
Directly hired (%)	71	74	71	96	99	12
> 10 years current employer (%)	10	9	10	12	12	12
> 4 farm employers past year (%)	1		1	1		1
FVH crops (%)	93	74	93	72	56	83
Harvest and post-harvest jobs (%)	46	38	47	44	26	56
Wages						
Average hourly earnings ($)	8.98	10.90	8.93	9.20	9.71	8.85
Farm days worked, past year	191	210	191	196	179	208

FVH = fruits and nuts, vegetables and melons, and horticultural specialties.
Source: National Agricultural Workers Survey, U.S. Department of Labor.

According to the National Agricultural Workers Survey, foreign-born crop workers in California and the rest of the United States got their first farm jobs at age 23 and had done an average of 12 years of farm work when interviewed. About 71% of foreign-born workers were hired directly by growers in California, versus 94% in the rest of the United States. Very few crop workers in California and the rest of the country were with their current employer more than 10 years, and almost none had four or more employers in the past year.

Foreign-born workers are more likely to be working in so-called FVH crops than U.S.-born workers, that is, fruits and nuts, vegetables and melons, and horticultural specialties that include flowers and nursery products. Some 93% of California's foreign-born crop workers were employed in FVH crops, versus 74% of U.S.-born workers, a gap of 19%. In the rest of the United States, the gap was 27%. Foreign-born crop workers are more likely to fill harvest and post-harvest jobs than U.S.-born workers, and the gap was significantly larger outside California than in California.

California crop workers had lower average hourly earnings and fewer days of farm work in the past year than crop workers outside California. U.S.-born workers earned more than foreign-born workers, but the premium for U.S.-born workers was almost $2 an hour in California and less than $1 an hour in the rest of the United States. A full-time worker employed 5 days a week for 50 weeks has 250 days of work; the average crop worker had almost 200 days of farm work in the year before being interviewed.

If S 744 is enacted, most eligible unauthorized farm workers are expected to register and become legal workers; if the House bill is enacted, some unauthorized workers may be reluctant to leave the United States to receive legal re-entry visas as required. However, both the Senate and House bills are likely to give agriculture a more legal workforce comprised of perhaps a million currently unauthorized workers who register and become legal immigrants, and later an equivalent number of legal guest workers who replace them as they leave for nonfarm jobs. Both the Senate and House immigration reform proposals would allow guest workers to remain in the United States up to 36 months, which may encourage farm employers to seek workers farther afield (for example, in Asia).

Second, farm labor costs should be stable, since average hourly farm worker earnings are already above the minimum wage that must be paid to guest workers. Even if farm employers have to pay a housing allowance of up to $2 an hour to future guest workers, the $9.64 that must be paid to guest workers in 2016 plus a $2-an-hour housing allowance is less than the average hourly earnings of crop workers in California in 2012, $12.56 an hour.

Third, both the Senate and House bills should reduce uncertainty. However, the Senate bill may give growers in high-wage states such as California and Washington a competitive edge over those in lower-wage areas. Growers will be able to hire guest workers at $9.64 an hour, and wage increases would be limited to 2.5% a year, which should make it easier for California employers to plan investments and secure financing.

The agricultural provisions of the Senate bill were negotiated by farm worker advocates and farm employers, and both have said they will strongly resist efforts to change what they describe as a "delicately balanced compromise." The House guest worker bill, on the other hand, is supported by many farm employers, including the California Poultry Federation and the North American Meat Association, but opposed by farm worker advocates such as the United Farm Workers. The Senate bill may stall due to opposition to legalization, but the House bill is unlikely to be enacted unless there is a severe farm labor shortage that threatens widespread crop losses and consumer price increases.

The most likely outcome of the immigration reform debate is a continuation of the status quo. This "broken immigration system" is not the first preference of any major actor, but it is the second-best solution for growers who get their work done more cheaply with unauthorized workers and for most unauthorized workers who prefer to live with uncertainty in the United States rather than leave. Until the logjam in Congress is broken, there is unlikely to be comprehensive immigration reform, and without a severe farm labor shortage, there is unlikely to be action on farm-specific immigration reforms.

Further Reading

Martin P. 2013. Immigration and farm labor: policy options and consequences. Am J Agr Econ 95(2):470-75. http://ajae.oxfordjournals.org/content/95/2/470.full

Rural Migration News. Quarterly. http://migration.ucdavis.edu/rmn/

UC Cooperative Extension helps farming sprout in the city

As the sustainable food movement grows, farming is taking root in California cities from San Francisco to San Diego. Urbanites are asking for — and receiving — municipal approval to plant vegetable gardens in empty lots and under power lines, and to raise backyard chickens and bees. To help the state's urban agriculture thrive, UC Cooperative Extension (UCCE) researchers are working to boost resources and programs for city growers.

"People are passionate about keeping bees, growing their own food, and distributing it to the community," says Rachel Surls, who recently became the first Sustainable Food Systems advisor in UCCE Los Angeles County and is also a member of the Los Angeles Food Policy Council, which promotes local agriculture, sustainability and healthy food for underserved communities.

But passion isn't enough, and Surls soon learned that reliable information on city farming is lacking. "It became clear that while many people are enthusiastic, we don't know much about the needs of urban agriculture or even what it looks like," she says.

To help find out, she was the client for a UCLA study of urban agriculture in Los Angeles County (see sidebar on page 202). In addition, she assembled a team that was awarded a 2-year UC Agriculture and Natural Resources (ANR) grant to identify proven benefits of urban farming and to assess ANR's current urban agricultural services as well as needs for the future. The 15-member team includes experts in urban agriculture, small-scale farming, sustainable agriculture, integrated pest management and urban planning.

Urban agriculture is undergoing a revival in California, and research shows that community gardens increase consumption of fresh produce, provide nutrition education and build community.


Mike Poe

"Issues like food safety and pest management are important for small, urban growers just as they are for large, rural ones," Surls says. "Who better than UC ANR and UCCE to say, 'Here are the best practices'?"

Historical ups and downs

While today's upswing in urban agriculture is new to most of us, the United States has a long history of growing food in the city. Industrial cities in the Northeast used farming to build skills among unemployed workers in the 1890s; the federal government funded subsistence gardens during the Great Depression; and Victory Gardens helped people get enough to eat during the world wars. But as the post-World War II economy boomed, suburbs spread into farmland, and cities set new zoning codes to keep the two land uses separate.

Fast forward to today, and the boundary between cities and farming is beginning to blur again. The 2010s have seen a resurgence of legal urban agriculture in California, including farms and on-site sales of produce and eggs in San Francisco and Berkeley, chickens in Sacramento, and bees and miniature goats in San Diego. In addition, Los Angeles is poised to allow growing food plants in sidewalk strips.

Health and social benefits

These changes in municipal codes are driven by people who embrace green living under local, sustainable and slow food movements as well as by local governments seeking to tap urban agriculture's social benefits. Advocates tout city farming as a remedy for obesity, poverty and other woes. However, these complex issues have many causes. "There's a lot of hype about the health and social benefits," Surls says. "We wanted to see the data."

Her team reviewed studies of urban agriculture nationwide and found that, hype aside, there are plenty of well-documented direct benefits that make a strong case for cities to welcome and support farming within their limits. Community gardens boost consumption of fresh produce, can save participants hundreds of dollars per season in food costs, and, along with farmers markets, provide nutrition education that increases healthy cooking and eating.

Farming also builds community in cities. People gather at farmers markets, and come to consensus when planning and working in community

Claire Napawan

The attractive edible landscaping at the UC Davis Good Life Garden includes vegetables, herbs and flowers that are grown organically and sustainably. In addition, the university shares food and health information via educational signs in the garden.

gardens. In addition, urban agriculture brings young and old together, and many programs give skills, training and jobs to troubled youths. City farming has individual benefits too, instilling a sense of pride and ownership in participants.

Next, Surls and her team surveyed UC ANR staff statewide to see how they are currently serving the needs of urban agriculture. Answers include training UCCE Master Gardeners to give edible landscaping workshops, guiding community gardens and small urban growers and advising on urban chicken and beekeeping.

Edible landscaping

Lettuce, peppers and other food plants are popping up in urban spaces from gardens to balconies to roofs. "Every county has a UCCE Master Gardener hotline for questions and suggestions, and edible landscaping is a trending topic," says UCCE academic coordinator Missy Gable, who directs the UCCE Master Gardener Program, which provides research-based information on sustainable landscaping and disseminates it through the state's more than 5,400 Master Gardeners.

To meet the demand for edible landscaping, the Master Gardeners developed a new "train the trainer" program with a UC ANR grant. Offered at six sites around the state this spring and fall, the 2-day program has drawn hundreds of participants who then trained other Master Gardeners and held workshops for the public. "We want to increase food security by increasing food production in the home landscape," Gable says.

The training program covers the basics of growing edibles from beginning to end, including landscape design, planting, maintenance — such as irrigation, integrated pest management and crop rotation — and harvest. Another major focus is food safety. "You have to think about proximity to animals, which can carry disease," Gable says, "and make sure not to prune your crops with the same shears used on plants treated with chemicals that are not food safe." In addition, the program addresses policies that affect edible landscaping, such as whether corn is allowed in the front yard as well as the restrictions on water use in urban landscapes under California Assembly Bill 1881. Also in the works is an edible landscaping handbook that will be available online.

Backyard hen houses

Chickens are also on the rise in cities, but their fast-growing popularity has raised concerns for their health. "Urban chicken owners generally aren't trained to recognize signs of illness; there are few if any chicken vets in the city, and online forums are not moderated by experts," says Sarah Stinson, a researcher at the California Animal Health and Food Safety Lab at UC Davis. To help keep home flocks healthy, the lab offers a free diagnostic service that tells people why their chickens died. Then hen keepers can give the diagnosis to a veterinarian, who can treat the rest of the flock.

Funded by the California Department of Food and Agriculture as a biosecurity measure, this service also gives insight into chicken-keeping trends. Numbers on backyard hens are hard to come by because people

Mike Poe

Backyard flocks are a better fit in the city when they do not include roosters, which can crow loudly day and night, and when chickens are kept in the coop until neighbors wake up. Likewise, sharing eggs can earn goodwill.

Mike Poe

Backyard chickens should be kept in coops that protect them from cats and other urban predators. They also should be fed specially formulated chicken feed, not chicken scratch or scraps.

who keep them illegally don't report problems and, while urban hens are increasingly legal in California, most people skip registering their flocks. But two indicators suggest a huge jump in urban chickens. "The popularity of online chicken forums has exploded, and we've had a significant increase in chicken submissions over the last 5 years — from about 170 in 2007 to more than 800 in 2012," says Stinson, who keeps hens herself.

Besides keeping their flocks disease-free, people should keep hens in coops that protect them from cats and other urban predators, and give them specially formulated chicken feed from feed stores rather than chicken scratch or scraps. And even where chickens are legal, it's a good idea to talk to the neighbors before setting up a coop. Ways to earn goodwill include keeping hens in the coop until neighbors are awake, sharing eggs and, most of all, forgoing roosters, which can crow loudly day and night, and are illegal in some municipalities.

Bees and the city

Today's interest in urban beekeeping is linked partly to the decline of honey bees. While once common, most feral honey bees were knocked out by the *Varroa destructor* mite that was introduced in 1987. Now, however, their numbers are growing again, partly due to urban beekeeping. "It's a good thing for bees and for pollination," says Eric Mussen, a UCCE apiculturist at UC Davis. Another benefit of city bees is that people who keep them may be more careful about using pesticides in their gardens.

While bees can be a hard sell in cities, they mix well with people as long as you take their behavior into account. "You want to let bees do their own thing but you should never vex your neighbors," Mussen says. As with chickens, it's important to talk to neighbors before keeping bees, particularly because some people have life-threatening allergic reactions to bee stings.

Ways to accommodate bees and people in close quarters include installing fences or tall hedges near hives, which redirects the bees' flight path overhead instead of across sidewalks and streets. While many California cities still prohibit or restrict hives, Mussen points out that honey bees and people get along in some of the nation's biggest cities. New York City allows urban hives, for example, and Washington, D.C., began allowing them when Michelle Obama wanted to keep bees at the White House to pollinate her vegetable garden.

To keep up with and anticipate needs as urban agriculture grows in California, Surls and her team are currently interviewing urban growers and planners. "We're asking what they wished they had known so we can identify gaps in services and develop resources to fill them," she says. Ultimately, her team envisions a comprehensive online portal to provide science-based information on urban agriculture. Says Surls, "When it comes from UC, it's a trusted resource."

—*Robin Meadows*

Honey bees can be a good fit even in a dense city when their flight paths are redirected away from sidewalks and streets, and when no one nearby is allergic to bee stings. Urban hives may also help stem the honey bee decline.

Kathy Keatley Garvey

A snapshot of urban agriculture in Los Angeles

The state of urban agriculture — from who's doing what and where, to what they need to do it well — recently became clearer in Los Angeles, thanks to a 6-month capstone project by a team of UCLA graduate students in urban planning. The project captured the range of city farming throughout the county, and included identifying and mapping nearly 1,300 urban agriculture sites, documenting the agriculture-related regulations in the county's 88 cities, and giving recommendations on how to support farming in cities.


Genevieve Hernandez

Researchers verified and mapped 118 community gardens, 761 school gardens, 211 nurseries and 171 farms in Los Angeles County.

Collectively, people in LA cities grow food plants in school and community gardens as well as in yards and under power lines, and keep rooftop beehives and backyard chickens. But what's allowed varies tremendously from city to city. To streamline the current maze of confusing and contradictory regulations, the researchers called for making health and zoning codes clearer and more consistent. "Model ordinances, which are a common urban planning tool, could be developed to make it easier for cities," says Stephanie Pincetl, director of the California Center for Sustainable Communities at UCLA, who was an advisor on the project.

Another barrier to urban agriculture is lack of knowledge. "Many people are so disconnected from agriculture that they don't know a thing about growing food," Pincetl says. "They don't know about soil types or vulnerability to disease and drought." To help them learn, the researchers recommended creating an online database of agricultural resources and best practices geared toward urban gardeners and growers.

In addition, city growers face challenges that their rural counterparts don't have to contend with. "There are enormous obstacles like expensive water, and soil and air pollution," Pincetl says. Soil can be contaminated by lead paint and industrial chemicals, while car exhaust and copper from brake linings may contaminate lettuce and other food plants in sidewalk strips. "There's a lot of room to grow food in the city — there are thousands of miles of street — but you have to be judicious," she says, adding that sidewalk strips may be better suited to citrus trees, which are tidy and produce fruit that is protected by a peel.

Another consideration is that while urban agriculture can build community, Pincetl points out that it can also create conflict. "People disagree about using pesticides in community gardens, and there can be tension if someone doesn't weed," she says.

The researchers' findings are presented in the June 2013 report *Cultivate L.A: An Assessment of Urban Agriculture in Los Angeles County* (http://cultivatelosangeles.org/). "This is a great resource for developing programs," says Rachel Surls, the Sustainable Food Systems Advisor at UCCE Los Angeles who was the project client. "Our role is guidance and this will help UCCE provide science-based information to inform the issues."

—*Robin Meadows*


Zachary Zabel

Regulations for backyard flocks vary widely among municipalities, and could be streamlined with a model code that includes best practices for keeping fowl.


Judi Gerber

Los Angeles County allows farming in the rights-of-way under power transmission lines, a rare source of land in cities.

Popular Backyard Flock program reduces biosecurity risks of amateur production

by Sarah Stinson *and* Aslı Mete

The California Animal Health and Food Safety laboratories provide free necropsy (postmortem examination) services to owners of backyard poultry through the Backyard Flock program funded by the California Department of Food and Agriculture. We collected and analyzed data on the number of poultry submissions to the program between 2007 and 2012, the lab totals by location and the diseases diagnosed. During those 6 years, submissions increased 383%, with chickens representing 91% of them, and the greatest increases occurred in Santa Clara, Los Angeles and Sonoma counties. The necropsy data showed that the digestive (32.5%) and hemolymphatic (16.9%) systems were the most commonly affected. Marek's disease accounted for 13.3% of diagnoses (492 cases). With the rapid rise in the number of poultry being raised by amateur producers, biosecurity education is essential.


Sarah Stinson

The Backyard Flock program encourages backyard poultry owners to submit dead birds for postmortem examination. The program monitors for diseases that could devastate California's commercial poultry industry.

The popularity of backyard flocks has steadily increased over the past several years (Crespo and Shivaprasad 2008; Pollock et al. 2012). Sunset magazine listed backyard chickens as one of the "Top 100 Cultural Trends Shaping the West" in 2011 (Sunset 2011), and the number of websites, blogs and magazines devoted to urban chickens has increased exponentially. Membership of BackyardChickens.com, a popular website and discussion forum, grew from 1,000 in 2007 to over 115,000 by January 2011, with more than 7 million posts by site users (Ludlow 2012). Another popular site, MyPetChicken.com, boasts of receiving tens of millions of page views per year (Torres 2012).

These websites provide a community forum for advice on everything from breed selection to coop construction and veterinary care. They also provide information on how to lobby for changes to local ordinances to allow the keeping of backyard poultry in urban areas (Palermo 2010). Such public lobbying has resulted in widespread changes to many ordinances, including, for example, in Sacramento County, where the grassroots organization CLUCK, the Campaign to Legalize Urban Chicken Keeping, has pushed the issue to the forefront of local politics (Cary 2009). A Sacramento city ordinance was amended in 2011 to allow the legal ownership of up to three hens (Sacramento City Code § 9.44.860) in urban neighborhoods.

The rapid rise in the number of poultry being raised by amateur producers with no education on biosecurity (the protection of agricultural animals from infectious agents) is creating an increased risk of the transmission of infectious diseases, both to other backyard flocks and ultimately to commercial flocks as well. The Backyard Flock program offered through the California Animal Health and Food Safety (CAHFS) laboratory system provides owners of backyard flocks with valuable diagnoses and disease information at no charge. This information improves flock management and biosecurity and is also invaluable for tracking disease trends and statistics within a population from which it is difficult to collect data.

Federal, state, local regulation

The U.S. Department of Agriculture (USDA) regulates aspects of the noncommercial industry related to disease prevention under the Poultry Products Inspection Act (21 U.S.C. § 451 et seq.) and the Egg Products Inspection Act (21 U.S.C. § 1031 et seq.). The California Department of Food and Agriculture (CDFA) regulates poultry in California in much the same way. Under specific circumstances in which a foreign animal disease is suspected, the CDFA (in conjunction with the USDA) has the authority to quarantine and, if necessary, to destroy potentially infected animals (CDFA 2006). This authority is reserved for serious threats to biosecurity and consumer safety, such

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v067n04p203&fulltext=yes

doi: 10.3733/ca.v067n04p203

as the recent outbreaks of highly pathogenic avian influenza (HPAI) and exotic Newcastle disease (END), and extends to all poultry within the state.

Other federal and state laws that regulate poultry and egg production are applicable only to large producers. Zoning, and every other aspect pertaining to backyard flocks, is left to the discretion of city and county regulators. Permitting; neighbor consent; personal use versus production; minimum lot size and setback requirements; and coop design, materials, maintenance and placement are elements often included in local regulation, though regulations vary by city (Salkin 2011).

Very little data exists on backyard flock size, health or distribution. Regulations that would monitor and regulate flocks for infectious and zoonotic (communicable from animals to humans) diseases such as avian influenza and *Salmonella* have met with a significant lack of compliance, as have the city of Sacramento's attempts to mandate the licensing of chickens, with similar requirements to those already in place for dog and cat owners (Sacramento City Code § 9.44.880). Since 2011, when the city legalized backyard flocks, only about 12 flocks have been registered (Arrington 2012). The true number of flocks within city limits is undoubtedly much higher, as just one online community group, Sacramento Backyard Poultry Group, boasts 222 members (Frawley 2013). This lack of data is combined with a lack of education of owners on appropriate biosafety and a lack of resources for flock health (poultry veterinarians), which together create an increased potential for disease transmission to commercial poultry facilities. If poultry health is affected on a large scale, it could cost the state and producers millions of dollars.

Past health surveys

A 1990 survey of backyard flocks in close proximity to commercial poultry facilities in California revealed seropositivity for several highly transmissible diseases, including *Mycoplasma* species, *Salmonella pullorum*, Newcastle disease virus, avian encephalomyelitis virus, *Bordetella avium*, hemorrhagic enteritis virus, infectious bronchitis virus and also infectious bursal disease virus, which can cause significant disease and decreased productivity in commercial birds. Only a small percentage of surveyed owners used pharmaceuticals or biologics for disease prevention (McBride et al. 1991).

In 2004, the USDA conducted a national survey of the poultry industry, called the National Animal Health Monitoring System (NAHMS) Poultry '04 survey. It was designed as "a thorough assessment to determine the information needs of the poultry industry, researchers, and Federal and State Governments" and clearly illustrated a need for information regarding bird health, bird movement and biosecurity practices of nontraditional poultry industries, such as backyard flocks, game fowl and live poultry markets (Garber et al. 2007). According to the survey, only 2.9% of backyard flock owners used veterinary services, and the highest percentage (24.4%) used medication obtained from local feed stores. With such low use of veterinary services, there was a demonstrable lack of information being distributed on backyard flock management practices, including important information on flock health and disease risks.

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According to a 2004 survey, only 2.9% of backyard flock owners used veterinary services.

Mike Poe

Between 2007 and 2012, submissions to the California Animal Health and Food Safety (CAHFS) laboratories increased 383%, with chickens representing 91% of all Backyard Flock submissions. Analysis of Backyard Flock diagnoses showed that digestive and hemolymphatic systems were the most commonly affected.

Backyard Flock program

On July 19, 1988, the CAHFS laboratory system initiated a Backyard Flock program to encourage owners of backyard poultry flocks to submit birds for necropsy (postmortem) examination. The program was established to continue the state's surveillance program, previously offered by CDFA's Veterinary Services, to monitor and detect the immediate threat of HPAI and END. Should the need arise, the program's data will help state officials identify and contain an outbreak from the start and prevent statewide devastation of backyard and commercial flocks.

Branches of the CAHFS laboratory in Davis, Turlock, Tulare and San Bernardino conduct the necropsy service, which is available to owners of fewer than 1,000 birds (chickens, turkeys, game birds and waterfowl). Standard diagnostic work for one or two birds is performed at no charge to the owner; the cost is covered by CDFA. The information obtained from the necropsies is invaluable for monitoring the disease distribution in and statistical data of a relatively unregulated population. In our research project, we conducted a retrospective analysis of the data to define and assess the scale of the Backyard Flock program and its locations, and summarized the diagnostic findings.

Data review

Data from avian necropsy cases submitted from backyard flocks (any flock of < 1,000 birds) in the CAHFS laboratory computer database (STARLIMS 10.5.67) were compiled and analyzed. When an animal is submitted for a necropsy examination, a submission form is filled out by either the flock owner or veterinarian. It is then assigned a unique number in the computer system. The form captures information such as flock size, history and location. Submissions that qualify for the Backyard Flock program are categorized separately, and we extracted our data from those submissions for the period between Jan. 1, 2007, and Dec. 31, 2012, including all CAHFS laboratory locations. SQL (Structured Query Language) and Crystal reports were used to extract data based on the following parameters:

1. Total number of Backyard Flock submissions processed by all laboratories from Jan. 1, 2007, to Dec. 31, 2012.
2. Total number of avian submissions processed during this time period that were not covered by the program (pet birds, birds from large commercial producers, racing pigeons, etc.).
3. Number of Backyard Flock submissions received from each county per year from 2007 to 2012.
4. Species type submitted.
5. Cases given a structured diagnosis (SD), which indicates the primary necropsy finding by the examining pathologist. These cases were categorized according to the affected organ system, and etiologies were recorded when available. The traumatic and nutritional/toxicosis groups of conditions were regarded as separate categories and not included in the organ system grouping, since in these cases there were multiple organ systems affected and they were mostly not reported.

Statistical analysis of the data was performed using a chi-square test (Rosner 2000).

Disease findings

Over the 6-year period, CAHFS received 19,539 avian submissions, 2,775 of which were Backyard Flock submissions, a significantly large percentage of all avian submissions, with a *P* value of < 0.0000001, increasing significantly from 3.6% (*n* = 173) in 2007 to 30.9% (*n* = 835) in 2012 (fig. 1). Chickens represented 91% (*n* = 2,532) of all Backyard Flock submissions during this time period. A 43% decrease in overall avian submissions was also observed within this period (fig. 1). The distribution of submissions by county is shown in figure 2; Santa Clara, Los Angeles and Sonoma counties had the largest increases.

A total of 3,708 SDs were entered for Backyard Flock cases (some cases had multiple SDs in situations where more than one disease was present or more than one individual carcass was submitted under one submission number). Analysis of those cases according to affected organ systems showed digestive (32.5%) and hemolymphatic (16.9%) systems being the most commonly affected (fig. 3). Marek's disease, which was included in the hemolymphatic system, accounted for 492 cases, 13.3% of the total. The number of cases entered as unexplained death was 72 (1.9%). The observed disease conditions reported as SDs in correlation to affected organ system and etiologies when available were as follows: Digestive system diseases (*n* = 1,204) were bacterial infections (clostridial, mycobacteriosis, salmonellosis, staphylococcosis), parasitic infections (coccidiosis, nematodiasis, trichomoniasis, cestodiasis), neoplasia, fatty liver syndrome, intestinal volvulus and intussusception, and foreign body ingestion and obstruction. Hemolymphatic system diseases (*n* = 628) were lymphoproliferative diseases, infectious bursal disease and bursal cryptosporidiosis. Cardiovascular system diseases (*n* = 82) were ascites syndrome, vitamin E deficiency, *Streptococcus* species and *Escherichia coli* infections, and

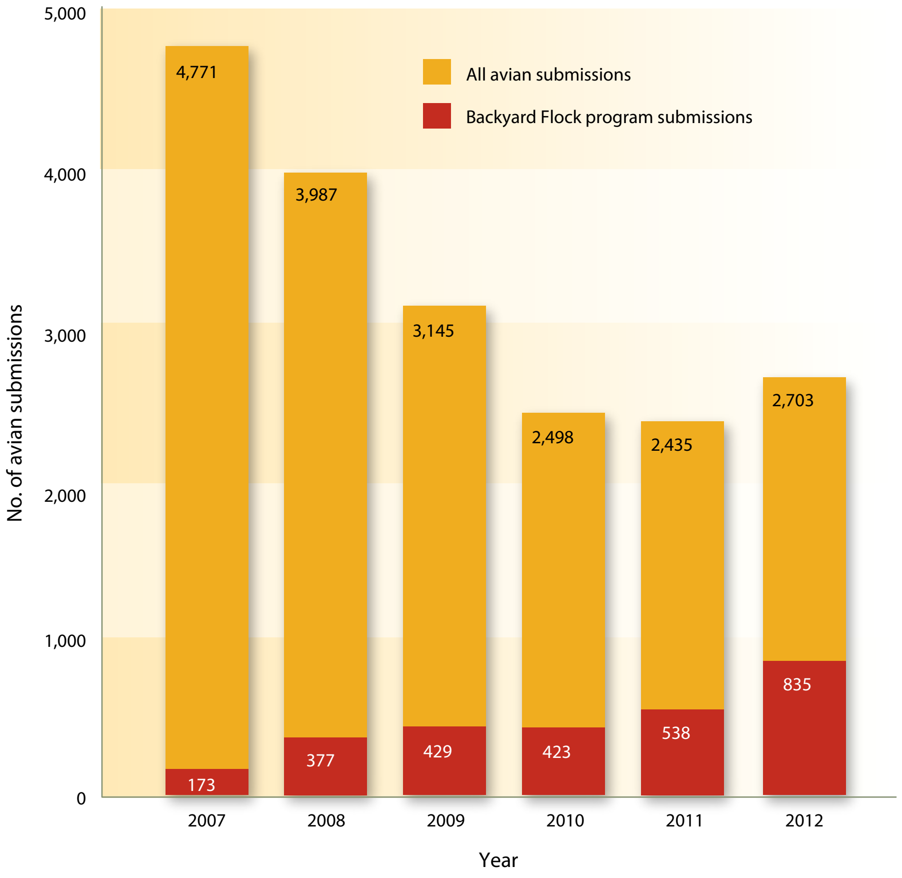


Fig. 1. Number of total avian and Backyard Flock submissions for necropsy examinations, 2007–2012.

congenital malformations. Respiratory system diseases (*n* = 512) were aspiration pneumonia, rhinitis, sinusitis, airsacculitis, tracheitis, chronic respiratory disease, and pneumonia due to aspergillosis, *Mycoplasma* species, *Avibacterium paragallinarum*, *Avibacterium gallinarum*, *E. coli*, *Klebsiella* species, infectious bronchitis virus, inclusion body tracheitis, and infectious laryngotracheitis infections. Integumentary system diseases (*n* = 128) were cutaneous pox virus, ectoparasitism by lice and mites, and a few bacterial dermatitis or cellulitis cases. Musculoskeletal system diseases (*n* = 69) included arthritis, discospondylothesis, bone deformity, foot injury, myopathy, muscle necrosis (one reported cause was vitamin E deficiency), muscle neoplasm, rickets, and bone and musculoskeletal diseases where the most commonly isolated infectious agents were *Staphylococcus* species, *Clostridium* species and *Pasteurella multocida*. Nervous system diseases (*n* = 58) were caused by parasite migration (presumptive *Baylisascaris* species), listeriosis, aspergillosis, West Nile virus, bornavirus, peripheral neuropathy and congenital malformation. Urinary/renal system diseases (*n* = 60) included infectious bronchitis virus, bacterial and fungal infections, neoplasia and renal gout. Reproductive tract diseases (*n* = 521) were omphalitis, salpingitis, peritonitis/coelomitis mostly caused by *E. coli* and *Gallibacterium anatis* biovar haemolyticum, internal layer, egg bound, oviduct

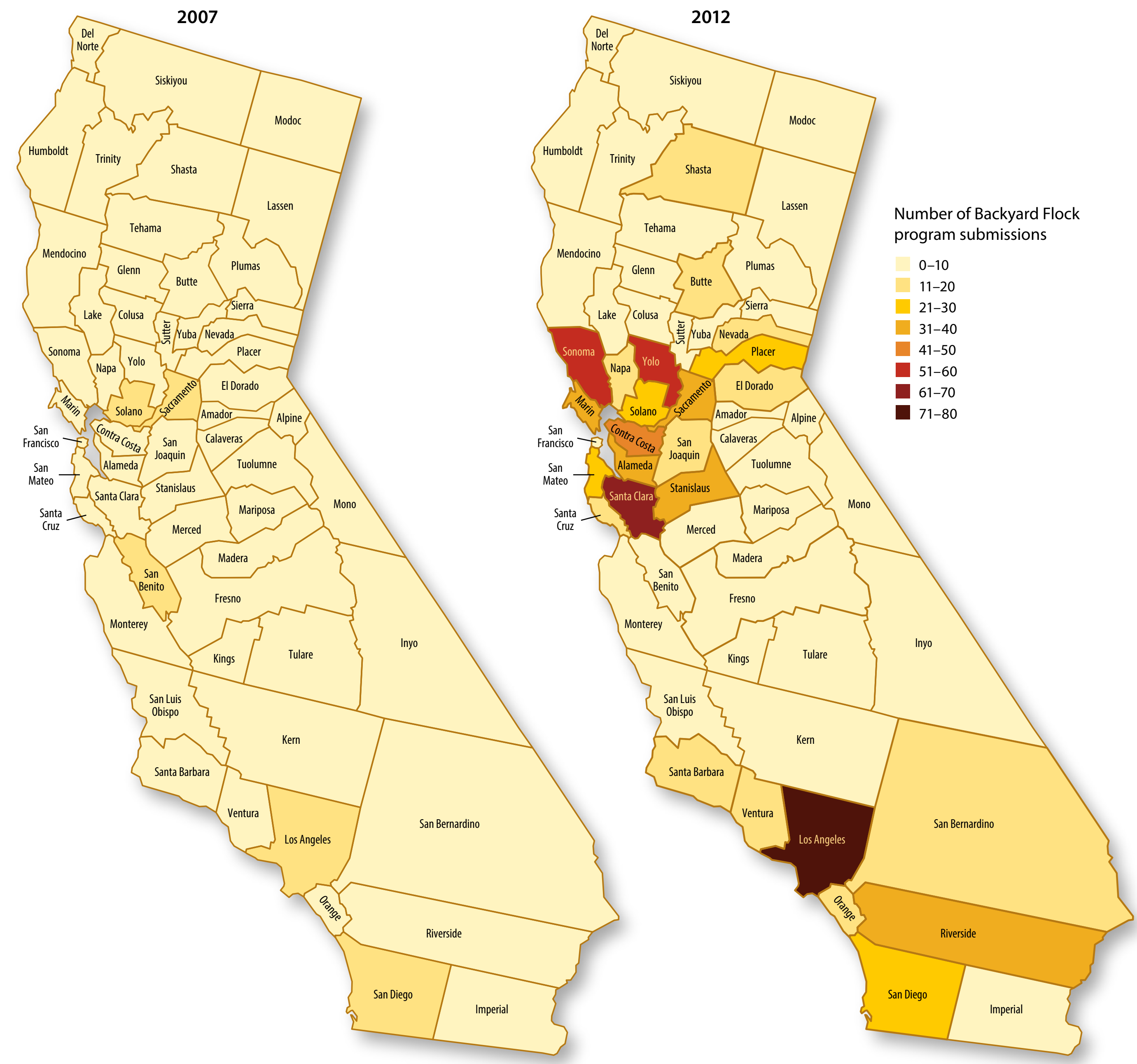


Fig. 2. Number of poultry submissions to the Backyard Flock necropsy program, by county in 2007 and 2012.

prolapse, yolk sac disorders and neoplasia. Sensory (eye and ear) diseases ($n = 23$) were mostly due to bacterial infections. Endocrine system diseases and neoplasia ($n = 4$) and systemic diseases ($n = 214$) were primarily caused by the aforementioned etiologic bacterial, fungal or viral agents. Apart from starvation, emaciation, malnutrition, dehydration and obesity, the nutritional/toxicosis diseases ($n = 97$) were primarily toxicoses and comprised of botulism, anticoagulants, malathion, organophosphate, lead, copper, selenium, strychnine, vitamin A and zinc; riboflavin, vitamin A, vitamin E, zinc and selenium deficiencies also caused disease in 51.5% of nutritional conditions. Trauma-associated disease or death was primarily due to predation ($n = 36$).

Program use, needs

The increased popularity of keeping backyard chickens and the increased awareness of the free Backyard Flock program resulted in a 383% increase in necropsy submissions to the CAHFS laboratories over the 6 years. The 43% decline in the overall number of avian submissions from its peak in 2007 to 2012 demonstrates that the increase in Backyard Flock

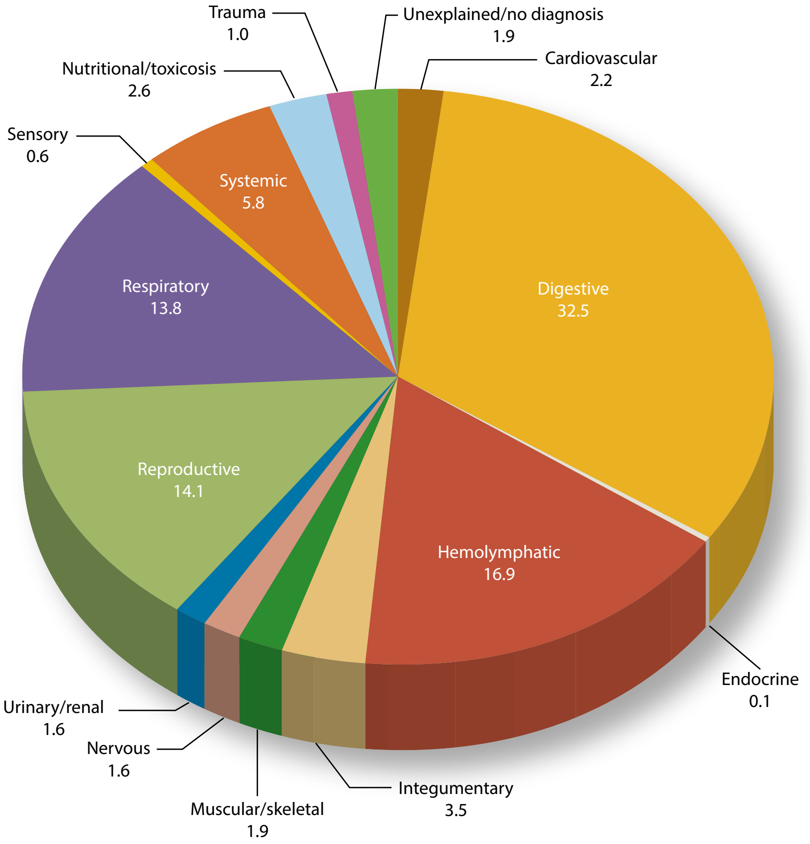


Fig. 3. Structured diagnoses of diseases from Backyard Flock necropsy examinations, 2007–2012, by category.

Health programs, resources

CDFA has several avian health programs in place to assist the poultry industry in maintaining biosecurity and breeding standards, although many of them are focused on commercial poultry production, not backyard flocks. The National Poultry Improvement Plan (NPIP) is one such program; it helps to establish breeding standards and standards for hatcheries to prevent egg-transmitted and hatchery-disseminated diseases by monitoring certain diseases in flocks of producers who are participants in the program. The program is voluntary, costly and currently has only 15 California backyard flock participants (Monica Della Maggiore, NPIP, personal communication; Mattos 2012). The Quality Assurance Program (QAP), another voluntary program implemented by CDFA and managed by the California Poultry Health Board/NPIP, is targeted toward large commercial producers that seek to ensure food animal biosecurity and consumer protection. It has an extremely high percentage of participation, representing about 95% of California's commercial egg and poultry producers (CDFA 2012a).

CDFA recently published an information pamphlet specifically for owners or potential owners of backyard flocks that provides basic flock management information and explains how to recognize signs of illness (CDFA 2012b). UC Davis Department of Animal Science, UC Cooperative Extension, and the companion animal and pet exotics (CAPE) departments also have services and online resources to aid backyard poultry owners, including links to statistical information, disease control and biosecurity, and the CAHFS diagnostic laboratory system (Animal Science 2012). The university is also the location of the Davis branch of the CAHFS laboratory, where many of the tests for the NPIP and QAP programs are performed.


Annette Jones

For more information:

CDFA
http://www.cdfa.ca.gov/ahfss/Animal_Health/Avian_Health_Program.html

UC Agriculture and Natural Resources (ANR) publications
http://anrcatalog.ucdavis.edu/Items.aspx?hierId=19250

UC Cooperative Extension
http://cecentralsierra.ucanr.edu/Livestock_and_Range_Management/Poultry_Resources/

UC Davis Department of Animal Science
http://animalscience.ucdavis.edu/Avian/

USDA
http://www.aphis.usda.gov/animal_health/birdbiosecurity/

Chickens made up 91% of all Backyard Flock program submissions between 2007 and 2012.

submissions is significant and cannot be attributed to a general increase in avian submissions.

The county distribution data demonstrated a substantial increase in submissions in certain counties; however, there is a potential for bias in these results due to a variation in the ease of making a submission close to a CAHFS laboratory. While the cost of the necropsy is covered, shipping expenses are not. The cost of shipping and lack of easy access to a shipping facility may be deterrents to owners of flocks in more isolated areas, whereas owners in the vicinity of a CAHFS laboratory can simply drive their samples to the laboratory. This bias was demonstrated during the END outbreak of 2002–2003, when a spatial distribution study showed a strong correlation between proximity to a CAHFS laboratory and number of Backyard Flock necropsy submissions (Soberano et al. 2009).

The diagnostic data supports the finding that Marek's disease is the most commonly diagnosed disease throughout California. When introduced into an unvaccinated and previously unexposed flock, this disease causes depression, paralysis and death in up to 80% of birds. Marek's disease was also found to be the main disease in a recent retrospective study of chicken mortality focusing on flocks located specifically in Northern California (Mete et al. 2013), and Senties-Cue and Charlton (2012) reported that Marek's disease accounted for 18.6% of all SDs from backyard poultry throughout the CAHFS laboratories in the past 10 years.

Website forums and blogs may offer convenient opportunities for discussion, but there is usually no screening to check the reliability of the information distributed among members, which has the potential to encourage misinformation and could lead to poor flock management

Hotline for sick birds

What should you do if you find an unusual number of sick or dead hens in your poultry flock? If yours is a large-scale commercial operation, your company's manual probably advises: "Remove and isolate the affected birds; sanitize the area where they were found; have birds and environment tested by staff veterinarian."

But what if you've got a smaller operation with no in-house vet, or just a few backyard hens? According to California state veterinarian Annette Jones, DVM, you still need to take quick action. Ideally, you already have a relationship with a veterinarian familiar with poultry, so you should call her or him and describe the situation. But even if you do not have a poultry veterinarian, you can and should call the bilingual State Bird Hotline, 866-922-BIRD (922-2473). Poultry disease can travel fast, so it's essential that it be identified and controlled as quickly as possible, before it has a chance to spread to other flocks.

The hotline was established by the California Department of Food and Agriculture's Division of Animal Health and Food Safety Services (AHFSS) in recognition of the dual facts that poultry flocks are important to an increasing number of Californians, and that many flock owners aren't trained to recognize the signs of potentially devastating diseases.

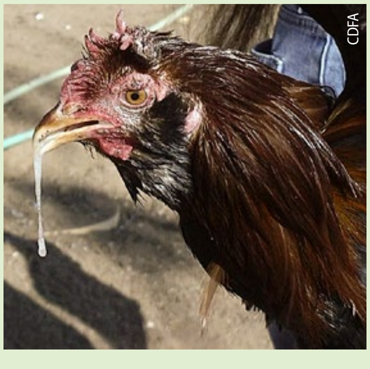
The first thing you'll hear when you call the hotline is an automated answering system. After you choose to get information in Spanish or English, you can select one of the options — such as "report a sick or dead bird" or "learn how to recognize signs of disease." You are then connected to a staff veterinarian (or his or her voicemail) or to helpful recorded information. If you do get the voicemail, be assured that a veterinarian will call you back as soon as possible.

Speed here is definitely of the essence. Southern California's 2002 outbreak of exotic Newcastle disease showed that. The quicker a veterinarian can identify and control the disease, the fewer other birds will be affected, and the better off everyone will be.

Depending on circumstances, you may be instructed to contact one of the California Animal Health and Food Safety (CAHFS) laboratories directly for free diagnostic services or you may be visited by a veterinarian from one of four field offices located up and down the state who will help you determine what's wrong with your birds and what can be done to fix it. All of this is provided at no cost to you.

For more about the hotline and a wealth of information on poultry health, check out the AHFSS Avian Safety Program website: http://www.cdfa.ca.gov/ahfss/Animal_Health/Avian_Health_Program.html.

— W. J. Coats



Chickens diagnosed with exotic Newcastle disease. Note the dropped head as evidence of depression, the swollen eyelid (above and right) and discharge from the mouth (right). The feathers are matted down and the hen hasn't been cleaning herself.

practices. CDFA has a strong incentive to provide reliable information but has seen a significant decrease in its funding, which has contributed to a reduction in outreach efforts. CAHFS and UC Cooperative Extension faculty routinely give public talks during related community events such as the Davis Tour de Cluck or the Heirloom Exposition in an effort to improve outreach. Nevertheless, the shortage of CDFA funds eventually may translate into a lack of disease surveillance and public awareness of biosecurity that, combined with owner noncompliance and lack of education, could contribute to an increased risk of disease.

Advertising state and federal avian health programs and providing incentives for backyard flock owners to use them would expand their effectiveness.

As mentioned earlier, the federal and state programs that are in place are vastly underutilized by the backyard poultry community. After the END outbreak of 2002–2003, a study showed that fewer than 2% of backyard poultry owners interviewed were aware of the CAHFS Backyard Flock program and had submitted birds for testing (Soberano et al. 2009).

The estimated cost to CAHFS, and ultimately to CDFA, for performing each necropsy averages $172 (Emily Sanson-Smith, CAHFS Davis, personal communication). Funding for the Backyard Flock program is crucial in order to continue surveillance for important diseases such as HPAI and END while establishing information on flock distribution, size and encountered disease conditions, which is valuable for improved biosecurity and consumer safety, and is difficult to obtain in other ways. In addition, the low number (1.9%) of cases in the unexplained death category indicates that valuable data was reliably obtained from the majority of cases, giving owners useful information on the health of their flock.

Advertising state and federal avian health programs and providing incentives for backyard flock owners to use them would expand their effectiveness. Also, public and privately run websites and forums might be encouraged to add links to government websites, programs and information, helping CDFA and USDA more effectively disseminate information and obtain data on backyard flocks. This would cost nothing but the time to network with the web hosts. Increased availability of online information from reliable sources could help to decrease the biosecurity risk presented by the increasing number of unregulated backyard flocks in California and nationwide.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Marek's disease is the most commonly diagnosed cause of death in California poultry; when introduced into an unvaccinated flock, it can affect up to 80% of birds.

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Testing protocol ensures the authenticity of organic fertilizers

by Fungai N.D. Mukome, Timothy A. Doane, Lucas C.R. Silva, Sanjai J. Parikh *and* William R. Horwath

There is a pressing need for methodology to confirm the authenticity of fertilizers labeled "suitable for organic production." In this study, we developed a testing protocol that can be used by laboratories and regulatory agencies to detect adulteration of organic fertilizers and soil amendments with a synthetic nitrogen source. By conducting an extensive literature review and analysis of 180 commercially available raw materials, organic fertilizers, soil amendments and synthetic fertilizers, we compiled a comprehensive database of quantifiable properties of those materials. We analyzed their ammonium content, C:N ratio and stable nitrogen isotope ratio, and for each metric we set thresholds that flag products with a high probability of adulteration. The protocol can be used to authenticate organic fertilizer products and bring transparency to the industry.


Fungai Mukome

Researchers developed a database and six-step testing protocol that can be used to detect potential adulteration of organic fertilizers with synthetic compounds. *Above*, some of the diverse organic fertilizers available for use by growers.

From 2000 to 2011, the organic industry grew from $6.1 billion to $29 billion in sales (OTA 2011). Year-to-year growth during that time was 8%, compared to 1% for the entire food industry (OTA 2011). Despite the organic industry accounting for only 3% of all farm-gate sales (2008 data), California leads the national organic charge, with the highest number of farms, land under production and sales (Klonsky 2010). Also, according to the 2008 Organic Production Survey (OPS), administered by the National Agricultural Statistics Service, the California industry accounts for 19% of all organic farms and 36% of all organic farm-gate sales in the nation (Klonsky 2012). With ever-increasing consumer demand for organic products, this industry is projected to continue its rapid growth in the short to medium term.

This demand has increased pressure on organic growers to maintain and increase productivity. However, this productivity has been partially constrained by availability and consistency (quality) of organic fertilizers. The wide array of fertility products on the market is daunting, presenting a selection challenge for many end users and, due to the natural variability of inputs, product consistency from batch to batch is a major challenge for fertilizer manufacturers. Inputs permissible for the manufacture and handling of organic fertilizers are regulated by the National Organic Program National List of Allowed and Prohibited Substances (USDA 2009a), a list mandated by the Organic Foods Production Act of 1990 (OFPA) and effective as of October 2002.

The list allows for the use of non-synthetic inputs while prohibiting the use of synthetic inputs with a few named exceptions including alcohols, chlorine materials and ozone gas (these synthetic inputs are permissible provided they do not contribute to the contamination of crops, soil or water). Prior to 2009, this list formed the basis of oversight on the organic fertilizer industry, providing moderate penalties for known violations (civil penalty of not more than $10,000). However, no emphasis was placed on monitoring and independent verification of the final products to ensure consistency and authenticity of the products.

In December 2008, the Sacramento Bee newspaper published an article titled "Organic farms unknowingly used a synthetic fertilizer," revealing an investigation by the California Department of Food and Agriculture (CDFA) on the activities of a Salinas-based company (Downing 2008). The company, a one-time supplier of organic fertilizer to approximately one-third of the state's organic farms, was believed to be adulterating their organic fertilizer with ammonium sulfate. At about the same time, another California supplier was implicated in fraud charges, amounting to over $40 million, arising from using cheaper inorganic compounds as substitute nitrogen sources in organic fertilizer made of fish meal and bird guano. These unscrupulous practices increased concern about the authenticity and integrity of soil and crop amendments sold for use in organic production.

To address this, California Assembly Bill AB856 was passed in 2009. This bill, which now governs the oversight of organic input materials sold in the state (Chapter 257, Statutes of 2009), substantially increased the penalties for violation of organic fertilizer standards, required

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registration of all organic fertilizers sold in the state and gave regulators greater authority to monitor and review organic fertilizer label claims and test the compliance of the guaranteed analyses (CDFA 2012). This oversight is performed by the CDFA Fertilizer Research and Education Program (FREP), a program within the industry-funded Fertilizing Materials Inspection Program (CDFA 2012).

However, until now, regulators administering this law have had no systematic protocol for evaluating and testing the authenticity of the organic products sold. Depending on the degree of adulteration, basic laboratory tests often fail to identify a problem. For example, analysis of nitrogen content may confirm the amount on a product label but will not indicate the source of nitrogen (organic or inorganic).

Stable isotopic ratio analysis can distinguish between organic and inorganic sources of nitrogen and has been used to detect adulteration of food, including honey (Kropf et al. 2010; Stocker et al. 2006) and lamb (Piasentier et al. 2003), as well as inferring the diet and history of cattle from beef samples (Schmidt et al. 2005) and the agricultural regime (organic versus conventional) of cultivated carrots, tomatoes and lettuce (Bateman et al. 2005; Freyer and Aly 1974). Due to large differences in the isotopic ratio of synthetic nitrogen (atmosphere-derived nitrogen isotope ratio [$\delta^{15}N$] zero or negative) and organic nitrogen (animal–derived nitrogen has higher $\delta^{15}N$), this approach offers a rapid and reliable technique for detection of potential adulterants in organic fertilizers (Peterson and Fry 1987).

Other routine methods for developing potential metrics for adulteration detection are calculating the carbon to nitrogen (C:N) ratio and total nitrogen as ammonium (NH_4-N). Typical values of C:N ratios for organic materials are fish and fish larvae 3.9, zooplankton 5.4 to 5.9, blue-green algae 6.5, corn plants 30.4 and legumes 15 to 25 (Müller 1977). Total nitrogen as ammonium in most organic materials is < 1%, except for liquid fish and seabird guano, but much larger for synthetic inorganic compounds such as urea and ammonium sulfate.

Our research provides insight into the analyses that can be used to assess the quality and regulate the production and testing of organic fertilizers and amendments. The first major objective of our study was to construct a database of materials used in organic and synthetic fertilizers through chemical and physical analyses of these materials and a detailed review of the literature. Our second objective was to establish parameters for the natural ranges of specific chemical properties (i.e., ammonium [NH_4^+], $\delta^{15}N$ and C:N ratio), which can be used to distinguish between pure, or unadulterated, materials and adulterated ones. Our third study objective was to develop a stepwise protocol that labs and regulatory agencies can follow to identify fertilizers that may have been adulterated by synthetic fertilizers.

Database development

Fertilizer analysis methodology. Synthetic and organic samples (solid and liquid) were obtained from commercial fertilizer suppliers for analysis ($n = 180$). Prior to analysis, all nonhomogenous liquid samples, such as raw fish, were homogenized by mechanically shaking the sample with glass beads or steel balls. Solid samples were homogenized by grinding with a mortar and pestle, or in the case of very fibrous samples, by mechanically shaking in a steel ball mill.

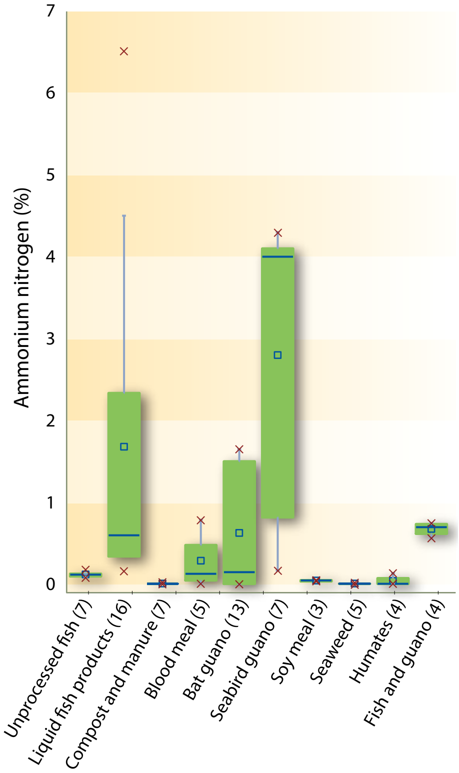
A subsample of the solid samples, approximately 200 milligrams, was shaken with 100 milliliters of water for about an hour. The solids were removed, either by centrifugation or filtration, and the remaining solution diluted as required for colorimetric ammonia and nitrate determination (Doane and Horwath 2003; Verdouw et al. 1978). For liquid samples, aliquots were taken and transferred to a volumetric flask for appropriate dilution, and concentrations of ammonia and nitrate were determined as above.

Digestion and combustion were utilized to determine the total nitrogen content of all the samples. The method for calculating total nitrogen by digestion was adapted from Lindner (1944). A subsample, typically 700 milligrams, was dispensed into a 100-milliliter volumetric flask and the weight of the sample recorded. Five milliliters of concentrated sulfuric acid were added, and the samples were heated to approximately 302°F (150°C) until all of the moisture was driven off. Subsequently the samples were heated strongly to 752°F to 932°F (400°C to 500°C) until clear and colorless or almost colorless. The samples were made to volume with water (with a purity of 18.2 MΩ-cm) and the NH_4^+ concentration, and therefore total nitrogen concentration, determined.

For total nitrogen by combustion (carbon determined simultaneously), an appropriate amount of sample (2 to 5 milligrams) was dispensed into standard tin capsules used in elemental analysis. The amount of sample required was estimated using the values for total nitrogen previously obtained by the digestion analysis. For liquid samples, a small piece of glass fiber filter was placed inside the tin capsule to absorb the sample. The samples were analyzed by combustion-gas chromatography (Elementar Vario MicroCube, Elementar, Germany), and results for all


William Horwath

To obtain $\delta^{15}N$ isotopic data from organic and synthetic fertilizer samples, researchers used a PDZ Europa 20-20 isotope ratio mass spectrometer in the UC Davis Stable Isotope Facility. Analyses using ATR-FTIR and FT Raman spectroscopy were also performed.



samples were expressed as percentage by weight of nitrogen or carbon. The C:N ratio (weight by weight, w/w) was calculated from these data.

The relative abundance of $\delta^{15}N$ was determined with an isotope ratio mass spectrometer (PDZ Europa 20-20 IRMS, Sercon Ltd., Cheshire, U.K.) at the UC Davis Stable Isotope Facility. For liquid samples that were difficult to homogenize adequately, the $\delta^{15}N$ content was also determined by diffusion of the ammonium in a sulfuric acid digest (Sørensen and Jensen 1991). This allowed for a larger subsample to be used than in combustion analysis.

Fig. 1. Ammonium nitrogen content of the different categories of organic fertilizers. Percentages were calculated weight to weight (w/w) for solids and weight to volume (w/v) for liquids. The lines of the boxplot represent the median, 25th and 75th quartile values, and the whiskers represent the maximum and minimum values used in the calculation. The x's represent the range of data. Number of samples are shown in parentheses.

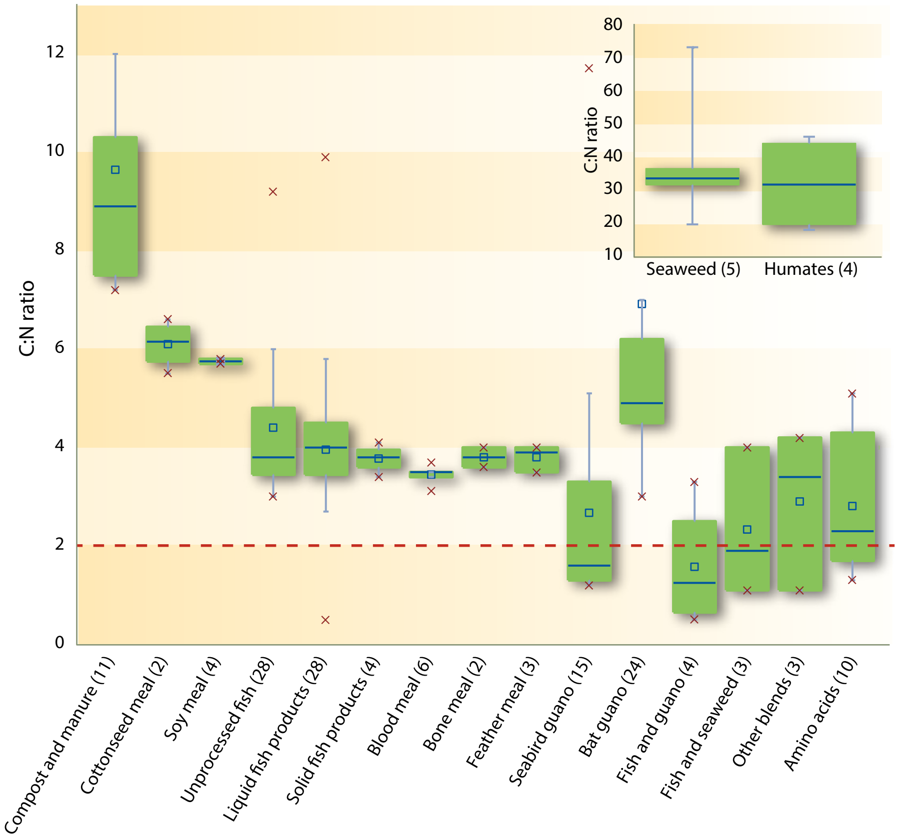


Fig. 2. C:N ratios of the different categories of organic fertilizers. The dashed line denotes the threshold value, based on typical protein C:N ratios; organic fertilizers with C:N ratios lower than the threshold might warrant investigation for potential adulteration. Based on 99% confidence intervals, guano and guano blend fertilizers are a possible exception. The lines of the boxplot represent the median, 25th and 75th quartile values, and the whiskers represent the maximum and minimum values used in the calculation. The x's represent the range of data. Number of samples are shown in parentheses.

Spectroscopic analysis (single-bounce attenuated total reflectance [ATR] Fourier transform infrared [FTIR] spectroscopy and Fourier transform [FT] Raman spectroscopy) of the organic fertilizers was also performed. ATR-FTIR spectra were collected on a Thermo Nicolet 6700 spectrophotometer (Thermo Scientific, Madison, WI), with 128 scans per sample and a resolution of 4 cm^{-1}. FT Raman spectra were collected on a Bruker RFS 100/S FT Raman spectrometer (Bruker Optics, Coventry, U.K.) with a Nd:YAG laser operating at 1,064 nanometers. The spectra were collected at a power level of 100 milliwatts and a resolution of 4 cm^{-1}, with the spectra being an average of 256 scans per sample.

Data and literature review. Data from the analysis of 168 organic and 12 synthetic fertilizer samples were combined with data collected from the literature. For ease of comparison and analysis, the organic fertilizers were classified into categories based on feedstock components as used by the Organic Materials Review Institute (OMRI). Blends of varied composition, containing more than two components, were combined into an "other blends" category; for example, a composition of kelp or seaweed extract, humic acid, molasses, vinegar, compost and alfalfa tea; or liquid compost with humates and molasses; or 4-2-3 formulations of fish emulsions, seaweed extract, humic acid and molasses.

Ammonium (NH_4^+) content, C:N ratio and $\delta^{15}N$ were identified as most useful for the initial inspection of the database and evaluation of fertilizers. Databases of expected values for certain parameters were created from laboratory organic fertilizer analyses and a review of raw materials and organic fertilizer literature (figs. 1 to 3). All data are shown together, including data from possibly adulterated products, resulting in a large spread of data in some categories.

All but three categories (i.e., liquid fish products, bat guano and seabird guano) of the fertilizers had < 1% NH_4-N, with considerable variability in the liquid fish and seabird guano fertilizers (fig. 1). Naturally, categories such as seaweed, blood meal, compost and feather meal (not included in fig. 1) do not contain much ammonium, and thus the amount of NH_4-N could be an effective determinant of potential adulteration. However, fish-derived and guano fertilizers can contain elevated NH_4-N concentrations (created from industrial processes such as heating and enzymatic hydrolysis), thus making this measurement less effective as a determinant of potential adulteration in these materials. Furthermore, the decomposition of fish tissue and products can also naturally result in increased ammonia concentrations (Spotte 1970).

The review of the literature values of the C:N ratio of different organic fertilizers revealed variable values and all mostly > 2. The only exceptions were the seabird guano–derived fertilizers, urea, proteins and amino acids, and uric acid. Several of the analyzed samples (fig. 2) showed a C:N ratio of < 2 (liquid fish products, seabird guano, fish and guano blends, and fish and seaweed blends), which suggests possible adulteration. This is consistent with an addition of nitrogen from a chemical source without carbon, such as urea and ammonia, which would lower the C:N ratio.

Most of the organic fertilizers had $\delta^{15}N$ values > 5 (fig. 3). The exceptions were fertilizers derived from feather meal, soybean and seaweed. Leguminous plants such as soybeans, certain seaweeds and algae are capable of fixing atmospheric nitrogen ($\delta^{15}N$ of zero), resulting in very low $\delta^{15}N$ values. The blends (fish and guano, fish and seaweed, and the blends in the other blends category containing fish and grain, or grain and feather) had lower $\delta^{15}N$ values than the fertilizers containing the individual blend components, for example, liquid fish and bat guano. The majority of synthetic fertilizers (urea, ammonium sulfate, ammonium nitrate, and nitrates) had $\delta^{15}N$ values < 5. Although not marked, this difference between organic and inorganic fertilizers enabled us to set threshold values for determining potential adulteration, but the situation is complicated by the low values of some organic fertilizers such as seaweed and soy meal products. A similar study of the nitrogen isotopic ratios of organic fertilizers by Verenitch and Mazumder (2012) observed data ranges and magnitudes consistent with those observed in our study.

ATR-FTIR spectra of organic fertilizers and several synthetic fertilizers were combined to create a database of spectra. Due to the fact that some chemical bonds absorb infrared light at different wavelengths, FTIR spectroscopy can be used to elucidate the presence of specific chemicals in a given sample (e.g., soil, fertilizer, plant tissue). The infrared light is absorbed differently by various bonds (e.g, N-H, C-N, C-O, C-H, P-O), causing unique vibrations, which then can be used to identify unique compounds or compound classes.

Clear trends based on fertilizer category are evident, making this an important point of reference for future spectral comparison (spectra not shown). Selected fertilizer samples were doped with ammonium sulfate and urea (potential adulterants) to test the robustness of ATR-FTIR spectroscopy in detecting their presence. Spectra of the doped samples showed the technique was sufficiently sensitive to detect the presence of the adulterants at an addition of 1% (w/w) (fig. 4).

For example, a sample of blood meal fertilizer was doped with 1% urea, and the spectra of the doped sample (trace v) was different than the undoped sample (trace iii). The concurrent presence and enhanced peaks at approximately 3,450 cm^{-1} (N-H vibrational bond stretch), 1,450 cm^{-1} (urea N-C-N vibrational bond stretch) and 1,600 cm^{-1} (urea C=O vibrational bond stretch) in the doped sample (trace v) show the presence of urea. The undoped sample spectrum does not show all the urea peaks (e.g., 3,450 cm^{-1} peak absent); and the peaks that are present (1,600 cm^{-1} and 1,450 cm^{-1}) are less prominent and likely arise from other constituents in the fertilizer. Also, postprocessing

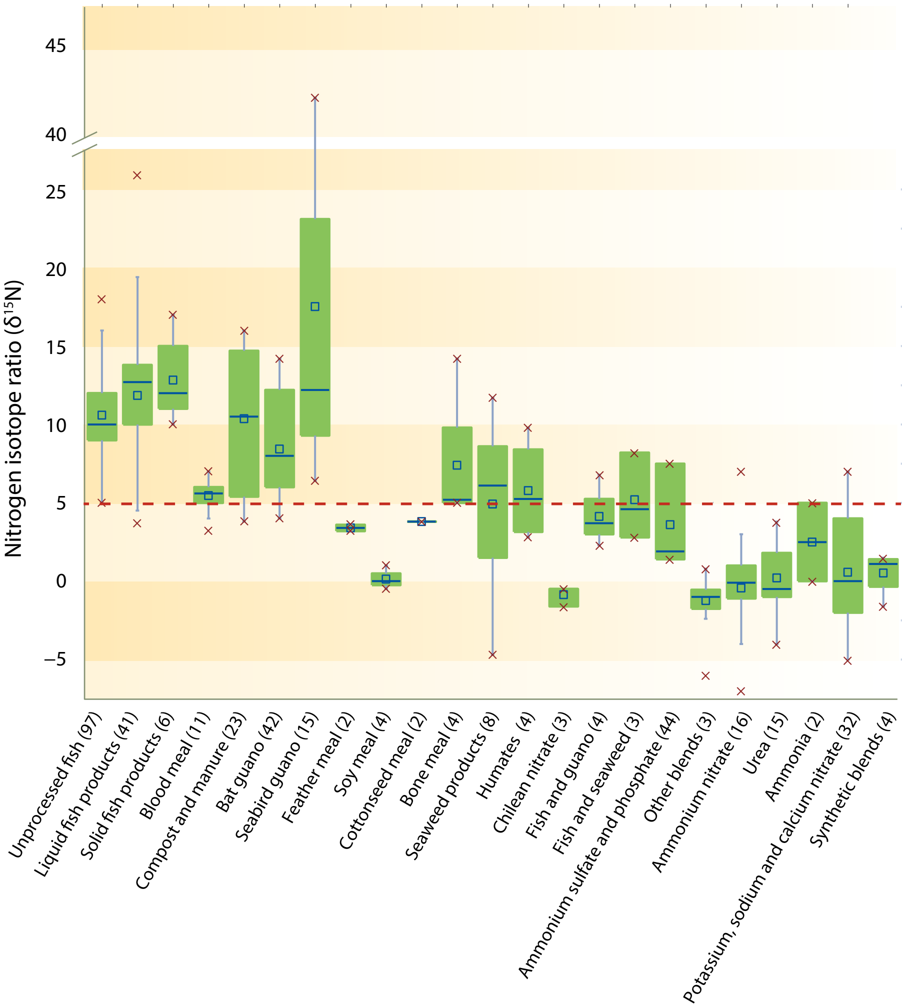


Fig. 3. Nitrogen isotope ratios ($\delta^{15}N$) of the different categories of organic and synthetic fertilizer. The dashed line denotes the threshold value, based on the natural isotopic abundance of different materials; an organic fertilizer with a ratio below the line may warrant investigation for adulteration. Based on 99% confidence intervals, seaweed, algae, Chilean nitrate and soybean fertilizers and their blends are possible exceptions. The lines of the boxplot represent the median, 25th and 75th quartile values, and the whiskers represent the maximum and minimum values used in the calculation. The ×'s represent the range of data. Number of samples are shown in parentheses.

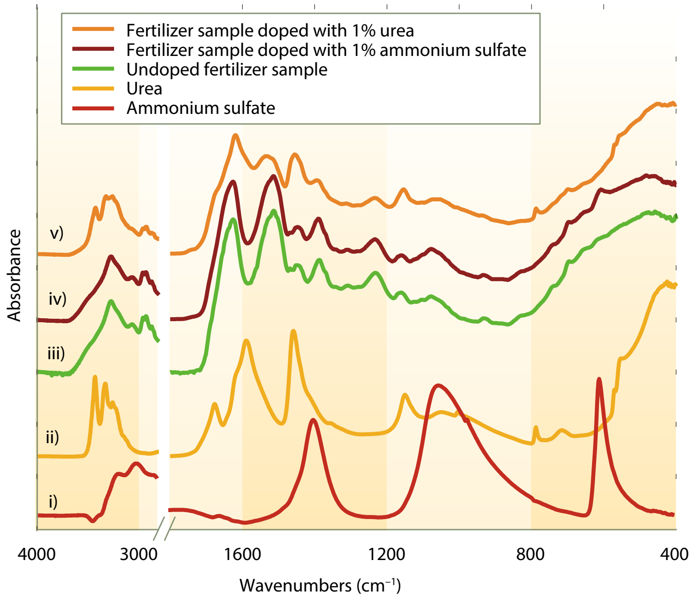


Fig. 4. ATR-FTIR spectra of adulterated and unadulterated fertilizer samples.

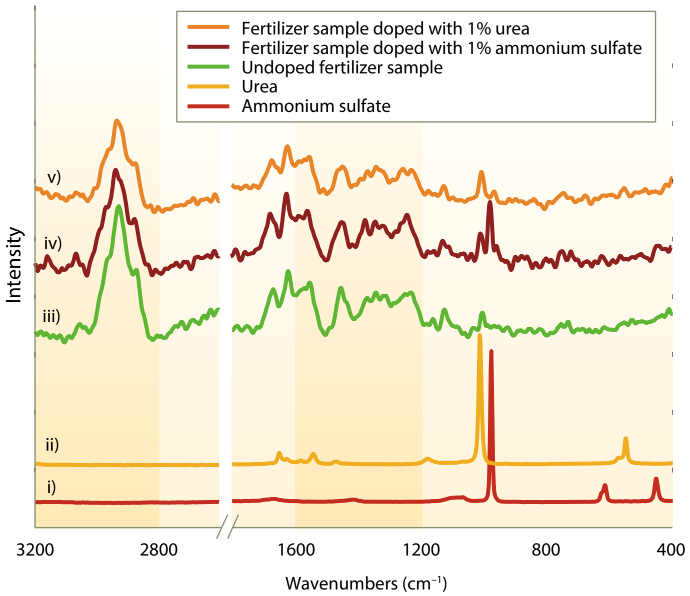
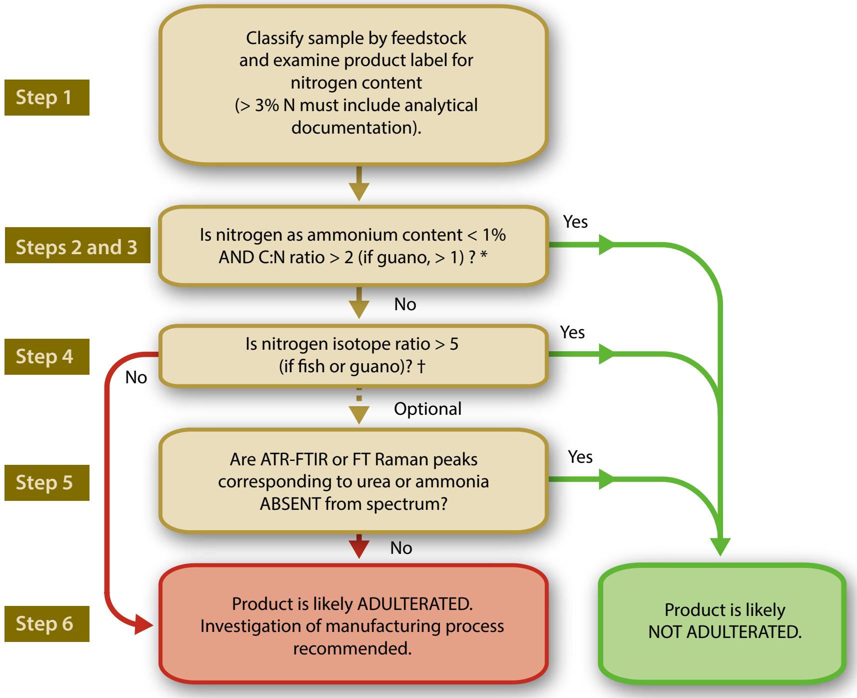


Fig. 5. FT Raman spectra of adulterated and unadulterated fertilizer samples.

the ATR-FTIR data by subtracting the undoped spectra from the doped spectra (example not shown) can give a clearer indication of the presence of the adulterant. Similarly, analysis of the sample doped with ammonium sulfate was also performed (fig. 4, trace iv), and differences were evident when compared to the undoped sample (trace iii). Peaks associated with ammonium sulfate (trace i) were detected at approximately 1,400 cm^{-1} (N-H bond deformation) and 600 cm^{-1} (sulfate SO_4^{2-} bending mode).

FT Raman analysis of the organic fertilizer samples also revealed clear trends based on fertilizer category (spectra not shown). As in ATR-FTIR analysis, selected organic fertilizer samples were doped with the adulterants (fig. 5, traces iv and v). FT Raman proved to be more straightforward than ATR-FTIR at detecting the presence of the adulterants, with minimal postprocessing of the spectra required. The presence of ammonium sulfate (trace i) and urea (trace ii) can be observed by significant peaks at approximately 980 cm^{-1} (ammonium sulfate SO_4^{2-} stretching mode) and 1,012 cm^{-1} (urea N-C-N bond stretch).

The success of the spectroscopic techniques bodes well for similar analysis of solid fertilizers using near-infrared reflectance spectroscopy (NIRS), which is routinely used in plant, forage and feed tissue analysis to determine components such as crude protein content. As a result, application of this technology to organic fertilizers would not require purchase of new instrumentation. However, the liquid nature of most organic fertilizers presents a challenge for NIRS due to water being a strong absorber of NIR light (Stuth et al. 2003).



* Chilean nitrate is an exception.
† Seaweed, algae and soybeans require ATR-FTIR or FT Raman analysis.

Fig. 6. A protocol for investigating possible adulteration of organic fertilizers.

Fertilizer screening protocol

The database of $\delta^{15}N$, C:N ratios and levels of NH_4-N provides a readily accessible resource for comparison of fertilizer samples and a cheap and rapid way to flag fertilizer samples for more comprehensive analysis. The results from the database compilation have also facilitated the setting of thresholds of expected values in ammonium content, C:N ratios and $\delta^{15}N$. By integrating the literature and laboratory information, we developed a protocol for detecting potential adulterants in organic fertilizers. This is the first such protocol and provides a quick and simple methodology for test labs and regulators of organic fertilizers.

The protocol assumes the most likely adulterants of organic fertilizers are various forms of ammonia (e.g., aqua ammonia or ammonium sulfate) or urea, which is converted to ammonium carbonate and ultimately ammonia in the presence of urease (Volk 1959). These adulterants are favored primarily due to their low cost and high nitrogen content. Since δ^{15}N, C:N ratio and ammonium content most effectively separate different classes of organic and synthetic materials, they best help indicate the presence of adulterants. Furthermore, these properties provide the greatest opportunity to compare with literature data, and are relatively easy to measure (and therefore most useful to a testing lab). Although not part of our study, adulteration by adding nitrate salts is also possible, but the protocol would be able to detect the added nitrogen in the C:N ratios and δ^{15}N values.

The protocol (fig. 6) involves six steps, which progress in order of increasing effort and expense. This protocol minimizes the chances of incorrectly flagging a fertilizer as potentially adulterated through a systematic approach and by ensuring no single metric is a sufficient determinant for classifying a sample as adulterated or unadulterated (Verenitch and Mazumder 2012).

Initially, identification of the category to which a sample belongs and knowledge of the components constituting the fertilizer are necessary in order to interpret the results of analysis and use the protocol effectively, since values that are suspect for one kind of sample may not be suspect for another kind.

Step 1. Before any laboratory analysis, attention is directed toward the label and price of a product (evaluation of the latter is important, as authentic organic fertilizers with elevated nitrogen content would require considerable processing reflected in a higher cost of production).

A key metric to focus on is the nitrogen content. As stipulated by the USDA, organic fertilizers labeled as containing > 3% nitrogen must be evaluated through a material evaluation program (USDA 2009b). This program requires oversight from third-party evaluators capable of verifying compliance of the component inputs (including processing and handling of the product) independently of the crop producer and fertilizer manufacturer. The suppliers of such products should thus have chemical data on their products showing the independent analytically determined nitrogen levels of the final product.

Due to the numerous potential formulations of organic fertilizers, knowledge of the fertilizer constituents is an important step in directing subsequent analytical tests. For example, in the case of urea-enhanced sawdust, knowledge of sawdust constituents will be important in using the NH_4-N content and nitrogen isotope ratios to flag a sample with a borderline C:N ratio.

Correct classification of the fertilizers according to the major constituents present is of paramount importance for subsequent interpretation of the data. As a guide, utilizing classifications similar to other organic fertilizer organizations (e.g., OMRI) will limit potential incorrect classification. Fertilizers containing blends may present a challenge if the relative proportions of the constituents are not revealed.

Step 2. A first analytical step to evaluating a product is determination of the ammonia (ammonium) content. For common, well-characterized categories of products such as nonfish- or non-guano–based fertilizers, this is an easy preliminary step toward selecting samples for further investigation. Any product in these categories found to contain more than 1% nitrogen as ammonium (10,000 mg L^{-1}) should be retained for further analysis. Potential adulteration of samples that naturally have ammonia (e.g., fish products) can be detected by other tests in the protocol.

Step 3. The C:N ratio is a good indication of how organic a material is. The nitrogen in organic materials is derived primarily from protein, for which the ratio does not fall below 1. The same is true of guano, although guano may contain much of its nitrogen in the form of uric acid rather than protein. For the threshold, our calculated upper limit of the 99% confidence interval (CI) for the average C:N ratio of the five fertilizer categories with the lowest ratios (i.e., seabird guano, fish and guano, fish and seaweed, amino acids, and other blends, fig. 2) is 1.28. Any fertilizers that do not contain these materials and yet show C:N ratios below the CI value probably (99% likely) contain inorganic nitrogen. However, if the values are higher than these thresholds, it is impossible to say whether the sample has organic nitrogen only. Despite the calculated value of 1.28, it is extremely rare that any protein would have a C:N ratio of less than about 2, hence a threshold value of 2 has been selected for this protocol.

For seabird guano fertilizers, a reasonable threshold, based on literature values and the current database, would be a C:N ratio of 1. An obvious exception is Chilean nitrate, an approved product with a naturally high level of nitrogen relative to carbon. Due to the potentially low C:N ratios of blends containing guano and Chilean nitrate, questionable samples should be further analyzed.

Samples with an ammonium nitrogen content of < 1% (exceptions discussed above) and having a C:N ratio > 2 may be considered likely not adulterated. Failure to meet the criteria of either step warrants further investigation.

Step 4. The nitrogen isotope ratio (δ^{15}N) of natural materials also rarely falls below a certain threshold, with a few exceptions. Fish tissue and guano, for example, do not have ratios less than 5, and they are typically greater. A threshold value of 2.3 was calculated based on the 99% CI for the average of the nitrogen isotope ratios of all nonorganic sources and accounting for variations in sample size (number of values used in the calculation of each product's CI).

Any products that go beyond this threshold (i.e., show higher δ^{15}N values) are almost certainly not adulterated. It is important to note, however, that plants that rely on symbiotic nitrogen uptake can have δ^{15}N values as depleted, or close to atmospheric values, as nonorganic

Any organic grower suspecting adulteration could submit a fertilizer sample to a commercial soil test lab or the CDFA to determine with high probability whether the fertilizer is authentic.

nitrogen sources. So in fertilizers where biomass from nitrogen-fixing plants (e.g., legumes) has been added, it may be difficult to distinguish them from nonorganic sources.

Step 5. The two spectroscopic techniques provide additional tools for investigating the authenticity of organic fertilizers. Detection of adulterants by ATR-FTIR can be performed by 1) comparing sample spectra with spectra of samples from a similar feedstock, 2) comparing the sample spectra with that of urea or ammonium sulfate and looking for characteristic peaks for ammonia or urea or 3) intentionally doping the sample with urea or ammonium sulfate and analyzing for increased magnitude in peaks characteristic to the adulterants, as in figure 4.

For FT Raman, similar methods of analysis can be used. The spectral interpretation of FT Raman is much simpler, with clear peaks associated with potential adulterants being evident (fig. 5). Both techniques require no sample preparation and very little sample setup, resulting in high throughput of samples. The cost of the instrumentation may be prohibitive; hence the use of these techniques is suggested after all other less expensive options of verification are exhausted.

Step 6. When a sample clearly fails all or some of the tests, adulteration is likely and warrants further investigation of the manufacturer and process of production.

Suggested protocol

Due to the large diversity of organic fertilizer formulations (many with more than two constituents), this protocol may, with ongoing validation tests and analysis of more samples, undergo modifications that improve its robustness. This initial version, nonetheless, presents a useful approach and methodology for detecting, with high probability, the adulteration of organic fertilizers and other amendments by a synthetic fertilizer or other chemical nutrient sources. Its low cost and relative simplicity ensure regulators and test laboratories can use it to efficiently test commercially available organic fertilizers.

The required analyses for ammonia and total carbon and nitrogen are readily available at soil test labs and the CDFA Inspection Services Center for Analytical Chemistry. These tests alone can flag the majority of samples adulterated with synthetic sources of nitrogen; and any organic grower suspecting adulteration could submit a fertilizer sample to a commercial soil test lab or the CDFA to determine with high probability whether the fertilizer is authentic. Additional stable nitrogen isotope and spectroscopic analysis can likely confirm an adulteration. Since these analyses are not routine for soil test labs, we surmise that the CDFA Inspection Services Center for Analytical Chemistry might be approached to perform further analysis of these suspected samples.

The strength of the organic industry lies in maintaining the integrity of its "organic" brand. Without simple verification methods and rigorous oversight of the fertilizers used in organic production, consumers' trust in this brand may be jeopardized. With a defined testing protocol in place, manufacturers adulterating fertilizers will face the appropriate scrutiny, and legitimate producers of fertilizers will benefit by having the quality of their products assured.

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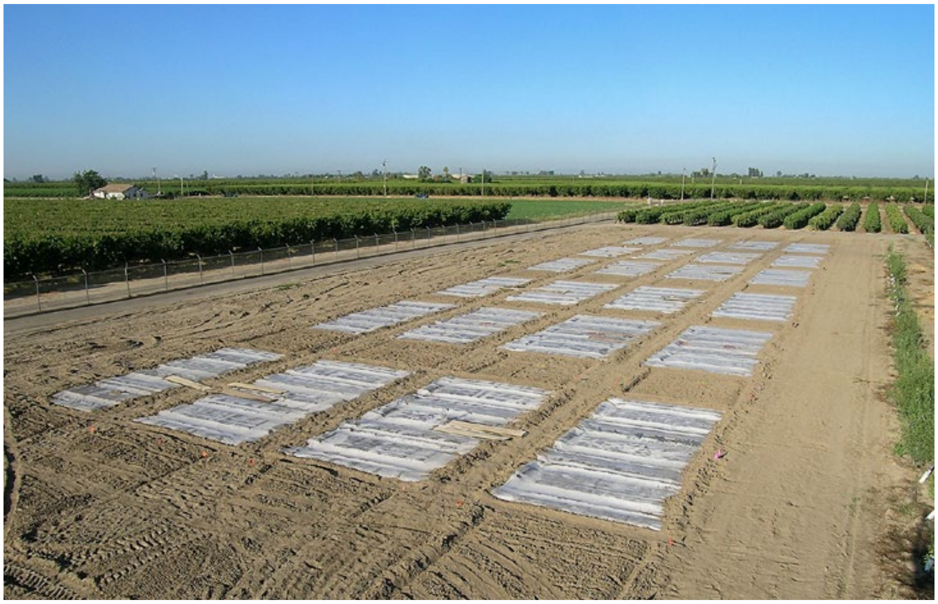
RESEARCH ARTICLE

Totally impermeable film (TIF) reduces emissions in perennial crop fumigation

by Suduan Gao, Bradley D. Hanson, Ruijun Qin, Jose Cabrera, James S. Gerik, Dong Wang *and* Greg T. Browne

Many perennial nursery fields and replanted orchards and vineyards in California are treated with preplant soil fumigants to control soilborne pests. In annual crops, such as strawberry, covering fumigated fields with totally impermeable film (TIF) has shown promise in controlling emissions and improving fumigant distribution in soil. The objective of this research was to optimize the use of TIF for perennial crops via three field trials. TIF reduced peak emission flux and cumulative emissions by > 90% relative to polyethylene tarp during a 2-week covering period. After the TIF was cut, emissions were greatly reduced compared to when tarps were cut after 6 days. TIF maintained higher fumigant concentrations under tarp and in the soil than polyethylene film. The results indicate that TIF can increase fumigation efficiency for perennial crop growers.


Suduan Gao

Data from three field trials conducted near Parlier, *above*, show that totally impermeable film (TIF) maintained higher fumigant concentrations under tarp and in the soil than polyethylene film.

In California, successful orchard replanting in many situations still depends on soil fumigation to control soilborne pests. Additionally, producing perennial tree and grapevine nursery stock that is free of plant-parasitic nematodes (to meet regulations [CDFA 2008]) is achieved primarily by growing the stock in open fields treated with preplant soil fumigation. The most effective fumigant, methyl bromide, was phased out in January 2005, although some uses are currently allowed under critical use exemptions (CUEs) and as treatments for meeting quarantine and preshipment (QPS) criteria. Many perennial crop growers have adopted methyl bromide alternatives such as 1,3-dichloropropene (1,3-D) and chloropicrin. These alternatives, however, are also highly regulated because of their toxicity and the emission of volatile organic compounds (VOCs), which degrade air quality by forming ground-level ozone.

Controlling emissions from soil fumigation can help maintain the availability of fumigants to growers, and it is required by environmental regulations in ozone non-attainment areas such as the San Joaquin Valley (CDPR 2009; US EPA 2009). Research in reducing emissions from soil fumigation of perennial crops has been supported by the USDA-ARS Pacific Area-Wide Pest Management Program for Integrated Methyl Bromide Alternatives. Phase I of the research (2006–2008) evaluated plastic tarping and surface treatments with water, organic amendments and chemicals. Low-permeability tarps demonstrated significant emission reductions, while the irrigation, organic matter and chemical treatments tended to sacrifice efficacy near the soil surface because of the reduced fumigant concentrations there; the findings have been summarized in Gao et al. (2011), Hanson et al. (2013) and Jhala et al. (2012). Phase II (2009–2010) focused on developing fumigation methods using low-permeability tarps, including totally impermeable film (TIF), and we report those results here.

Low-permeability films, such as TIF (Chow 2008), have been shown to effectively control emissions and improve fumigation efficacy in annual crops such as strawberry by retaining higher fumigant concentrations and creating a more uniform distribution of fumigant in the soil profile compared to standard polyethylene tarp (Qin et al. 2011). However, the benefits of TIF for soil fumigation in perennial crops have not been evaluated.

During 2009 and 2010, we conducted field trials to address how to use TIF efficiently in perennial orchards, vineyards and nurseries. Although tarps have not typically been used for replanted orchards, TIF may improve efficacy and allow the use of reduced fumigant rates. Our research objective was to optimize the use of TIF to reduce emissions, improve efficacy and potentially reduce fumigant application rates. This research was also conducted to determine how to avoid the surge of emissions that had been observed when TIF was cut after 6 days, the cutting time that is commonly used for standard polyethylene film (Qin et al. 2011). This paper includes our research data for fumigant concentration in the air under the tarps (above soil

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surface), emission flux during tarp covering and after tarp cutting, cumulative fumigant emissions, fumigant gas concentration in the soil profile, and residual fumigants. Detailed efficacy data are reported in Cabrera et al. (2011).

Three field trials

Three field trials were conducted between October 2009 and October 2010 at the USDA-ARS San Joaquin Valley Agricultural Science Center, near Parlier. The plots had previously been planted with a vineyard, and the soil was a Hanford sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthents). For all three trials, Telone C35 (a mixture of 1,3-D 61% and chloropicrin 35%, weight per weight [w/w]) was shank applied at an 18-inch depth with a 20-inch shank spacing using a commercial Telone shank applicator. Three replications were conducted for each treatment.

The TIF (VaporSafe, 1-mil thickness, clear, Raven Industries, Sioux Falls, SD) was 10.5 feet wide for the first trial (the first time it was available for field testing) and 13 feet wide for the other two trials. In the first trial, two sheets of TIF were joined by gluing and applied to a 20-foot-wide plot; a single sheet was applied to a 12-foot-wide plot for the second trial; and three sheets were applied to a 36-foot-wide plot for the third trial. These corresponded to fumigant application passes of two, one and three (representing the width of treatment plot) for the first, second and third trials, respectively. The polyethylene film (1-mil thickness and 13-foot width) was provided by Trical, Inc. (Hollister, CA) and applied in a single sheet for the first two trials and three sheets joined in a plot for the third trial.

For all three trials, soil was cultivated and irrigated before fumigation to produce soil moisture conditions that met Telone C35 label requirements. Soil water content profiles were similar in the fall trials, but with a slightly drier surface in the fall 2010 trial (fig. 1). The soil in the summer 2010 field trial had higher water content. According to CIMIS data (Station 39, at Parlier), soil temperatures averaged 72.8°F, 73.9°F and 63.6°F during the fall 2009, summer 2010 and fall 2010 field trials, respectively. For all trials, sampling procedures in the field, sample processing and laboratory analyses followed established procedures as described in Gao et al. (2009).

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Researchers used dynamic flux chamber equipment, *top*, to measure fumigant emissions throughout the fall 2009 trial period and 24 hours after tarp cutting. *Bottom left*, fumigant injection; *bottom right*, plastic tarp installment at Parlier, Fresno County.

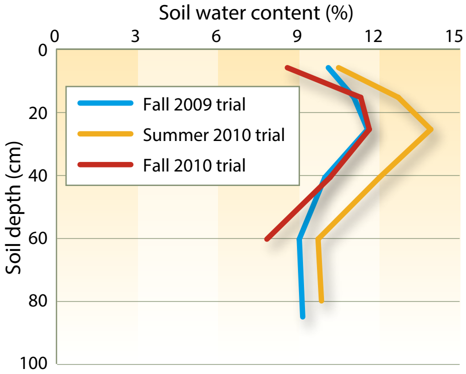

Fig. 1. Soil water content 1 day before fumigant application in the three field trials. Plotted are averages of three location measurements across the field. Error bars are omitted for readability.

A summary of the field trials is provided in table 1. The fall 2009 trial was designed to evaluate fumigant emission, distribution and efficacy from three Telone C35 rates (full rate: 100% of the maximum label rate, which is 48 gallons, or 540 pounds, per acre; 75% of full rate [0.75]; and 50% of full rate [0.5]) plus a nonfumigated control and two types of plastic tarps, standard polyethylene and TIF. Measurements were made of fumigant concentration changes in the air under the tarp, emission flux during tarp covering and after tarp cutting, and residual fumigants in the soil at the end of the trial. Fumigant emissions throughout the first trial period (2 weeks) and 24 hours after tarp cutting were measured using dynamic flux chambers (Gao et al. 2008; Gao and Wang 2011). Malfunctions of the fumigant application equipment resulted in an overapplication of the 0.75 rate, resulting in an actual rate similar to the full rate. Due to application rig emitter clogging problems, the calculation of total emission loss as a percentage of total amount applied could not be performed; thus, relative emissions and differences between treatments, rather than absolute values, are presented.

The summer 2010 trial was conducted on the same soil as the fall 2009 trial. Fumigant distribution in the soil profile and concentration in the air under the TIF tarp at the full and 0.5 rates were monitored and compared with data from the plots with standard polyethylene tarp and a full-rate application.

The fall 2010 trial focused on fumigation efficacy and correlation with fumigant concentration and time (CT) exposure index values, and tested full, 0.5 and 0.25 fumigation application rates under polyethylene and TIF tarps, as well as nonfumigated controls. Fumigant concentrations in the air under the tarp and in the soil profile (soil-gas phase) were monitored.

Fumigant in air under tarp

High fumigant concentrations in the air under the tarp benefit pest control near the soil surface but can cause an emissions surge at tarp cutting, which risks workers' and bystanders' safety. 1,3-D concentrations measured during the fall trials immediately under the tarp are shown in figure 2. Chloropicrin concentrations (data not shown) followed a similar pattern but were substantially lower than 1,3-D because the initial application rate was lower and the half-life of chloropicrin in soil is generally much shorter than that of 1,3-D.

During the fall 2009 trial, 1,3-D concentration was up to three times higher under TIF than under standard polyethylene film at the full application rate (fig. 2A). At the half rate, 1,3-D concentration under TIF was similar to or even higher than at the full rate under polyethylene film. Prior to tarp cutting, the average 1,3-D concentration at the full rate was 0.6 µg cm^{-3} under the TIF tarp compared with only 0.2 µg cm^{-3} under the polyethylene tarp.

Similarly, during the summer 2010 field trial, the average of 12 under-tarp air samples 1 week after fumigant application showed a higher 1,3-D concentration at the half rate under TIF than at the full rate under polyethylene film (data not shown).

Concentrations of 1,3-D under the tarps during the fall 2010 trial (fig. 2B) were again the highest under TIF at the full rate, and few differences were observed among the 0.5 rate under TIF and the full rate under polyethylene, with the 0.25 rate under TIF (data not shown) showing slightly lower 1,3-D concentrations than the 0.5 rate under TIF.

The under-tarp concentrations of 1,3-D were much higher for the fall 2010 trial (fig. 2B) than for the other two trials, especially in the first few days after application. And, in that trial, the concentrations increased faster initially and dropped more rapidly with time. This was most likely due to temperature differences: soil was warmer in September 2010 than in October and November 2009; soil moisture conditions were similar except that the soil surface and deeper layers were drier in the fall 2010 trial (fig. 1). The higher temperature in fall 2010 may have resulted in greater volatilization of the fumigants from the soil to the headspace under the tarp, followed by a drop in concentrations due to greater degradation of the fumigants in the warmer soils.

TABLE 1. Summary of the treatments and emissions monitoring in three field trials

Field trial	Treatment (shank injection of Telone C35)	Field measurement
Fall 2009 (Oct 27–Nov 9)	Rate: full rate (48 gallon/acre, the maximum label rate), 0.75* and 0.5 of the full rate, nonfumigated control Tarp: standard polyethylene, TIF	Fumigant concentrations in air under tarp Emission flux after tarp cutting Residual fumigants
Summer 2010 (Jun 9–Jul 1)	Rate and tarp: full rate, 0.5 of the full rate under TIF, full rate under standard polyethylene film	Fumigant concentrations in air under tarp Fumigant distribution in soil
Fall 2010 (Sep 8–Oct 13)	Rate: full rate, 0.5 and 0.25 of the full rate, nonfumigated control Tarp: standard polyethylene, TIF	Fumigant concentrations in air under tarp Fumigant distribution in soil

* The 0.75 rate (75% of the full rate) was overapplied, and data from this treatment were integrated into the full rate.

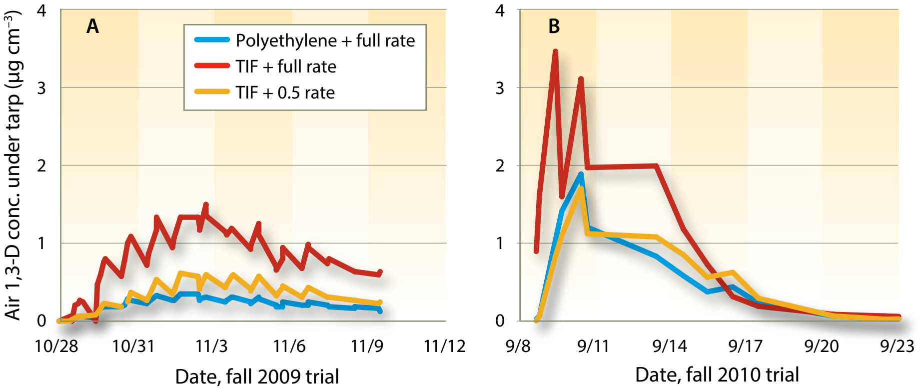

Fig. 2. Fumigant concentration changes in air under the tarp. In the fall 2010 trial, the 0.25 rate under TIF (not plotted) had slightly lower 1,3-D concentrations than the 0.5 rate under TIF. Plotted are averages of three replicates.

The data suggest that using TIF tarp in early fall may have the advantage over using it in summer and late fall.

Data from the summer 2010 trial (collected in June, when temperatures were the highest among the three trials) showed concentrations just one-third of the concentrations in the fall 2009 trial 1 week after application of the same rate, possibly due to faster dissipation of fumigation at high temperatures (data not shown). Higher amounts of fumigants under TIF were observed after the 2-week tarp covering in fall 2009 than under polyethylene (fig. 2A), but most of the fumigants under TIF had dissipated after 2 weeks in summer 2010. These data demonstrate that high temperatures enhanced fumigant dissipation and degradation.

The air under tarp data suggest that using TIF tarp in early fall may have the advantage over using it in summer and late fall by maintaining higher fumigant concentrations in soil following fumigation. The tarp was cut after 2 weeks, when very low fumigant concentrations (< 0.01 µg cm^{-3}) were monitored under the tarp in the fall 2009 trial, indicating a low risk of an emissions surge.

Flux and cumulative emissions

TIF reduced both emission flux and cumulative loss by > 90% compared to standard polyethylene tarp during the 2-week tarp-covering period (figs. 3 and 4) in the fall 2009 trial. However, emissions

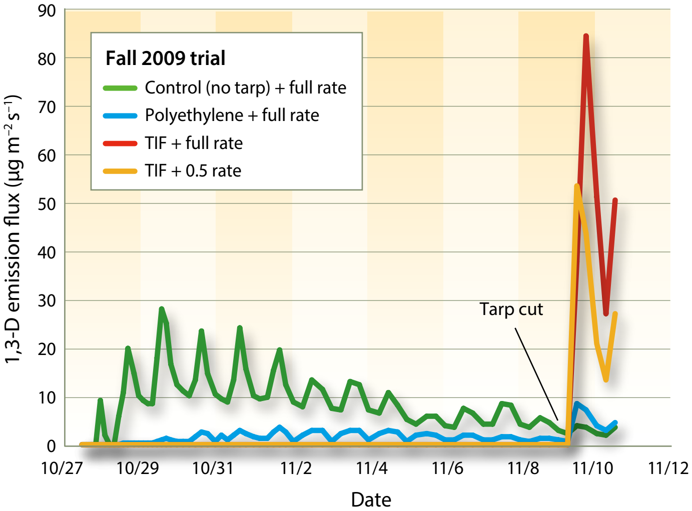

Fig. 3. Emission flux of 1,3-D in the fall 2009 field trial. Plotted are averages of three replicates.

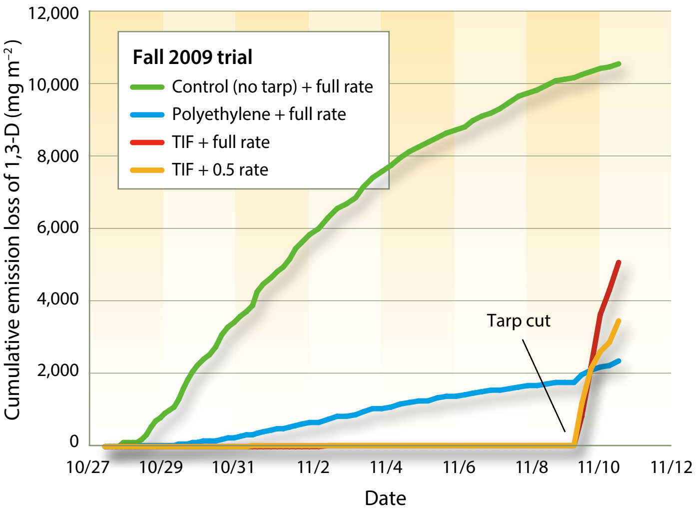

Fig. 4. Cumulative emission loss of 1,3-D in the fall 2009 field trial. Plotted are averages of three replicates.

still surged following tarp cutting with much higher emission rates from TIF plots than from the polyethylene plots due to the higher concentrations of fumigant remaining under the tarp (fig. 2A). The flux values after tarp cutting (13 days after application) in the fall 2009 trial were substantially lower than those reported (over 200 µg m^{-2} s^{-1}) when tarp cutting occurred 6 days after fumigant application (Qin et al. 2011). Emissions of chloropicrin were lower than 1,3-D emissions (data not shown) because of the lower amount of chloropicrin applied and its faster degradation; following an application of Telone C35, it's 1,3-D that is the major concern for worker safety in an emissions surge.

Total fumigant emission loss from the field is also a concern because VOCs degrade air quality. The total loss includes loss during the tarp-covering period and loss after tarp cutting. Figure 4 shows that during tarp covering, total emissions from the TIF plots were extremely low, but emissions spiked at tarp cutting, resulting in cumulative emissions that were higher than those from the plots with polyethylene tarp. The 0.5 rate applied under TIF resulted in lower emissions than the full rate. Total emissions following tarp cutting could have been greater than reported in figure 4 because monitoring was done for only about 24 hours after tarp cutting.

Fumigant distribution in soil

In the summer 2010 trial, fumigant distribution was monitored by measuring gas fumigant concentration changes over time in the soil profile. Fumigant concentration in the soil-gas phase was not significantly different between the TIF and polyethylene film treatments at the same application rate (data not shown). It is possible that the high soil temperature in the summer caused fast dispersion of fumigants in the soil and also possibly from the soil at the edges of the single strip of tarp. In the fall 2010 trial, soil-gas concentrations between the injection lines at the center of the three sheets that covered the plots were monitored, and the averaged data are shown in figure 5.

The TIF full-rate treatment resulted in generally higher 1,3-D concentrations throughout the soil profile than were found in the polyethylene full-rate plots, at various sampling times (fig. 5). The highest 1,3-D concentrations measured for the TIF full-rate, polyethylene full-rate, TIF 0.5 rate and TIF 0.25 rate treatments were 17.4, 12.2, 5.5 and 3.8 µg cm^{-3}, respectively, as determined at 55 centimeters depth and 24 hours following fumigant application. The data indicate that although TIF may increase fumigant concentration and improve fumigant distribution in perennial crop fields, it is not as effective as it is with annual crops, which usually require shallower injections than perennials (Qin et al. 2011).

Residual fumigant

TIF increased fumigant residence time in soil based on measurement of soil samples collected at the end of the fall 2009 trial, 2 weeks after fumigant application (fig. 6). The highest residual 1,3-D concentration in the soil was from the TIF full-rate treatment followed by the polyethylene full-rate, the control (no tarp) full-rate, and the TIF half-rate treatments. TIF also increased residual chloropicrin in soil, but the concentration was generally an order of magnitude lower than that of 1,3-D.

The increased residual fumigant under TIF provides the source of emissions after tarp cutting. In cool temperatures, TIF may need to be left in place longer to allow the fumigant to degrade and reduce the emissions surge. If residual fumigant concentrations are high after tarp cutting, planting time may need to be delayed to avoid phytotoxicity to roots.

Industry benefits

TIF can substantially reduce fumigant emissions by retaining fumigants under the tarp. However, to allow for fumigant degradation and avoid significant emission surges at tarp cutting, TIF needs to remain in the field for longer than polyethylene tarp, especially during periods of lower temperature such as late fall. When temperatures are high, 2 weeks of TIF tarp covering may be sufficient without high risk of exposure at tarp cutting. When temperatures are cool, more than 2 weeks of tarp covering may be needed.

All of our fumigant-monitoring data support that TIF can effectively increase fumigant concentration under the tarp and potentially increase fumigant residence times in the soil profile compared to polyethylene film when fumigants are shank applied at 18 inches depth. The increased and prolonged concentrations offer better pest control per amount of fumigant applied. Efficacy data reported in Cabrera et al. (2011) indicate there is potential for using reduced rates under TIF. TIF tarps are more expensive than standard polyethylene tarps, but the extra cost might be offset by savings from reduced fumigant application rates. The net cost will need to be determined.

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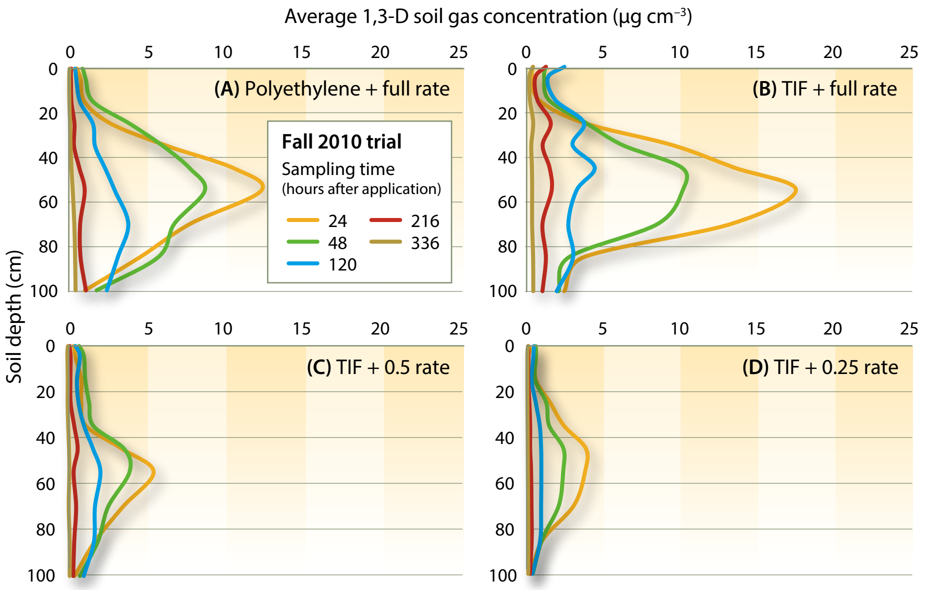

Fig. 5. Changes in 1,3-D concentration in the soil-gas phase, in the fall 2010 trial. Plotted are averages of three replicates. Soil depth is in centimeters (1 inch = 2.54 centimeters).

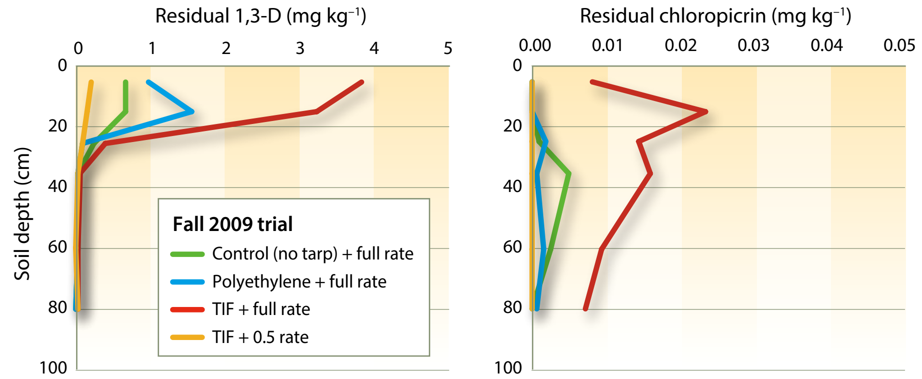

Fig. 6. Residual soil fumigants (1,3-D and chloropicrin) 14 days after fumigant application in the fall 2009 trial. Plotted are averages of three replicates. Soil depth is in centimeters (1 inch = 2.54 centimeters).

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Tractor-mounted, GPS-based spot fumigation system manages Prunus replant disease

by V. Udompetaikul, Robert W. Coates,
Shriniyasa K. Upadhyaya, Greg T. Browne,
Mir Shafii *and* Matt Gillis

Our research goal was to use recent advances in global positioning system (GPS) and computer technology to apply just the right amount of fumigant where it is most needed (i.e., in a small target treatment zone in and around each tree replanting site) to control Prunus replant disease (PRD). We developed and confirmed the function of (1) GPS-based software that can be used on cleared orchard land to flexibly plan and map all of an orchard's future tree sites and associated spot fumigation treatment zones and 2) a tractor-based GPS-controlled spot fumigation system to quickly and safely treat the targeted tree site treatment zones. In trials in two almond orchards and one peach orchard, our evaluations of the composite mapping and application system, which examined spatial accuracy of the spot treatments, delivery rate accuracy of the spot treatments, and tree growth responses to the spot treatments, all indicated that GPS spot fumigation has excellent potential to greatly reduce fumigant usage while adequately managing the PRD complex.

Trial results suggest that GPS-controlled spot fumigation has the potential to reduce fumigant use. *Above*, testing the fumigant applicator at UC Davis.

California almond and stone fruit orchards cover nearly 1 million acres and produced revenues of $3.6 billion in 2010 (NASS 2013). To maintain their productivity and economic competitiveness, however, almond and stone fruit orchards must be replaced every 15 to 25 years. Preplant soil fumigation with 1,3-dichloropropene (1,3-D) or mixtures of 1,3-D with chloropicrin (Pic) is widely practiced in the process of replacing almond and stone fruit orchards. Fumigant treatments are often applied in strips of land that are centered over future tree rows and cover about half of the orchard area. Alternatively, soil fumigation is applied as a full-coverage treatment covering an entire orchard area. When administered properly, soil fumigation prevents serious biological replant problems, which include nematode parasitism (McKenry 1996; McKenry and Kretsch 1987) and the Prunus replant disease (PRD) complex (Browne et al. 2006; Browne et al. 2013). Plant-parasitic nematodes were estimated to infest up to a third of California's almond and stone fruit acreage (McKenry and Kretsch 1987), potentially causing root damage and suppressing yields throughout an orchard's lifetime. PRD is a poorly understood yet widespread soilborne disease complex that suppresses tree growth and cumulative yields in successive plantings of almond and stone fruit orchards (Browne et al. 2006; Browne et al. 2013).

For several reasons, soil fumigation must be carefully managed. In California, uses of fumigants and other volatile organic compounds are regulated to reduce their contributions to formation of ground-level ozone (DPR 2012a, 2012b). In addition, the high cost of soil fumigation and increasingly stringent regulations dealing with fumigant rates, buffer zones and surface sealing methods for fumigated soils are incentives for growers to reduce dependence on soil fumigation and keep fumigant rates low.

In previous research, it was determined that the most widespread replant problem of almond and stone fruits, PRD, could be controlled by spot fumigation (Browne et al. 2006). Preplant spot fumigation administered with a hand-held probe to tree planting sites (applied at a single point per tree site) greatly improved growth of trees in several replanted orchards that were subject to PRD but not infested with significant populations of plant-parasitic nematodes.

Spot treatments achieved acceptable PRD control using 25 to 100 pounds of soil fumigant per orchard acre, whereas typical strip and full-coverage treatments require 170 to 400 pounds per orchard acre. However, hand-held probe application of fumigant is considered undesirable for several reasons: It puts workers in close proximity to fumigant hoses and discharge points; it involves large amounts of labor to auger and refill tree planting sites to facilitate probe and fumigant penetration in the soil; and it is relatively slow compared to conventional shank fumigation of an orchard. Also, it is likely that the dose of fumigant administered through a hand-held probe to a single point at a tree planting site would be more effective if it

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were applied to an area surrounding as well as including the tree site.

In addition to the need for safe and practical delivery methods for fumigants or other preplant treatments to tree sites, there is an associated need for an efficient tree site mapping process; preplant treatments typically occur months before tree planting, and it can be a logistical challenge to accurately place and relocate tree sites throughout the period before planting when cultivation, surface sealing and other cultural operations remove physical tree site markers. A GPS-based mapping system for tree sites would be helpful.

The goal of this research was to engineer and test a safe and practical spot fumigation system for the control of PRD with minimal fumigant. Our specific objectives were to 1) develop GPS-based gridding software that maps tree planting sites and associated spot treatment zones in user-selected tree planting patterns, 2) retrofit a conventional tractor-powered shank fumigation applicator to administer GPS-controlled spot fumigation treatments, 3) evaluate the accuracy and effectiveness of the retrofitted applicator and 4) adapt the system to a commercially available variable-rate application system (VRA) equipped with a sub-inch accuracy real-time kinematic (RTK) GPS-based autoguidance system.

Gridding software

A key component of our system is the gridding software that computes the future planting sites of the trees and associated spot treatment zones in an orchard. Coordinates of field corners are needed to create the planting map. These coordinates can be obtained using a GPS unit with an accuracy that is similar to or higher than the high-performance GPS (HP GPS) unit connected to the precision fumigant controller (PFC). The HP GPS used in this study had an accuracy of 4 to 8 inches. Most growers may want higher accuracy and decide to use a sub-inch accuracy RTK GPS unit.

Orchard sites that involve rows of uneven length and rows that are discontinuous are accommodated by the software. The gridding software allows the user to select row direction, edge of the field along which the first tree in each row would be planted, row spacing, tree spacing along each row, fumigant spot treatment zone length (i.e., the length of the rectangular area to be treated at each tree site) and pattern of planting (rectangle or diamond). The software processes the inputs and produces a transferable file containing the tree site and treatment zone map. Figure 1 shows a partial tree site map developed for an orchard in Arbuckle, Colusa County.

Fumigant application system

Based on the earlier work by Coates et al. (2007), we developed a second-generation site-specific fumigant application system, shown in figure 2. This system was retrofitted on to a conventional shank-type fumigation rig made available to us by Trical, Inc. (Hollister, CA). The conventional rig included a wheeled tractor, shanks, a Raven flow controller (Model SCS 4400, Raven Industries, Sioux Falls, SD) and additional fumigation hardware assembled by Trical, Inc. The conventional rig had five shanks spaced 20 inches (51 centimeters) apart, and each shank was tipped with a horizontal wing attachment that released fumigant from two points that were 8 inches (20 centimeters) apart. Figure 2 shows the components of the conventional rig (only three shanks are shown, as spot fumigation did not use the outer two shanks) as well as additional electronics included to implement spot fumigation.

The enhancements to the conventional system were assembled by Holtz and Needham Development (San Francisco, CA) based on our designs and field experiences with those designs. The system consisted of a precision fumigant controller, which was connected to an HP GPS unit (Model RPR 410, Raven Industries, Sioux Falls, SD), an inclination sensor (Model S121T, Murata Electronics, Vantaa, Finland) and a pulse width modulation (PWM) unit with solenoid-actuated nozzles (Capstan Synchro PWM, Capstan Ag Systems, Topeka, KS).

In preparation for spot fumigation, the file of the GPS-referenced tree site and treatment zone map is downloaded as output from the mapping software and uploaded into the PFC, and the desired fumigant application rate and width of the treated area are entered into the Raven flow controller unit. Standard width options include 20, 60 and 100 inches (51, 153 and 250 centimeters) using one, three or five shanks, respectively.

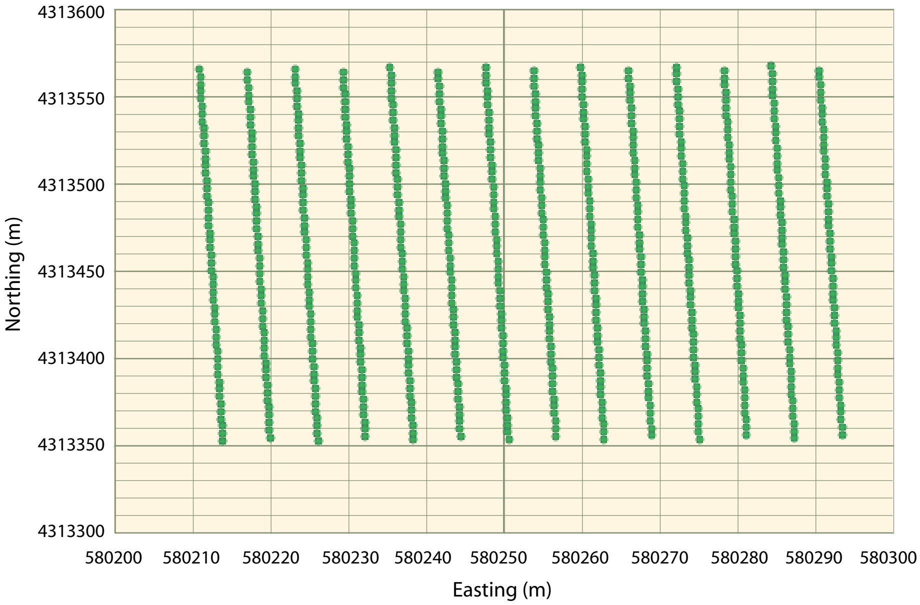

Fig. 1. Part of a tree site map generated by the gridding software for an orchard in Arbuckle, Colusa County. Tree spacing is 14 feet (4.3 meters), row spacing is 20 feet (6.1 meters) and the planting pattern is diagonal. Note that the scales are not the same along the horizontal and vertical axis. Northings and eastings are distance measurements in a Universal Transverse Mercator projection (2-D) commonly used in GPS measurements.

> **The spot treatments tested here reduced fumigant amounts used per orchard acre by 71% to 74% compared to strip treatments with the same fumigant.**

System operation

Once the PFC and Raven flow controller inputs are specified, the system operates as follows:

1. The inclination sensor indicates to the PFC whether the shanks are raised above or submerged in the soil.
2. If the inclination sensor indicates that the shanks are in a raised position, the PFC performs a global search to determine which tree planting spot the applicator is approaching. When the applicator enters the spot treatment zone, the PFC connects the Raven controller to the PWM unit through a software switch (fig. 2), provided the shanks are submerged in the soil (as indicated by the inclination sensor). The PWM unit actuates solenoid nozzles and holds them open for an appropriate duration (i.e., the duty cycle, defined as the ratio of "on" time to total cycle time) to deliver a specified fumigant application rate. The PFC takes into account the response time of the system and applicator travel speed (i.e., it uses an appropriate look-ahead value [LAV]) to anticipate when it will arrive at the treatment zone.
3. The PFC disconnects the PWM unit from the Raven controller when the applicator exits the treatment zone (using an appropriate LAV). This action turns off the nozzles.
4. After the planting site of the first tree is treated, the PFC searches the neighbors of this tree (maximum of eight trees) to determine which tree site will be treated next. The treatment procedure is similar to the one used for the first tree.
5. Once the first and second trees in a row are identified, the PFC determines the direction of travel and locates the rest of the trees in that row using the planting pattern.
6. Spot treatment continues until the inclination sensor indicates that the shanks are raised (e.g., at the end of the row), at which time the PFC disconnects the PWM unit from the Raven controller. This action turns off the nozzles.
7. The operation returns to step 1, repeating through step 6 for the next row, and so on.

Road tests

The PFC may also be operated in a road test mode, during which it ignores the inclination sensor to allow positional accuracy tests with the shanks lifted up in the air. Positional accuracy tests were conducted near the Western Center for Agricultural Equipment (WCAE) on the UC Davis campus using eight marked points spaced 50 feet (15.2 meters) apart on a paved surface.

The applicator was operated in both the east-west and north-south directions with the shanks raised in the air in the road test mode at four different travel speeds: 2, 3, 4 and 5 mph (3.2, 4.8, 6.4 and 8.0 kilometers per hour). The shank nozzles (using water for testing) were supposed to turn on 3.5 feet (1.05 meters) before and turn off 3.5 feet (1.05 meters) after each of the marked points (for a spot treatment zone length of 7 feet). However, due to the system response time (i.e., delay between opening the nozzles and fumigant spraying from the shanks), the spray turned on and off at different locations than expected.

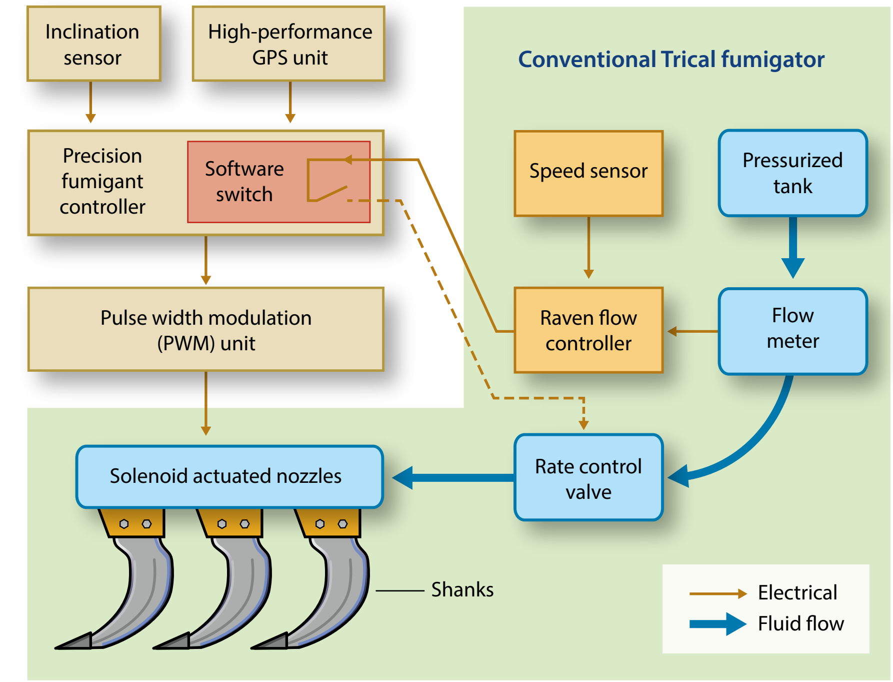

Fig. 2. Schematic of the second-generation site-specific fumigant application system.

The positional errors were measured to determine appropriate LAVs to minimize the error irrespective of travel speed. The appropriate values (one corresponding to turning the nozzles on and one corresponding to turning them off) were uploaded to the PFC, and another set of road tests was conducted to determine the final positional accuracy of the system.

Field tests

The applicator was then tested to determine accuracy of its delivery rates and delivery placement at the WCAE. The gridding software and a HP GPS unit were used to map 30 hypothetical tree sites. The points were marked off in a rectangular area consisting of six rows spaced 50 feet (15.2 meters) apart, each including five tree sites located 40 feet (12.2 meters) apart.

A spot application zone length of 7 feet (2.1 meters) was selected. The applicator was filled with a colored liquid to be used for injection, and the system was operated at 3 mph (4.8 kilometers per hour) with the shanks submerged in the soil. Liquid deposited from the center shank into the soil was used to evaluate the positional accuracy of the system. To determine the accuracy of delivery rates, fumigant supply tubes were disconnected from shanks and inserted into liquid-catching bottles; the liquid delivered per spot treatment zone was determined. Nine replicates were obtained at a set application rate of 24 gallons per acre. Limited tests were also conducted at other application rates (20 and 33 gallons per acre), and the results were similar.

Orchard tests

The composite mapping and spot applicator system was next evaluated in orchard replant trials, one near Arbuckle, another near Madera, and a third near Parlier. The Arbuckle site was on Arbuckle sandy loam soil and had been devoted to almond on various rootstocks for 27 years (an almond rootstock trial site). The Madera site was on El Peco, Fresno and Lewis sandy loam soils and had grown almonds on 'Nemaguard' rootstock for approximately 20 years. The Parlier site was on Hanford sandy loam soil and had grown plums on 'Nemaguard' rootstock for 7 years. The trial sites were cleared of their trees in spring (Arbuckle) or summer 2007 (Madera, Parlier). Each replanted orchard was to receive preplant treatments of strip fumigation, spot (tree site) fumigation and a nonfumigated control.

In preparation for the experimental treatments, the orchard mapping software was used to generate a tree site and treatment zone map for each trial. The GPS coordinates of field corners were determined and entered into the software, along with the desired row spacing, the in-row tree spacing, the planting pattern, and the spot treatment zone length (i.e., the length of the treated area desired around the tree sites destined to receive spot treatments). The width of the spot treatment zone is determined by the number of shanks operated.

The HP GPS system was used with the tree site map to place surveying flags to delineate positions of rows and boundaries of replicate plots for the treatments. At the Arbuckle trial, the plots measured 60 feet by 140 feet (three orchard rows wide by 10 tree sites long); the Madera plots measured 66 feet by 126 feet (three rows wide by 9 tree sites long); and the Parlier plots measured 20 feet by 144 feet (one row wide by 12 tree sites long). There were five replicate plots per treatment for each replant trial.

In October 2007, the preplant fumigation and control treatments were applied. At each trial location, its tree site and treatment zone map was uploaded to the PFC. The applicator was used to apply spot fumigation treatments, strip fumigation treatments and nontreated controls to replicate plots. The fumigants used were Pic, and a mix of 1,3-D and Pic (63:35, Telone C35).

The same fumigation rig was used for all fumigation treatments. It was operated in conventional mode for strip fumigation treatments and in spot treatment mode for the tree site treatments. In each trial, the depth of fumigant application by the shanks was 18 to 20 inches (46 to 51 centimeters). The experimental treatments, as well as additional treatments described in Browne et al. (2013), were arranged in randomized complete blocks. The fumigant supply cylinders on the application rig were weighed before and after applying fumigant to known land areas, so that accuracy of fumigant rates could be assessed.

The Arbuckle and Madera trials were planted with almond on 'Nemaguard' rootstock in March and January 2008, respectively; the Parlier plots were replanted with peach on 'Nemaguard' rootstock in February 2008. Efficacy of the treatments in each trial was initially assessed by measuring increases in tree trunk diameters annually from the time of planting through the end of the second growing season. Long-term assessments of the treatments described here, as well as of additional treatments, are presented in Browne et al. (2013).

Road test results

Road test results indicated that LAVs, which measure the system response times, were 328 milliseconds while turning on the solenoid-actuated nozzles and 317 milliseconds while turning them off. When these were incorporated into the system, the location accuracy of the system was independent of the travel speed and was within the accuracy range of the HP GPS unit used in this study, that is, 4 to 8 inches (10 to 20 centimeters).

Field test results

Field test results (table 1) indicate that the system tended to turn on and off early, by 8 to 10 inches (20 to 25 centimeters), in both the east-west and north-south directions. Even a slight error in positioning the shank nozzles could result in errors of this magnitude. Moreover, the movement of soil at the surface caused by the passage of the shank also contributed to this error. The root mean square (RMS) error was in the range of 4.7 to 6 inches (12 to 15 centimeters) for all the tests. The actual spot application zone length was about 87 inches (221 centimeters) in both east-west and north-south directions (a 3.8% error compared to the expected value of 84 inches, or 213 centimeters). These error values are within the range expected for the HP GPS system used (4 to 8 inches, or 10 to 20 centimeters).

Table 2 presents the results of the application rate test for a set delivery rate of 24 gallons per acre. The mean application rate was found to be 22.98 gallons per acre, with a coefficient of variation of 7.34%. This level of accuracy was considered reasonable in this study.

Orchard test results

At the Arbuckle trial, where treatments called for application of 1,3-D:Pic (60:39) at 400 pounds per treated acre either to spot treatment zones 7 feet long by 5 feet wide or to strips 8.3 feet wide centered over future tree rows, actual fumigant application rates were acceptable. However, there were no significant growth responses in

TABLE 1. Positional accuracy of application zones during field tests, when the applicator was operated in east-west and north-south directions, UC Davis, 2007

	East-west direction		North-south direction	
	Mean	Standard deviation	Mean	Standard deviation
	inches (centimeters)			
Turn-on error	−10.4 (−26.5)	4.8 (12.1)	−10.0 (−25.3)	5.9 (14.9)
Turn-off error	−7.5 (−19.0)	5.1 (12.9)	−10.0 (−25.3)	5.9 (14.9)
Application zone length	86.9 (220.6)	3.6 (9.1)	87.0 (221.0)	5.6 (14.1)

TABLE 2. Fumigant delivery rate accuracy during field tests, with the applicator set at 24 gallons per acre, UC Davis, 2007

Test number	1	2	3	4	5	6	7	8	9	Mean
	gallons per acre									
Set rate	24	24	24	24	24	24	24	24	24	24
Actual rate	22.0	22.3	23.2	23.2	23.1	22.9	21.1	27.0	22.0	22.98*

* Coefficient of variation (CV) = 7.34%.

the replanted trees to preplant fumigation as compared to the control treatment.

Based on cylinder weights, the actual spot application rate averaged 10% above the target rate for the spot treatment zones (standard deviation 14%, based on three determinations). The strip application rate averaged 2% above the target rate (standard deviation 1%, three determinations). The mean increase in trunk circumference from the time of planting to 1 year later ranged from 4 to 4.2 inches (10.1 to 10.7 centimeters) among the control, spot and strip treatments; there was no significant treatment effect (*P* = 0.5).

At both the Madera trial and Parlier trial, actual spot and strip fumigation rates were acceptably close to the targeted rates, and there were positive growth responses to all fumigation treatments (tables 3 and 4). At Madera, spot and strip application rates each averaged 2% above rates targeted for the application zones; standard deviations of the spot and strip application rates were 22% and 2%, respectively (each based on three measurements). At Parlier, the mean spot application rates were equal to the targeted rates (standard deviation 22%, based on three measurements), while the mean strip application rates averaged 2% above targeted rates (standard deviation 2%, three measurements).

Both spot and strip treatments significantly increased growth in trunk circumference from the time of planting through the second growing season (tables 3 and 4). In the Madera trial, compared to the nonfumigated control, fumigation treatments increased mean trunk circumference growth by 33% to 37% (spot treatments) and 37% to 40% (strip treatments) by the end of the first growing season, and by 22% to 23% (spot) and 31% to 35% (strip) by the end of the second growing season (table 3). In the Parlier trial, compared to the control, fumigation treatments increased mean trunk circumference growth by 87% to 102% (spot treatments) and 140% (strip treatment) by the end of the first season, and by 68% to 71% (spot) and 110% (strip) by the end of the second growing season (table 4).

TABLE 3. Effect of spot and strip treatments on growth of replanted almond trees, Madera trial, 2008–2010

				Mean increase in trunk circumference†	
Fumigant	**Coverage***	**Fumigant rate**		**End of first growing season**	**End of second growing season**
	% of plot area treated	*lb/treated acre*	*lb/orchard acre*	*inches*	
Nonfumigated control	None	0	0	2.8b	6.5b
Pic	Spot (11%)	400	44	3.8a	8.1a
Pic	Strip (38%)	400	152	4.2a	8.8a
1,3-D:Pic (63:35)	Spot (11%)	550	60	3.7a	8.0a
1,3-D:Pic (63:35)	Strip (38%)	550	209	3.9a	8.5a
Value of *P* for effect of treatment				0.002	0.002
95% CI‡ values				+/– 0.5	+/– 0.9

* Spot coverage indicates treatments applied to areas 5 feet wide by 7 feet long centered on tree planting sites. Strip coverage indicates treatments applied to continuous strips 8.3 feet wide, centered over future tree rows, which were to be spaced 22 feet apart.

† Increases in trunk diameter measured from time of planting, January 2008, to end of first and second growing seasons, winter 2009 and 2010, respectively, at 7.9 inches above soil line.

‡ CI = confidence interval.

TABLE 4. Effect of spot and strip treatments on growth of replanted peach trees, Parlier trial, 2008–2010

				Mean increase in trunk circumference†	
Fumigant	**Coverage***	**Fumigant rate**		**End of first growing season**	**End of second growing season**
	% of plot area treated	*lb/treated acre*	*lb/orchard acre*	*inches*	
Nonfumigated control	None	0	0	2.2c	4.9c
Pic	Spot (13%)	400	50	4.4ab	8.3b
1,3-D:Pic (63:35)	Spot (13%)	550	69	4.1b	8.2b
1,3-D:Pic (63:35)	Strip (50%)	550	231	5.2a	10.3a
Value of *P* for effect of treatment				< 0.0001	< 0.0001
95% CI‡ values				+/– 0.7	+/– 0.8

* Spot coverage indicates treatments applied to areas 5 feet wide by 7 feet long centered on tree planting sites. Strip coverage indicates treatments applied to continuous strips 8.3 feet wide, centered over future tree rows, which were to be spaced 20 feet apart.

† Increases in trunk diameter measured from time of planting, January 2008, to end of first and second growing seasons,winter 2009 and 2010, respectively, at 7.9 inches above soil line.

‡ CI = confidence interval.

Fumigant savings, expectations

Overall, results of our orchard assessments, including the fumigant rate delivery evaluations and preliminary tree growth assessments, indicate that the GPS-assisted orchard mapping and spot fumigation system offers great potential to reduce the amount of fumigant required to control PRD. The spot treatments tested here reduced fumigant amounts used per orchard acre by 71% to 74% compared to strip treatments with the same fumigant. Such reductions could reduce overall fumigant use for almond production as well as aid growers in meeting buffer zone requirements, which are based to a significant extent on fumigant used per orchard acre.

Additional data, including canopy absorption of photosynthetically active radiation (PAR) at Madera, 2 and 4 years of crop yield data for the Madera and Parlier trials, respectively, and multiple-year treatment cost and value assessments for both trials are presented in Browne et al. (2013). The additional data support the conclusion of this paper, that GPS-controlled spot fumigation may afford practical and adequate control of PRD with less fumigant. Finally, the spot treatment technology may have additional utility beyond application of fumigants. For example, our system may be used to apply nonfumigant liquid soil amendments that may be beneficial for growth of replanted trees.

It is important to distinguish between responses that growers may expect from spot treatments when replanted orchards are impacted only by PRD and responses that may result from spot treatments when plant-parasitic nematodes also are present. In comparison to PRD, which typically has its most severe impact on young orchards in their first and second years

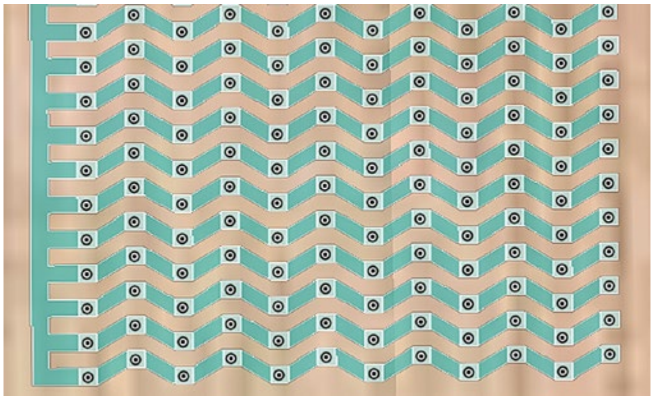

Fig. 3. A map of a section of the Arbuckle orchard (fig. 1) showing the grid points (tree sites, black dots), spot treatment application zone around the grid points (white square), and a single polygon created by joining application zones for each tree so that the map is compatible with commercial variable-rate fumigant applicators.

of growth, plant-parasitic nematodes that affect almond and stone fruits (i.e., ring, lesion and root knot nematodes) may have a later yet more persistent impact over the life of an almond or peach orchard, and spot treatments may not adequately protect trees from building of nematode populations. Nevertheless, whereas about 35% of almond and stone fruit orchards are impacted by plant-parasitic nematodes, it is considered likely that a much higher percentage of the acreage is impacted by PRD and therefore may benefit from spot treatments (Browne et al. 2006). We are currently optimizing the spot treatment system to facilitate its use in commercial agriculture.

New developments

Since establishing the technical feasibility of the spot treatment system, our focus has been on facilitating its use in agriculture. Major parts of this process have been adapting the system to meet commercial needs and taking advantage of emerging agricultural technologies. One set of the adaptations has involved replacement of the PFC with a variable-rate applicator (VRA) system produced by Ag Leader Technology (Ames, IA). VRA systems are used widely in precision agricultural applications, including soil fumigation, and the systems feature helpful visual displays and GPS-interfacing capabilities that are helpful in practical use.

Use of the VRA for spot treatment applications required accommodations in our gridding software; it was necessary that the map delineate all of the tree site treatment zones into a shape file containing just a few polygons. We decided to create a shape file containing a single polygon. Figure 3 shows a graphic representation of a shape file for tree sites arranged in a diagonal planting pattern. The wavy pattern is a consequence of the diagonal arrangement of tree sites; had the tree sites been arranged in a rectangular pattern, the interconnecting zones of the shape file would have been rectangular. Although within the required polygon the spot treatment zones are connected (fig. 3), the VRA uses the shape file to treat only the target spot treatment zones, which are still discontinuous along the tree row and selected according to the spot treatment zone length specified in the gridding software and the swath width option (20, 60 or 100 inches) selected according to the number of shanks used to deliver fumigant.

A serious limitation of the Ag Leader VRA system used in this ongoing study is that it does not report delivered flow frequently enough to produce an accurate as-applied map (i.e., a spatial GPS-referenced map recording actual deliveries of fumigant, relative to the targeted spot treatment zones). The VRA system works fine in generating as-applied maps of chemical application in field crops, but in these applications data are typically logged at the rate of 1 hertz or lower, which is too slow for fumigation of a very small targeted spot treatment zone. We are seeking solutions to this problem, because fumigant delivery records for all tree sites would have practical value for commercial applicators, growers and perhaps even regulatory personnel.

Additional adaptations have involved use of RTK-based autoguidance systems that achieve sub-inch accuracy using virtual reference stations (VRS). These stations are available through subscription in most parts of California and eliminate the need for expensive physical base stations. Preliminary tests have been conducted using the updated software and applicator components of our spot treatment system, and the results have been satisfactory. Additional tests will be conducted in the coming year.

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Preplant 1,3-D treatments test well for perennial crop nurseries, but challenges remain

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Preplant fumigation with methyl bromide commonly is used in open-field perennial crop nurseries in California for control of plant-parasitic nematodes, pathogens and weeds. Because this fumigant is being phased out, alternatives are needed to ensure the productivity of the perennial crop nursery industry as well as the ornamental, orchard and vineyard production systems that depend on clean planting stock. As part of the USDA Area-Wide Pest Management Program for Integrated Methyl Bromide Alternatives, several perennial crop nursery projects were conducted in California from 2007 to 2011 to test and demonstrate registered alternative fumigants and application techniques that maximize performance and minimize environmental impacts. The project was designed to evaluate shank application and soil surface sealing methods intended to reduce aboveground emission and improve soil performance of 1,3-dichloropropene, a leading methyl bromide alternative for nurseries. In these garden rose and tree nursery experiments, 1,3-dichloropropene treatments performed well regardless of application techniques. In this article, we highlight recent research and discuss the significance and remaining challenges for adoption of methyl bromide alternatives in this unique nursery stock production system.


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As methyl bromide is phased out, in-ground nursery stock systems face unique challenges. Soil fumigation with 1,3-D can control key nematode pests in nurseries with coarse-textured soils, but long-term sustainability of this option may be limited by other pests and changing regulations.

Pest- and pathogen-free planting stock is essential for successful establishment and future productivity of new orchards and vineyards. Clean stock is also a requirement for intrastate, interstate and international commerce of tree, vine and garden rose planting stock. To ensure the quality of commercially produced nursery stock in the state, the California Department of Food and Agriculture (CDFA) enforces laws and regulations related to the production of certified nursery stock as outlined in the Nursery Inspection Procedures Manual (CDFA 2011). Because of the potentially large and long-term impacts on the nursery crop as well as the subsequently planted orchards, vineyards and ornamental landscapes, control of plant-parasitic nematodes in nursery fields is a major focus of the nursery stock certification program.

Producers of perennial crop nursery stock in California can meet nematode certification requirements by fumigating the field at the beginning of the nursery cycle using an approved treatment or by conducting a detailed inspection of soil and planting stock at the end of the production cycle. If growers elect to use inspection procedures instead of approved treatments and soil or plant samples are found to contain prohibited nematodes, further sampling is conducted to delineate the extent of the problem, and nursery stock from the affected area usually is destroyed.

Preplant soil fumigation thus reduces the economic risk of a nonsalable nursery crop and is used in most tree and garden rose nurseries in California. Grapevine nursery stock also must meet phytosanitary requirements to be certified in California, but in contrast to tree and rose growers, many grape nursery producers elect to use the inspection procedures rather than fumigation. In practice, the risk of nematode occurrence in production of grapevine nursery stock without fumigants is reduced by spring planting, a relatively shorter nursery production cycle and market preference for smaller nursery stock. However, grape nursery operations with sandy soils or sites where grapes have been grown previously often use preplant fumigation practices comparable to tree and rose nurseries to reduce the economic and market risks of not meeting phytosanitary regulations.

Most field-grown perennial nursery operations have used methyl bromide (alone or in combination with

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chloropicrin) for preplant pest control because it effectively diffuses through the soil profile, penetrates roots and dependably provides effective pest control across a range of soil type and moisture conditions. Under the provisions of the U.S. Clean Air Act and the Montreal Protocol, the import and manufacture of methyl bromide is being phased out because of its deleterious effects on stratospheric ozone. Perennial nursery producers have largely continued using methyl bromide under the critical use exemptions (CUE) and quarantine/preshipment (QPS) criteria (US EPA 2010). However, increasing production costs and international political pressure on CUE and QPS regulations have spurred efforts to identify economically viable alternatives to methyl bromide for the perennial nursery industry.

Several factors limit the adoption of alternative fumigants in California nursery systems. First, there are very few fumigant or nonfumigant nematicides available (Zasada, Halbrendt et al. 2010). In the United States only a handful of fumigants are registered, including methyl bromide, 1,3-dichloropropene (1,3-D), chloropicrin, dimethyl disulfide (DMDS), and methyl isothiocyanate (MITC) generating compounds. Of these, DMDS is not currently registered in California and has had only limited testing in nurseries. Methyl iodide (iodomethane) was registered in California in late 2010, but the federal registration was withdrawn by the manufacturer in early 2012.

The nursery certification program and other regulations further limit available alternatives. Of the fumigants registered in the state, only 1,3-D (alone or in combination with chloropicrin or an MITC generator) is an approved treatment in nurseries with medium- to coarse-textured soils (table 1). However, it is not approved for nurseries with fine-textured (e.g., clay loam) soils because the registered rates are not sufficient to provide acceptable pest control.

Most of the alternative fumigants are heavily regulated due to concerns about human safety (workers, bystanders, neighboring populations) and environmental quality related to emission of fumigants and associated volatile organic compounds (VOCs). These concerns have led to a constantly changing regulatory environment, encompassing buffer zones, field preparation requirements, available compounds and rate limitations on a field and air basin level (US EPA 2012). Uncertainty within the nursery industry about current and pending fumigant regulations presents a continuing challenge to the adoption of methyl bromide alternatives in California.

Although fumigation in the perennial crop nursery industry is driven by nematode certification, there are serious concerns that the level of secondary pest control provided by methyl bromide will not be matched by the alternatives. Weed control with many of the available alternatives is generally not as reliable as with methyl bromide (Hanson and Shrestha 2006). Although weeds can be addressed to a large extent with tillage, hand-weeding, and herbicides, there are likely to be environmental and economic impacts of greater reliance on these techniques. More importantly, many nursery producers are very concerned about the consequences of soilborne diseases that are currently controlled with methyl bromide or methyl bromide and chloropicrin combinations. Reliance on alternatives with narrower pest control spectrums may result in problems with new diseases or the resurrection of old ones.

Research has been conducted in recent years to address issues limiting adoption of methyl bromide alternatives in California's perennial crop nursery industry (Hanson and Schneider 2008; Hanson et al. 2010; Jhala et al. 2011; Schneider and Hanson 2009; Schneider et al. 2009). As part of the USDA-ARS Pacific Area-wide Pest Management Program for Integrated Methyl Bromide Alternatives, two additional research and demonstration projects were implemented from 2007 to 2010. First, because current and pending regulations greatly affect how and when fumigants can be used, a research station field trial was conducted to simultaneously determine the effects of emission reduction techniques on pest control and fumigant emissions. Second, two trials were conducted in commercial nurseries

TABLE 1. Summary of currently approved treatment schedules for producing certified nematode-free nursery stock in California*

Material	Application method	Sandy soil	Clay loam soil
		pounds ai/acre	
Schedule A: Sites known to be infested with plant-parasitic nematodes, or not previously treated and with unknown nematode pest status			
Methyl bromide	Tarped†	300	400
Methyl bromide	Dual application‡	300 + 150	400 + 150
Schedule B: Protection for 26-month June-budded crop if soil has been previously treated or tested for nematodes.			
Methyl bromide	Tarped	300	400
Methyl bromide	Dual application	300 + 150	400 + 150
1,3-D	Dual application	313 + 142	Not approved
Schedule C, Chart I: Shallow-rooted nursery plants in place for only one season (strawberry, June-budded fruit trees, or vegetable plants).			
Methyl bromide	Tarped	200	300
Methyl bromide	Dual application	300 + 150	400 + 150
1,3-D	Dual application	285 + 142	Not approved
Schedule C, Chart II: Protection for a 26-month crop			
1,3-D	Tarped	332	Not approved
Schedule D: Lists a series of 1,3-D plus additional fumigants or nematicides with rates adjusted for soil moisture. Several of these treatments are approved by CDFA but not currently allowed due to California registration or label restrictions.			
Schedule E: Lists a series of methyl iodide treatments approved by CDFA; however, the fumigant is not currently registered in California.			

* More detail available from the Nursery Inspection Procedures Manual, Item 7 (CDFA 2011).

† Field is covered with a broadcast application of high-density polyethylene (HDPE) film.

‡ Field is treated once, then the soil is inverted with a plow, and the field is treated with the second application in an effort to fully treat the surface soil layers.

to test and demonstrate pest control and nursery stock productivity with 1,3-D treatments in an effort to increase grower experience and comfort with available alternatives.

Emission flux and efficacy trial

A shank fumigation trial was conducted in 2007 at the UC Kearney Agricultural Center (KAC), near Parlier, to determine the effect of two fumigation shank types and five soil surface treatments on 1,3-D emissions and control of representative soilborne pests following removal of a plum orchard. Soil texture at the site was a Hanford fine, sandy loam with pH 7.2, 0.7% organic matter, and a composition of 70% sand, 24% silt and 6% clay. The experiment included 10 treatments with 1,3-D in a split plot design with surface treatments as the main plots and two application shank types as the subplots, as well as an unfumigated control and a methyl bromide plus chloropicrin standard for comparison (table 2). Individual plots were 12 feet by 100 feet, and each treatment was replicated three times.

Fumigant application. Fumigants were applied using commercial equipment (TriCal, Hollister, CA) on Oct. 2, 2007. Methyl bromide with chloropicrin (98:2) was applied at 350 pounds per acre with a Noble plow rig set up to inject fumigants 10 inches deep through emitters spaced 12 inches apart while simultaneously installing 1-mil high-density polyethylene (HDPE) film. The 1,3-D (Telone II, Dow AgroSciences, Indianapolis, IN) treatments, at 332 pounds per acre, were applied using either a standard Telone rig with shanks spaced 20 inches apart and an injection depth of 18 inches or a Buessing shank rig with shanks spaced 24 inches apart and the fumigant injection split at 16- and 26-inch injection depths. The Buessing shank also had wings above each injection nozzle to scrape soil into the shank trace and minimize rapid upward movement of the fumigant (McKenry et al. 2003).


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In-ground production of perennial nursery stock often begins with a seeded or vegetatively produced rootstock planted in the fall followed by budding or grafting of a preferred scion the following spring. Most nursery fields are fumigated prior to planting the nursery crop in order to meet certification requirements.

Following 1,3-D application, a disk and ring roller was used to level and compact the surface soil before surface seals were applied over the fumigated plots. Average soil temperature at 20 inches during fumigation was 70°F, and soil moisture was 8.2% to 10.5% weight per weight (w/w) in the top 3 feet.

Surface treatments included HDPE film; virtually impermeable film, VIF (Bromostop, Industria Plastica Monregalese, Italy); and a series of intermittent water applications (water seals). HDPE and VIF film was installed after the disk and rolling operation using a Noble plow rig. The intermittent water seals treatment was applied using a temporary sprinkler system installed in the plots following fumigation and the postfumigation tillage operation; water was applied four times in the first 2 days after fumigation: 0.5 inch after 3 hours, 0.2 inch after 12 hours, 0.2 inch after 24 hours and 0.2 inch after 48 hours.

All plastic films were removed 10 days after fumigation. Fourteen days after the initial 1,3-D fumigation, the metam sodium treatment was applied through sprinklers at 160 pounds per acre in 2.75 inches of water. For the dual application treatment, 21 days after the initial treatment, soil was inverted with a moldboard plow and an additional 1,3-D treatment (150 pounds per acre) was applied with

TABLE 2. Treatments in an emission flux study in 2007, a rose nursery in 2007 and a tree nursery in 2008 to evaluate effects of surface treatments and application rigs on nematode, pathogen and weed control with 1,3-D

Treatment	Rate	Surface treatment*	Shank system
	pounds ai/acre		
Untreated	--	--	--
Methyl bromide†	350	HDPE film	Noble plow
1,3-D	332	HDPE film	Standard Telone rig
1,3-D	332	HDPE film	Buessing shank rig
1,3-D followed by metam sodium	332 +160	Bare soil	Standard Telone rig
1,3-D followed by metam sodium	332 + 160	Bare soil	Buessing shank rig
1,3-D	332	Intermittent water seals	Standard Telone rig
1,3-D	332	Intermittent water seals	Buessing shank rig
1,3-D	332	VIF	Standard Telone rig
1,3-D	332	VIF	Buessing shank rig
1,3-D dual application‡	332 + 150	Bare soil	Standard Telone rig
1,3-D dual application	332 + 150	Bare soil	Buessing shank rig

* HDPE, VIF and intermittent water seals were surface seal treatments, while 1,3-D dual application and 1,3-D followed by metam sodium were surface soil treatments.

† The methyl bromide formulation used in these experiments was 98% methyl bromide plus 2% chloropicrin as a warning agent.

‡ 1,3-D dual application treatments were included only in the 2007 rose nursery trial.

the previously described Telone rig and rolling operation.

Emissions data collection. Fumigant emissions from eight 1,3-D treatments — two application shank types times four surface seal methods (bare soil, water seals, HDPE, VIF) — were monitored in three replicate plots for 10 days following the initial application. Emission of 1,3-D from the soil surface was monitored using previously described dynamic flux chamber techniques (Gao and Wang 2011; Gao et al. 2011). Briefly, a flow-through flux chamber with a 10-inch-by-20-inch opening was installed on the surface (of the soil or plastic film) following fumigant injection and installation of the films or after the initial water seal treatment (chambers were relocated after each subsequent water seal).

These chambers allow semi-automated, continuous sampling of fumigant concentrations in the air above the surfaces. The *cis*- and *trans*-isomers of 1,3-D were trapped in charcoal sampling tubes (Orbo-32 standard charcoal tubes, Supelco, Bellefonte, PA). The two 1,3-D isomers were summed as total 1,3-D for data analysis and reporting. Individual tubes were removed from the flux chambers every 3 to 6 hours and stored frozen until laboratory processing. Emission flux and cumulative emission during the 10-day monitoring period were calculated based on surface area and air flow rates through the flux chambers, and treatment differences were compared using analysis of variance (SAS v.9.1, SAS Institute, Cary, NC).

The concentration of 1,3-D in the soil-gas phase was determined 6, 12, 24, 48, 120 and 240 hours after treatment. At each time point, samples were collected using a multiport sampling probe and a system of gas-tight syringes to draw air from eight depths (0, 2, 4, 8, 12, 18, 24 and 36 inches) through charcoal sampling tubes. Samples were stored frozen until analysis.

In the laboratory, all samples were processed using procedures described by Gao et al. (2011). Briefly, sample tubes were broken and trapped fumigants were extracted from the trapping matrix with ethyl acetate and analyzed using a gas chromatograph (Agilent Technology, Palo Alto, CA) equipped with a micro electron capture detector (µECD).

Pest control data collection. Pest control efficacy was evaluated using citrus nematode bioassay counts, fungal dilution plating, and weed emergence counts and biomass collections from each replicated plot. The pest control data from this research station emission flux experiment were reported in Jhala et al. (2011).


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Depending on the crop, dormant bare-root plants are harvested 14 to 26 months after budding or grafting. If the field was not fumigated before planting, plants and soil are inspected at harvest. If nematodes are present, the crop usually is destroyed.

Rose and tree nursery trials

In addition to the emission flux and efficacy study conducted at KAC, two field trials were conducted in commercial nurseries to evaluate pest control efficacy and nursery stock productivity. Fumigation and surface treatments in the nursery experiments were the same as in the flux study with minor exceptions (table 2). The commercial nursery trials were arranged as randomized complete block experiments with a split plot arrangement of 1,3-D treatments. The whole plot factor was surface treatment, and the split plot factor was the shank type. Individual plots in these experiments were 22 feet by 90 feet, and each treatment was replicated four times.

Fumigant application. In 2007, the experiment was established in a garden rose nursery near Wasco. The soil at the rose nursery site was a McFarland loam with pH 6.2, 0.9% organic matter and 74% sand, 13% silt and 13% clay. Treatments were applied on Nov. 7, 2007, when the soil temperature was 64°F and soil moisture averaged 9.2% w/w from 2 to 5 feet. The experiment was repeated in 2008 in a deciduous tree nursery near Hickman, in a Whitney and Rocklin sandy loam soil with pH 6.5, 0.8% organic matter, and 66% sand, 23% silt and 11% clay. Treatments in the tree nursery trial were applied on Aug. 13, 2008, when the soil was 80°F and soil moisture ranged from 5.0% to 12.6% w/w in the top 5 feet.

Immediately following 1,3-D application, a disk and roller were used to compact the soil and disrupt shank traces and HDPE and VIF were installed using the Noble plow rig. For the water seal main plots, a temporary sprinkler system was installed after the postfumigation tillage operation and intermittent water seals were applied: 0.5 inch after 3 hours, and 0.2 inch each after 12, 24 and 48 hours.

The dual application 1,3-D treatments were applied in the garden rose experiment on Nov. 28, 2007, but were not included in the 2008 tree nursery experiment. Metam sodium (150 pounds per acre) was applied in 2.75 inches of irrigation water through sprinklers 14 to 30 days after the initial 1,3-D treatment in both experiments. All plastic films were removed 2 to 3 weeks after fumigation at both sites.

Crop production and data collection. Both nursery trials were managed by the cooperating growers using their standard practices for planting, fertilization, in-season tillage and budding and harvest operations. In the 2007 rose experiment, two rows each of the rose rootstock 'Dr. Huey' and the own-rooted garden rose variety 'Home Run' were planted as hardwood cuttings in December 2007. Rose nursery stock was planted 7 inches apart in furrows spaced 3 feet apart, and the field was furrow irrigated during the 2008 and 2009 growing seasons. The own-rooted cultivar was harvested after one growing season in January 2009, and the unbudded 'Dr. Huey' rootstock was harvested in February 2010 after an additional growing season. At both harvest dates, all plants in one 90-foot row were lifted using a single-row undercutting digger, plants were bundled and tagged by plot, and graded in a commercial packinghouse.

In the 2008 tree nursery trial, two rows each of the peach rootstock 'Nemaguard' (from seed) and the plum rootstock 'Myro 29C' (hardwood cuttings) were planted with 8 inches between plants and 5 feet between rows in December 2008. The tree nursery plots were sprinkler irrigated during the 2009 growing season. Due to the market needs of the cooperating nursery, the rootstocks in the tree trial were not available for harvest and grading as a part of the experiment.

Pest control efficacy and crop productivity were evaluated during the 12- or 26-month nursery production cycle. Nematode control was determined using a citrus nematode bioassay in which two sets of muslin bags containing 100 grams of soil infested with citrus nematode (*Tylenchulus semipenetrans* Cobb) were buried at 6, 12, 24 and 36 inches below the soil surface in each plot prior to fumigation. The initial population of citrus nematodes in infested soil was 4,086 and 3,876 nematodes per 100 cubic centimeters of soil in 2007 and 2008, respectively. The bags were recovered 1 month after fumigation, nematodes were extracted from 100 cubic centimeters of soil using the Baermann funnel protocol, and surviving nematodes were identified and counted.

To evaluate the effect of fumigation treatments on soil fungal populations, ten 1-inch-by-12-inch soil cores were collected from each subplot 2 weeks after fumigation. Soils were homogenized, and a subsample was assayed for *Fusarium oxysporum* Schlecht. and *Pythium* species using dilution plating techniques on selective media. *Pythium* species samples were plated on P_5ARP medium for 48 hours, and *F. oxysporum* samples were plated on Komada's medium for 6 days.


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At a 2-acre commercial rose nursery trial near Wasco, 1,3-D was treated with a combination of application shank types and surface treatments. A similar trial was also conducted at a commercial tree nursery near Visalia.


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'Home Run' and 'Dr. Huey' garden rose cultivars growing in treated plots six months after fumigation with 1,3-D or methyl bromide.

Emerged weeds in a 1-square-meter area were identified and counted twice in the winter following the fall fumigation and several times during the subsequent summer growing season.

Nursery stock establishment, vigor and growth were monitored during the season. Visual evaluations of crop vigor were made on a scale of 1 to 7, where 7 was the most vigorous and 1 was dead or dying plants. Near the end of the growing season, trunk diameter of 10 plants in each subplot was measured 3 inches above the soil surface using a dial caliper. As previously described, rose nursery stock was harvested and graded to commercial standards ratings, but tree nursery stock was not harvested as a part of the experiment.

Data were subjected to analysis of variance, and initial analyses indicated that the shank types (i.e., standard vs. Buessing shanks) did not differ in their effect on any of the pest control or crop growth parameters measured. Thus, data from the two shank type treatments were grouped together within surface treatments and reanalyzed with seven treatments (2007) and six treatments (2008). The nematode, pathogen and weed density data were transformed [ln (x + 1)] to stabilize the variance prior to analysis; however, means of untransformed data are presented for clarity. Treatment means were separated using Fisher's protected least significant difference (LSD) procedure with α = 0.05.

KAC emission flux results

Emission flux. Within a surface treatment, there were no statistical differences in emission flux between the two application shank types, thus data were combined over application rig. However, significant differences in 1,3-D emission flux were observed among surface treatments (fig. 1). Fumigant emission flux from bare plots was two times higher than from water seals and HDPE and nearly 15 times higher than from VIF within 48 hours after treatment. Emission from water-sealed plots was reduced during the sequential water applications, but flux was similar to bare soil plots after 48 hours. HDPE film continued to give lower emission rates than the bare soil and water seals but was significantly higher than VIF. Throughout the monitoring period, VIF-covered plots had the lowest 1,3-D emissions; maximum flux was 11 micrograms per square meter per second (µg $\text{m}^{-2}\ \text{s}^{-1}$), which was at least 90% lower than that from the bare soil plots. Relative to the bare soil treatment, estimated cumulative 1,3-D emission losses for water seals, HDPE and VIF were 73%, 45% and 6%, respectively, which were similar to reports from a previous field study (Gao et al. 2011).

Headspace 1,3-D concentration. Concentration of 1,3-D immediately below the plastic film (headspace) indicated that 1,3-D retention is much greater under VIF film than under HDPE (fig. 2). Several other studies have shown that VIF can retain substantially higher fumigant concentrations without negatively affecting nematode, pathogen and weed control efficacy or crop yield (Fennimore and Ajwa 2011; Hanson et al. 2010).

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Large-plot soil fumigation experiments in commercial nurseries test and demonstrate available methyl bromide alternatives under real-world conditions. *Above*, HDPE application at a tree nursery trial near Yuba City, CA.

Fumigant distribution in soil. Initial analysis of fumigant distribution in the surface 90 centimeters (3 feet) indicated that there were no differences between the application shanks within a surface treatment in this zone; thus data were combined over application shank types (fig. 3). The 1,3-D concentration was highest near the injection depth, at 45 centimeters (18 inches) and lowest near the soil surface, at 5 centimeters (2 inches), and at 90 centimeters (3 feet), but this difference diminished over time.

The effect of depth on 1,3,-D concentration was most evident in water seals and bare soil plots. HDPE and VIF plots had more uniform distribution of the fumigant through the soil profile (5 to 90 centimeters, 2 to 36 inches) than the water seals plots, especially 48 hours after treatment. However, 1,3-D concentration under the VIF tarp was markedly higher than in all other treatments, which suggests that there could also be differences in the top 5 centimeters (2 inches) of soil. These results imply that the use of a highly impermeable tarp can lead to a more uniform distribution of fumigants in the soil profile and may allow satisfactory pest control with reduced application rates (Fennimore and Ajwa 2011; Gao et al. 2011; Hanson et al. 2010).

Soilborne pest control. Pest control data from the 2007 KAC emissions trial and a related 2008 emissions trial were reported previously (Jhala et al. 2011) and are not shown here. In general, however, there were few differences in pest control attributed to the fumigant application shanks used in the trial. *Pythium* species populations were lower in all treatments than in the untreated control, but no statistical differences were noted in *Fusarium* species populations among treatments. The high 1,3-D rates and well-prepared soils resulted in complete control of citrus nematodes in the bioassay bags in all treatments and depths.

Weed populations were variable among treatments but tended to be lowest in methyl bromide plots and 1,3-D plots sealed with VIF and highest in the water seals and dual 1,3-D application treatments.

Commercial nursery results

Nematodes and soilborne pathogens. All treatments of 1,3-D or methyl bromide effectively controlled citrus nematodes in bioassay bags buried at 12-, 24- and 36-inch depths in each plot. However, these results, which were obtained in

TABLE 3. Effects of surface treatments with 1,3-D on *Fusarim* and *Pythium* spp. propagules in a commercial rose nursery in 2007 and tree nursery in 2008

	Rose nursery				Tree nursery			
Treatment	*Fusarium*		*Pythium*		*Fusarium*		*Pythium*	
	*colony forming units/gram soil**							
Untreated	5.4	a	14.8	a	101.5	a	99.5	a
Methyl bromide	0.0	b	0.0	b	0.0	c	0.0	c
1,3-D dual application	0.0	b	1.9	b	—†		—	
1,3-D (HDPE film)	0.4	b	0.9	b	6.2	b	0.2	c
1,3-D (VIF)	0.8	b	0.6	b	2.1	bc	0.0	c
1,3-D followed by metam sodium	1.0	b	6.8	a	137.4	a	3.1	b
1,3-D (water seals)	0.0	b	7.5	a	65.7	a	11.4	b

* Representative soil samples were collected in the surface 12 inches of each plot. The data were log transformed [ln (x + 1)] for homogenous variance prior to analysis; however, data presented here are the means of actual values for comparison. Least square means within columns with no common letters are significantly different according to Fisher's protected LSD test where $P < 0.05$.

† The 1,3-D dual application treatment was not included in the 2008 tree nursery trial.

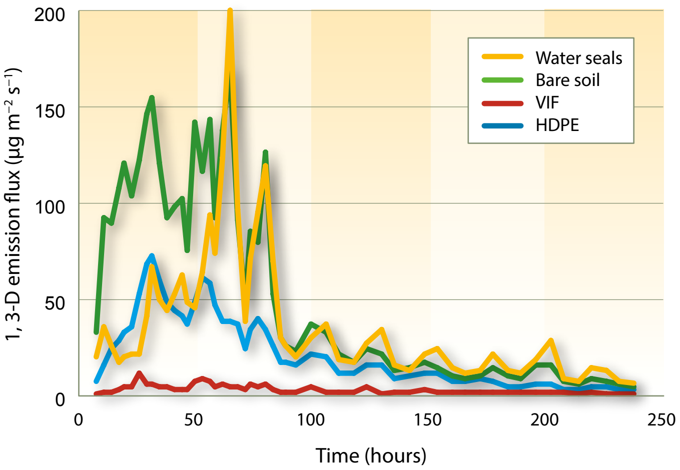

Fig. 1. Emission flux of 1,3-dichloropropene (1,3-D) with different surface treatments in a 2007 Kearney Agricultural Center field trial, near Parlier. Data were collected from three replicate plots and averaged over two application shank types ($n = 6$).

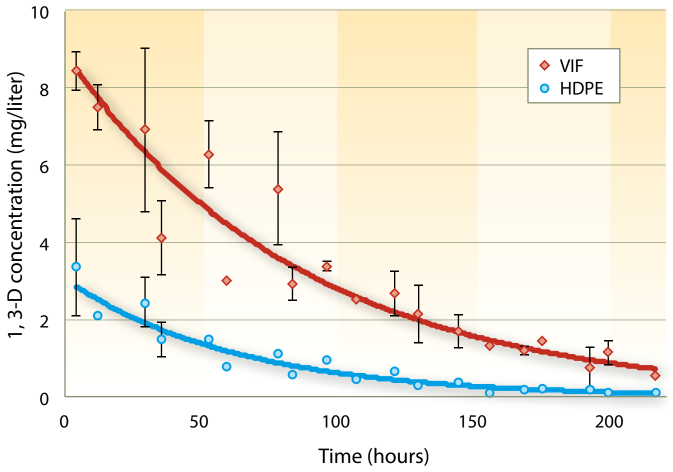

Fig. 2. Air concentration of 1,3-D between the soil surface and plastic film following application of 332 pounds per acre Telone II sealed with VIF or HDPE film ($n = 3$) in a 2007 Kearney Agricultural Center field study, near Parlier.

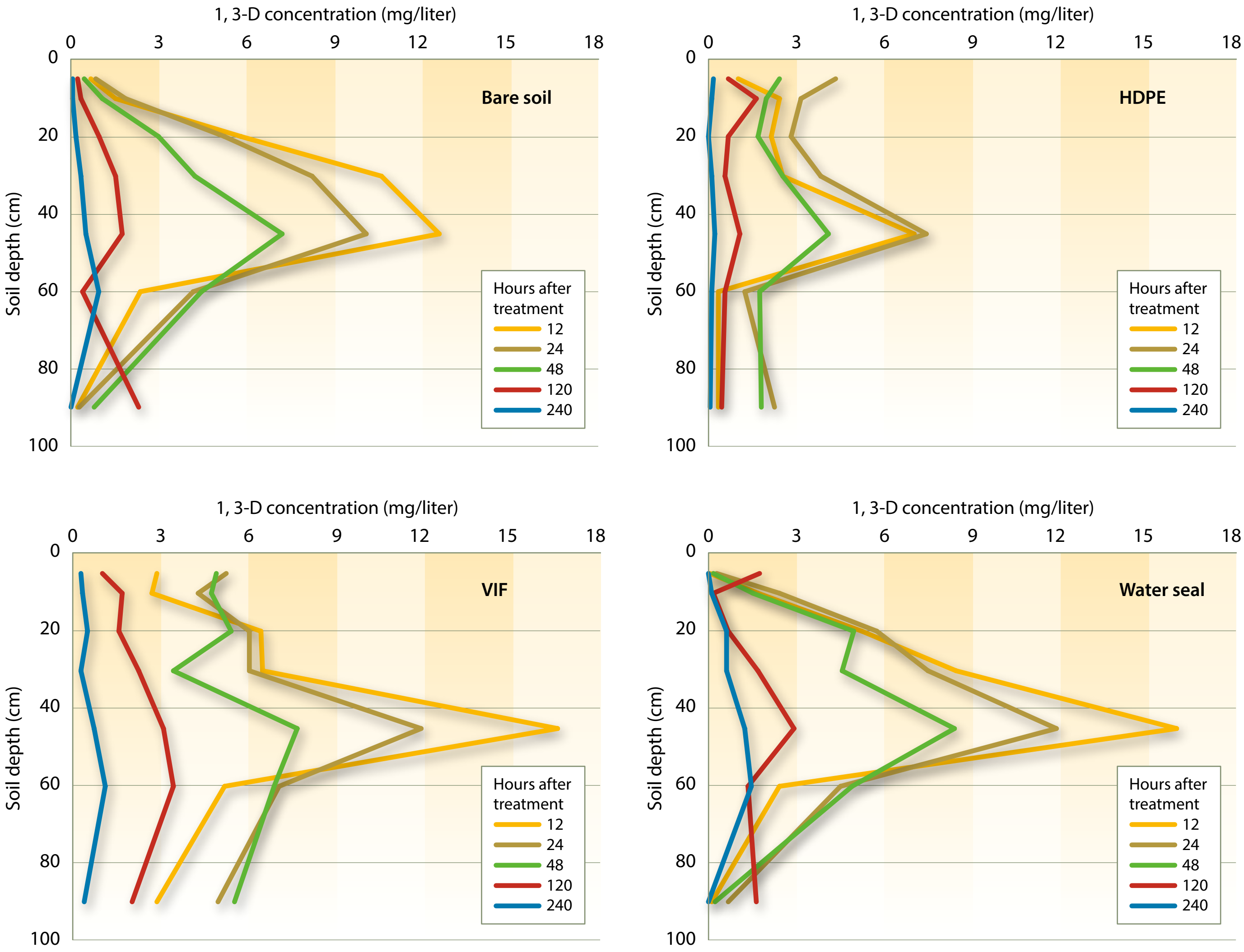

Fig. 3. Distribution of gas 1,3-D in the soil profile after shank injection in a 2007 Kearney Agricultural Center field study, near Parlier. Data were collected 12, 24, 48, 120 and 240 hours after treatment from three replicate plots and are averaged over two application shank types ($n = 6$).

well-prepared sandy soils with low pest and pathogen populations, may not apply to more challenging field conditions (Hanson et al. 2010). Applications of 1,3-D sealed with HDPE or VIF and dual application 1,3-D treatments reduced *Fusarium* and *Pythium* species propagules in the soil compared with the untreated plots (table 3). These treatments were comparable to methyl bromide in controlling *Fusarium* and *Pythium* species.

Soil pathogen control with 1,3-D followed by metam sodium and 1,3-D with intermittent water seals was inconsistent between the two experiments, which suggests that specific micro- and macro-level differences in environmental and field conditions may contribute to greater treatment variability and risk to growers.

Weed density. When 1,3-D was sealed with HDPE and VIF, broadleaf weed density was reduced to less than 6 weeds per square meter, which was comparable to methyl bromide (table 4). These results are similar to a previous nursery study that indicated 1,3-D or 1,3-D plus chloropicrin sealed with HDPE or VIF resulted in weed seed viability and hand-weeding time comparable to methyl bromide (Shrestha et al. 2008). Generally, intermittent water seals after a 1,3-D application resulted in broadleaf weed density similar to the untreated control. Most weeds germinate near the soil surface, thus techniques such as intermittent water seals that limit upward fumigant movement into surface soils can adversely affect weed control. The other surface treatments 1,3-D dual application and 1,3-D followed by metam sodium) had intermediate broadleaf weed densities compared to untreated plots and methyl bromide.

All fumigation treatments reduced grass weed populations compared to the control plots; however, the greatest reductions were observed in plots treated with methyl bromide, 1,3-D sealed with HDPE or VIF, and 1,3-D followed by metam sodium. It was clear in this study that effective surface treatments can greatly increase weed control with 1,3-D; however, even the best treatments will likely require supplemental weed control to meet grower expectations.

Stock vigor and performance. Effects of surface seal treatments and 1,3-D soil fumigation on nursery stock vigor and performance in two nursery trials were evaluated in 2007 to 2010 (table 5). In the rose nursery trial, all treatments had similar rootstock vigor and number of marketable plants except when 1,3-D was followed by metam sodium. During the 2008 growing season, roses grown in plots treated with 1,3-D followed by metam sodium had lower vigor than the other treatments; however, by harvest at the end of the second year, no differences in marketable plants were observed.

In the tree nursery trial, tree rootstock vigor was reduced in plots treated with 1,3-D followed by metam sodium and

TABLE 4. Effects of surface seal treatments with 1,3-D on broadleaf weed density in a commercial rose nursery trial in 2007 and on broadleaf and grass weed density in a tree nursery trial in 2008

	Rose nursery							
	'Home Run'		'Dr. Huey'		Tree nursery			
Treatment	Broadleaf		Broadleaf		Broadleaf		Grass	
	*weeds/sq meter**							
Untreated	32.5	a	44.7	a	243.7	a	24.3	a
Methyl bromide	0.6	c	0.4	c	5.4	c	0.0	c
1,3-D dual application	11.8	b	1.9	c	—†		—	
1,3-D (HDPE film)	2.3	c	0.6	c	6.0	c	0.0	c
1,3-D (VIF)	1.7	c	0.7	c	4.1	c	0.1	c
1,3-D followed by metam sodium	15.2	b	3.3	c	23.3	b	0.1	c
1,3-D (water seals)	29.0	a	16.7	b	182.1	a	9.1	b

* The data of weed density were log transformed [ln (x+1)] for homogenous variance prior to analysis; however, data presented here are the means of actual values for comparison. Least square means within columns with no common letters are significantly different according to Fisher's protected LSD test where $P < 0.05$.

† The 1,3-D dual application treatment was not included in the 2008 tree nursery trial.

TABLE 5. Effects of 1,3-D soil fumigation and surface treatments on vigor and performance of plants in two commercial nursery trials near Wasco and Hickman, CA, 2007–2010

	Rose nursery, 2007–2010										Tree nursery, 2008–2010			
Treatment	'Dr. Huey' rootstock vigor* 8/29/08		'Home Run' rose vigor 8/29/08		Marketable 'Home Run' plants† 1/28/09		'Dr. Huey' rootstock vigor 10/16/09		Marketable 'Dr. Huey' rootstock† 2/03/10		Tree rootstock vigor 5/09/09		Rootstock trunk caliper 4/07/10	
	1–7 scale				*No./90 ft row*		*1–7 scale*		*No./90 ft row*		*1–7 scale*		*mm*	
Untreated	4.5	A‡	4.3	a	60.0	a	4.3	a	94.7	ab	2.3	c	19.2	a
Methyl bromide	4.8	a	5.0	a	66.3	a	4.3	ab	101.5	ab	5.8	a	22.2	a
1,3-D dual application	4.8	a	4.6	a	57.5	a	3.9	ab	103.1	b	—§		—	
1,3-D (HDPE) film	5.1	a	4.8	a	55.0	a	4.0	ab	96.8	ab	4.2	ab	19.2	a
1,3-D (VIF)	5.1	a	5.3	a	59.4	a	4.5	a	89.1	a	4.2	ab	23.0	a
1,3-D followed by metam sodium	2.5	b	2.0	b	21.9	b	3.5	b	96.5	ab	3.6	bc	21.6	a
1,3-D (water seals)	4.0	a	4.3	a	55.6	a	3.5	b	93.6	ab	3.2	bc	21.2	a

* Vigor was estimated using a scale where 7 was the most vigorous and 1 was dead or dying plants.

† One row of the dormant nursery stock from each plot was harvested and graded according to commercial standards. Marketable roses included the own-rooted 'Home Run' roses or unbudded 'Dr. Huey' rootstock plants graded as #1 size with no visual root or cane defects.

‡ Least square means within columns with no common letters are significantly different according to Fisher's protected LSD test where $P < 0.05$.

§ The 1,3-D dual application treatment was not included in 2008 trial.

1,3-D with intermittent water seals compared with the other fumigation treatments, but rootstock caliper at the end of the first growing season did not differ among treatments.

Continuing challenges

Compared with some other fumigation-dependent industries, perennial fruit and nut nursery stock production systems face a more difficult transition to methyl bromide alternatives (Zasada, Walters et al. 2010). Despite several years of research, the following significant challenges to widespread adoption of alternatives in the perennial crop nursery industry remain: (1) National and international market expectations for nematode-free nursery stock limit nursery stock producers to alternatives with very high nematode efficacy at significant depths in the soil. (2) To meet California nursery certification requirements, producers are required to use approved fumigant treatments or conduct a postproduction inspection. A failed inspection may result in an essentially nonsalable crop. (3) Most alternative treatment schedules are based on the use of 1,3-D (with or without chloropicrin), a fumigant that faces its own serious and evolving regulatory issues in California. (4) No currently available alternative fumigant can be used in California to meet certification requirements in nurseries with fine-textured soil at registered rates. (5) Methyl iodide, the alternative fumigant with performance most similar to methyl bromide, is not currently registered in the United States due to a voluntary withdrawal by the manufacturer. (6) Concerns over control of weeds and fungal and bacterial pathogens in the short and long term may further limit adoption of alternatives with a narrower pest control spectrum. (7) Containerized nursery stock production systems are being used in some parts of the industry, but the production costs, market acceptance and long-term viability of this system have not been addressed at the required scale.

The cost of producing perennial nursery stock using more expensive, laborious or economically risky production methods . . . could have long-term impacts on the nursery, orchard, vineyard and ornamental industries.

Adoption of methyl bromide alternatives, where they exist, in the perennial crop nursery industry will ultimately be driven by state and federal regulations and economics. Although it's heavily regulated, 1,3-D is a viable alternative for growers with coarse-textured soil, but if 1,3-D becomes more difficult to use due to shortages or increasingly stringent regulations, it may be only a short-term solution. No viable fumigant alternatives exist for California nurseries with fine-textured soil, and some of them may be unable to produce certified nursery stock in the absence of methyl bromide. The cost of producing perennial nursery stock using more expensive, laborious or economically risky production methods will ultimately be passed on to customers and could have long-term impacts on the nursery, orchard, vineyard and ornamental industries.

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RESEARCH ARTICLE ABSTRACT

Soil type, crop and irrigation technique affect nitrogen leaching to groundwater

by John Letey *and* Peter Vaughan

Many groundwater resources in California are degraded by high concentrations of nitrate, most of which was transported to the groundwater in water percolating below the root zone of agricultural fields. Factors that affect the rate of water percolation — including soil type, crop and irrigation — along with nitrogen application influence the probability of this type of groundwater degradation. UC scientists have developed several useful tools, including the Nitrogen Hazard Index (NHI) and the ENVIRO-GRO (E-G) model, for use in developing best management practices (BMPs) to achieve high crop yields while minimizing groundwater degradation. We report the results of E-G simulations that quantify the effects of irrigation, soil type and organic and inorganic nitrogen (N) application amounts to corn yield and the amount of leached N. Simulation results indicate that a nitrate management strategy that also includes water management will be more effective in reducing N loading to groundwater. The research findings are discussed in the context of the track and report concept in comparison to the BMP approach.

The ENVIRO-GRO model simulates the consequences of irrigation water salinity and management practices on crop yield and nitrate leaching. Simulations indicate that strategies to minimize groundwater degradation must also include water management practices to be effective.

The downward percolation of nitrate-laden water from agricultural fields is a major contributor to the high levels of the contaminant found in many California groundwater resources (Viers et al. 2012). Many assume that this condition results from the excessive application of nitrogen (N) fertilizer to crops.

The word “excessive” can have any of several connotations, and because the term usually is not clearly defined in this context it can be taken by any number of people to mean any number of things. Excessive application could mean that more N is applied to the soil than can be removed by the crop, and there is no question that most agricultural applications could be included in this definition. Another definition would say that excessive application means that more fertilizer is applied than would be required to achieve high yields and maximum profits.

High yields and maximum profits almost always require the application of more N to the soil than is removed by the crop. Whether growers have historically applied more N than was necessary to obtain maximum profits is not clear and probably cannot be determined.

Other management factors (e.g., irrigation) have a great impact on the relationships between the amount of fertilizer applied, the crop yield, and the deep percolation of nitrate. Strategies that are intended to reduce nitrate degradation of groundwater but that ignore complex dynamic relationships with other management factors are likely to fail.

Nitrate reaches groundwater only by being transported by water that percolates through the soil, a factor often disregarded when assessing the relationship between fertilizer application and nitrate degradation of groundwater. Every crop requires sufficient water to meet its evapotranspiration (ET) needs, and any irrigation or precipitation that exceeds the soil’s water-holding capacity in the root zone will cause soluble chemicals, including nitrate, to leach into deeper groundwater. The amount of N that is leached varies with time and with the amount of water flow and the N concentration in the soil water at the time leaching occurs.

The rate of N uptake by a crop varies with its growth stage and, in cases of N deficiency, may also depend on the N concentration in the soil water. Total plant dry matter production usually has a linear relationship to ET. Therefore, if plant growth is reduced because there is too little water, too much salinity, or too little N, the plants will have less dry matter production and less ET, which means that any given irrigation regime will result in more leaching (Pang and Letey 1999).

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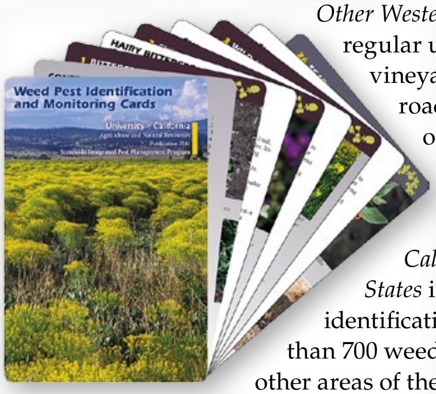

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Soil type, crop and irrigation technique affect nitrogen leaching to groundwater

by John Letey *and* Peter Vaughan

Many groundwater resources in California are degraded by high concentrations of nitrate, most of which was transported to the groundwater in water percolating below the root zone of agricultural fields. Factors that affect the rate of water percolation — including soil type, crop and irrigation — along with nitrogen application influence the probability of this type of groundwater degradation. UC scientists have developed several useful tools, including the Nitrogen Hazard Index (NHI) and the ENVIRO-GRO (E-G) model, for use in developing best management practices (BMPs) to achieve high crop yields while minimizing groundwater degradation. We report the results of E-G simulations that quantify the effects of irrigation, soil type and organic and inorganic nitrogen (N) application amounts to corn yield and the amount of leached N. Simulation results indicate that a nitrate management strategy that also includes water management will be more effective in reducing N loading to groundwater. The research findings are discussed in the context of the track and report concept in comparison to the BMP approach.

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The word “excessive” can have any of several connotations, and because the term usually is not clearly defined in this context it can be taken by any number of people to mean any number of things. Excessive application could mean that more N is applied to the soil than can be removed by the crop, and there is no question that most agricultural applications could be included in this definition. Another definition would say that excessive application means that more fertilizer is applied than would be required to achieve high yields and maximum profits.

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Nitrate reaches groundwater only by being transported by water that percolates through the soil, a factor often disregarded when assessing the relationship between fertilizer application and nitrate degradation of groundwater. Every crop requires sufficient water to meet its evapotranspiration (ET) needs, and any irrigation or precipitation that exceeds the soil’s water-holding capacity in the root zone will cause soluble chemicals, including nitrate, to leach into deeper groundwater. The amount of N that is leached varies with time and with the amount of water flow and the N concentration in the soil water at the time leaching occurs.

The rate of N uptake by a crop varies with its growth stage and, in cases of N deficiency, may also depend on the N concentration in the soil water. Total plant dry matter production usually has a linear relationship to ET. Therefore, if plant growth is reduced because there is too little water, too much salinity, or too little N, the plants will have less dry matter production and less ET, which means that any given irrigation regime will result in more leaching (Pang and Letey 1999).

Both positive and negative feedback loops between plant growth and soil condition can be observed, depending on circumstances. For example, if salinity in the soil reduces plant growth, the reduction

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in plant growth will reduce ET, resulting in greater leaching of salts, which will to some degree remedy the salinity problem. This is a positive feedback mechanism. However, if both plant growth and ET are reduced by a lack of adequate N or by other factors, leaching of nitrate will increase, further reducing the nitrate content of the root zone, thereby intensifying the problem. One consequence of this negative feedback mechanism is that any attempt to decrease nitrate leaching by reducing N applications may be counterproductive if the reduced N input further reduces plant growth, which would in turn increase N leaching. Groundwater degradation by nitrate is related both to time-dependent fertilizer and to water management.

N results from grower field studies

Based on extensive field research during the 1970s, it is fair to say that the optimal (i.e., profit-maximizing) amount for N application is dictated by the amount of precipitation and irrigation. That research focused on a total of 55 fields drained by tile systems and 31 naturally drained fields that did not have a shallow water table (Letey et al. 1977, 1979). By looking at the rate at which water discharged into the tile systems and the nitrate concentration of water samples collected in the tile systems, researchers were able to calculate how much nitrate in total was discharged into the tile systems. For the natural drainage studies, researchers drilled into the soil and analyzed samples from various depths, usually reaching to a depth of 50 feet. Procedures were then developed to calculate the rate of water flow through the soil profile. This water flow rate, multiplied by the nitrate concentration, provided an estimate of the nitrate leached below the root zone. Researchers obtained information on fertilizer application from the growers.

Results were similar for both systems: the correlation coefficient between the amount of N leached and the drainage volume was greater than the coefficient for the amount of N applied. This suggests that irrigation management is at least equal in importance to, and possibly of greater importance than, fertilizer application in affecting the leaching of nitrate. As expected, the highest correlation coefficient was between the amount of nitrate leached and a combination of drainage volume and fertilizer application, indicating that both factors are important.

Importantly, there was no significant correlation between the nitrate concentration of the drainage water and either the amount of fertilizer applied or the drainage volume. The linear regression analysis for all the tile systems resulted in the equation

$$C = 29.4 - 0.0007N$$

where C is the average nitrate-nitrogen concentration (mg/L) and N is the amount of fertilizer N applied (kg/ha) (Letey et al. 1977). Usually only the concentration is measured and there is no measurement of the water flow, making it impossible to calculate the discharge load. By itself, the numerical value of the concentration is of little value, and it may even lead one to make erroneous conclusions.

Irrigation management decisions dictate what nitrogen management options are available for achieving high yield with low groundwater degradation.

Growers are very observant when it comes to crop behavior. They may not know the amount of drainage volume from a given field, but they will know the crop yield. Our researchers hypothesized that growers would be likely to apply more N to fields that were N-deficient because the fields had a high drainage volume. Indeed, the experimental data supported this hypothesis. A linear regression analysis for naturally drained fields resulted in the equation

$$N = 78.8 + 4.07W, \text{ with } r = 0.618$$
$$\text{(significant at the 1\% level)}$$

where N is the fertilizer applied (kg/ha/yr) and W is the amount of drainage water (cm/yr). The tile drain systems yielded

$$N = 275 + 2.85W, \text{ with } r = 0.524$$
$$\text{(significant at the 5\% level)}$$

Greater drainage flows, therefore, induced growers to increase their N applications.

From the past to the future

If we simply assume that the large quantities of nitrate that migrated to groundwater decades ago were the exclusive result of excessive N applications, we may not be correct. The cause is just as likely to be related to irrigation management as to fertilizer management. Irrigation at the time in question was almost entirely applied as gravity flow rather than through pressurized irrigation systems. With gravity flow, the irrigator has little control over how much water infiltrates the soil, because the infiltration opportunity time (the amount of time when water is flowing over the soil) within the furrow and the hydraulic properties of the soil can vary so much. Pressurized irrigation systems allow more precise control over the amount and uniformity of water application and partially negate the effects of some soil properties, such as infiltration rate.

Another reason growers might purposely apply excess water is that they might be concerned that they could salinate the soil. Historical accounts of growers salinating soils in irrigated, semi-arid regions of the world are well known. Growers were educated about the need to leach salts from the root zone, and they considered this when setting up their irrigation practices. The leaching of destructive salts, though, also leaches out beneficial nitrate. Less efficient irrigation systems and the perceived need to leach salts contributed to high leaching of N and the resultant requirement for additional N application.

One reason to conclude that growers apply more N than is required for high crop yield is the common belief that growers typically apply more N than is recommended by universities and other research organizations. However, because those recommendations are commonly based on research done on small plots with carefully controlled irrigation, they may not apply so readily to the real-world conditions in many growers' fields. According to the results reported above, growers do tend to apply more N on a field that has a higher drainage volume. This supports the conclusion that growers do base their N applications at least partly on their field observations on yield.

Many growers and researchers may not have considered that converting gravity flow systems to pressurized systems provides an opportunity to reduce deep percolation and even reduce the amount of fertilizer applied without reducing crop yield. Field observation can show where too little N has been applied, but for most crops you cannot visually detect signs of excess application.

The availability of soluble commercial N fertilizer has been cited as a cause for the high levels of nitrate that have historically reached groundwater. Some maintain that organic forms of N have less potential to migrate below the root zone than inorganic forms. As will be demonstrated later, this is not always the case, and if the cause of a problem is misdiagnosed, the prescribed cure may not be effective.

If we were to assume, for instance, that the huge, long-term buildup of nitrate in groundwater is a result of a history of excessive N applications rather than a history of excessive water applications, we would be inclined to take poor, and possibly counterproductive, actions in an attempt to improve the situation. Regulations that attempt to reduce groundwater degradation by focusing strictly on the amount of N applied, without consideration for the interactions between the amounts and timing of both fertilizer and water applications, most likely will not achieve their desired goal. Furthermore, each individual crop, soil and irrigation technology comes with its own challenges and opportunities that must be assessed.

The Nitrogen Hazard Index (NHI) was developed by UC scientists and is available online at http://ciwr.ucanr.edu/Tools/Nitrogen_Hazard_Index/. A farm manager who uses this online tool to input his or her crop, soil and irrigation technology will receive a report that estimates the probability that nitrate will degrade groundwater in the field. The report also ranks the relative significance of effects from the crop, the soil and the irrigation system in terms of their contribution to the overall hazard, so the grower can focus management efforts toward those factors that are doing the most harm. The website also presents guidelines for management practices that minimize degradation according to the specific crop, soil and irrigation technology.


Kevin Connors

Regulations that focus only on the amount of N applied without considering the interactions between the amounts and timing of fertilizer and water applications may not be successful.

The California State Water Resources Control Board (SWRCB) recently submitted a report to the California Legislature with recommendations that address nitrate problems in groundwater (SWRCB 2013). The report emphasized the quantity of nitrogen applied but gave little recognition to the influence of irrigation management. The report specified high-risk areas for nitrate problems, but identified those areas only on the basis of hydrogeological conditions.

The report's authors cite a map that identifies areas at high risk for groundwater contamination with MTBE (methyl tertiary-butyl ether, a now-banned gasoline additive), which reached groundwater through leakage from underground storage tanks, and go on to assume that areas vulnerable to MTBE are also vulnerable to nitrate. This assumption, however, ignores all of the dynamic interactions that occur in the root zone and control the movement of nitrate below the root zone. Only after the nitrate has migrated below the root zone can its movement be affected by the hydrogeological features that affect the movement of MTBE. If only a small amount of nitrate migrates below the root zone, the risk that significant quantities of nitrate will move through the groundwater is small. The real probability of risk is related to the crop, soil and irrigation system as assessed using the NHI, and that is the proper means for determining likely problem areas.

Farm-level management is the most effective mechanism for reducing the continued degradation of groundwater from nitrate. A more useful report to the Legislature would have focused on best management practices (BMPs) and would have provided a plan by which they would be implemented on the farm. Management factors that influence both the yield of a specific crop and N leaching include irrigation events and the amount and timing of organic or inorganic N applications. There are other significant factors, such as soil hydraulic properties and rainfall, but those cannot be specifically managed.

Objectives

A major objective of this paper is to present scientific factors concerning the dynamic interactions between soil, crop and irrigation on crop yield and the leaching of nitrate.

ENVIRO-GRO (E-G), a model developed by UC scientists, simulates the consequences of various management factors on crop yield and nitrate movement below the root zone. In this paper, we use E-G to illustrate the effects of organic and inorganic N application amounts, rainfall amounts and irrigation amounts on crop yield and nitrate leaching on two soil types. The effects of soil temperature on the dynamic rate of organic matter mineralization and the implications of this on potential N leaching represent new findings. We discuss these findings as they relate to the NHI and BMP concepts as well as to the proposed track and report system.

The model

The E-G model (Pang and Letey 1998) was developed to simulate (1) water, salt and nitrate movement through soil with a growing plant; (2) plant response to stresses associated with matric water potential, salinity and N deficiency; (3) water, salt and nitrate leaching below the root zone; (4) cumulative relative transpiration and N uptake and (5) consequent crop yields as compared with those of an unstressed crop. The E-G model does not account for denitrification or N immobilization. The model allows us to simulate the consequences of irrigation water salinity and management practices on crop yield and nitrate leaching.

The E-G model has recently been reprogrammed to make it more efficient**.** Modifications include the addition of compensation for N uptake, a two-pool model for organic matter decay, mass balance calculations, comprehensive output routines and improvements to the transport calculations for salt and nitrate. The E-G program and user manual are available online for free at http://ciwr.ucanr.edu/Tools/ENVIRO-GRO. Running the model does require an understanding of using such models and is not useful for the general practitioner.

When you use the tool, you first input certain information: the potential ET as a function of time, the amount and timing of water addition (irrigation or precipitation), the potential N uptake of the crop as a function of time, the amount and timing of N applications, and soil and plant characteristics. The time and amount of application is sufficient for soluble inorganic N, but not for organic forms of N, since they are not immediately available for plant uptake. For organic N, the model also requires its rate of mineralization into inorganic N. One purpose of this paper is to evaluate factors, including soil temperature, that affect the dynamic rate of organic N mineralization.

Organic material mineralization

Pratt et al. (1973) proposed that one could characterize the mineralization of organic materials applied to soil in terms of a decay series, a sequence of numbers representing the fraction of the current organic N amount that can be expected to mineralize in successive years. For example, the decay series [0.40, 0.20, 0.10, 0.05] would indicate that 40% of the organic N would mineralize the first year, 20% of the remaining organic N would mineralize the second year, and so forth. The decay series is an important practical tool for estimating multiyear N mineralization for manure, compost or other organic N materials (Cusick et al. 2006).

Applications of organic N material should be timed to provide mineralized N when it will be needed by the crop, a condition that is hard to evaluate using decay series. A better choice in this case is a continuous decay function that predicts the production of plant-available nitrogen (PAN). It is this function that is required for models such as E-G that have variable time-stepping with intervals that are usually shorter than one day. The upgraded E-G model includes a two-pool decay model that is represented as

$$N_r(t) = (1 - \psi)N_0\exp(^{-}\lambda_1 t) + \psi N_0 \exp(^{-}\lambda_s t) \qquad (1)$$

The initial organic N applied is N_0 (kg/ha), which is divided into a fraction ψN_0 that is assigned to a slow-decay pool and a remaining fraction $(1 - \psi)N_0$ that is assigned to a fast pool (P. Vaughan, unpublished manuscript). The decay coefficients are λ_1 and λ_s for the fast and slow pools, respectively. Numerical values for these coefficients and fraction can be obtained using the decay series.

The relationship between the decay series and equation 1 can be viewed as data points of the decay series and a continuous function that can be fitted to these points. Yearly remaining organic N (N_r) can be calculated from the decay series if one assumes an initial applied amount. The resulting sequence of N_r values can be extended to 10 years under the assumption that decay rates after the final year of the explicit decay series are determined exclusively by the slow pool. The presumed decay coefficient of the slow pool is 0.0101, representing the decay rate of 1% per year that is commonly accepted for soil organic matter (Meisinger et al. 2008). By taking the curve that passes through the N_r values for exclusively slow-pool decay and extrapolating it backward to the application time, one can obtain the value of ψ. The remaining unknown, λ_1, can be determined by curve-fitting equation 1 to all N_r values using a nonlinear least-squares algorithm.

Although mineralization is known to be a temperature-dependent reaction, the effects of temperature variations have not generally been considered in the estimation of mineralization rates. For our work, we averaged the California Irrigation Management Information System (CIMIS) soil temperature data for 2000 through 2011 at Madera, California (site #145), to obtain daily values and then fitted these data to a sine function (fig. 1). Note that there is a great difference in soil temperature between winter and summer. One would expect this temperature difference to impact the temporal rate of mineralization. Vigil and Kissel (1995) proposed an exponential function to describe mineralization rate in the temperature range of 5°C to 30°C:

$$TF = 0.01\exp(0.13T_s) \qquad (2)$$

where TF is the temperature factor and T_s (°C) is soil temperature. These factors were input data for calculating temperature-dependent decay rates in E-G.

Crop and organic material demonstration

Corn *(Zea mays)* was selected as the crop for demonstration because a comparison had already been made between simulated (E-G) results and actual, observed experimental cornfield results. Pang and Letey (1998) compared the simulated results from E-G with field data reported by Broadbent and Carlton (1979) that included three water application treatments and four nitrogen application amounts. The mean relative yield for all observed treatments was 0.69, and 0.64 for simulated treatments. The mean N uptake was 158 kg/ha (observed) and 159 kg/ha (simulated). The poorest agreement between observed and simulated results involved extreme irrigation treatments that would not ordinarily be applied on a working farm. The E-G simulations were also compared to a cornfield experiment in Israel that included four irrigation water salinities and four irrigation intervals, though no N data were available (Feng et al. 2003). The mean relative yields were 0.68 (observed) and 0.70 (simulated). Overall, the model has been shown to produce values that are comparable to real-world values for corn crops.

The required model input information for a cornfield is also available from a study in the San Joaquin Valley. The total N uptake was measured as a function of time for 3 years (Feng et al. 2005). Based on these data, the potential N uptake rate as a function of time was computed as 300 kg/ha total.

Ninety percent of the organic material selected for illustration mineralized in 1 year and the other 10%, in the slow pool, mineralized at a rate of 1% per year. This approximates the results that Pratt et al. (1973) reported for chicken manure, with a decay series of 0.90, 0.10, 0.05. An organic N fertilizer that is known to mineralize almost entirely in 1 year was chosen in order to avoid large carryovers of unmineralized N in successive years that would continue to accumulate and require complex multiyear simulations.

The cumulative N uptake by corn and the cumulative amount of mineralized N from an application of manure that contained 370 kg/ha of N were computed as a function of time for manure applications on Jan. 1, April 1, May 15 or Oct. 1. Only the October and April applications are represented in figure 2. The mineralization amounts illustrated are adjusted for temperature-dependent effects (TD) or presented with the assumption of constant temperature (CT). Note that an Oct. 1 application allows enough N to be mineralized before the crop period to satisfy its N requirement. However, whatever mineralized N exceeds the crop uptake is subject to leaching during that time period. Application on April 1 does not allow time for mineralization of enough N to meet crop requirements during the first year, but it may do so in following years if the N is not leached. Note that the temperature adjustment alters the time sequence for mineralization.

Variables for simulations

The organic material data had two application dates and variables for adjustment for temperature (TD) or no such adjustment (CT). Inorganic N was applied one time, between the preplant irrigation and planting. A clay loam soil and a sandy loam soil that differ in hydraulic properties and water-holding capacity were selected. Two ratios of uniform irrigation amount (AW) to potential ET (PET) equal to 1.1 and 1.42 were applied. These would cause expected leaching fractions for a nonstressed crop of 9% and 30%, respectively.

The first annual results are highly dependent on the initial soil conditions at the beginning of the simulation and

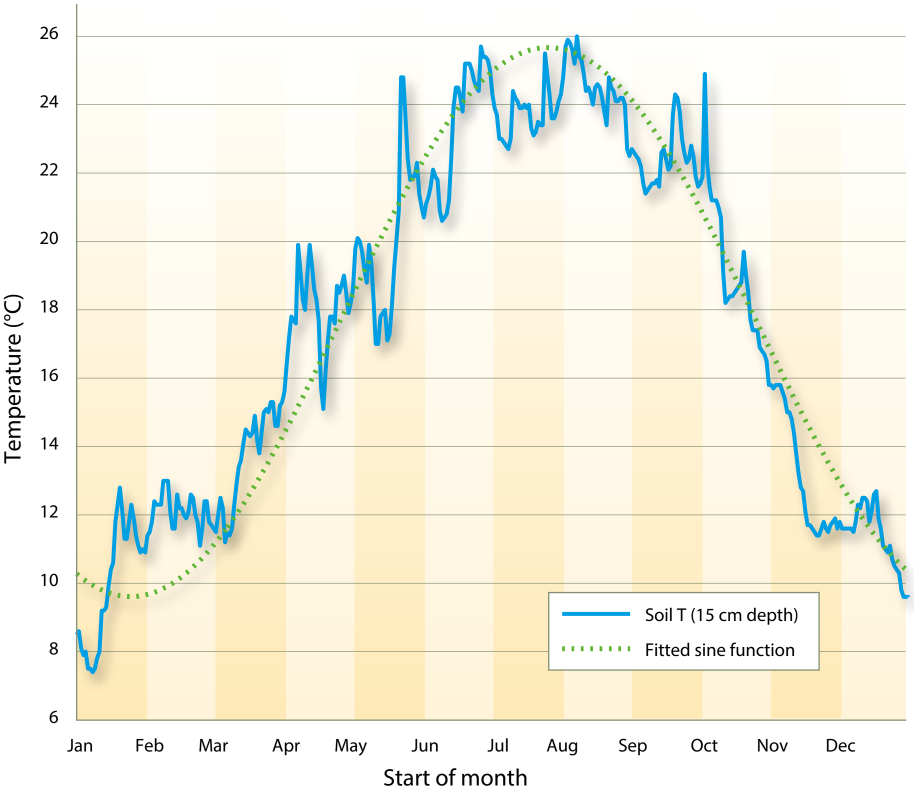

Fig. 1. Daily average CIMIS soil temperature at the 15 cm depth from 2000 through 2011 at Madera, site #145.

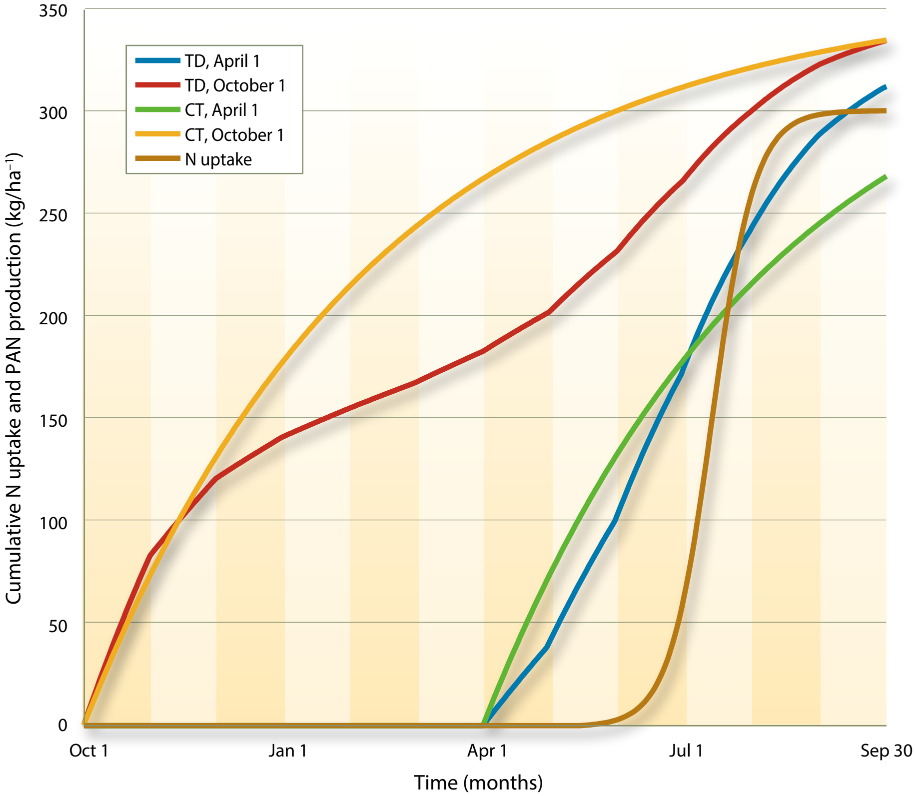

Fig. 2. Cumulative crop N uptake and the cumulative amount of plant-available nitrogen (PAN) production for organic material applied on April 1 or Oct. 1. The temperature is assumed constant (CT) for one set of data, and for the second set mineralization is adjusted for temperature dependence (TD) at different times of the year.

may not accurately reflect the long-term effects of the treatment. For example, Broadbent and Carlton (1979) found that for the first year, crop N uptake on the plot that received no N application was approximately 75% of what was taken up from the plot that received the highest N application. This ratio dropped to about 25% after about 3 years of treatment. These results emphasize the importance of multiyear field experiments in terms of getting an accurate picture of treatment effects. We ran simulations for 10 consecutive years. The effects of the initial soil conditions were dissipated after the first 2 years, but only the 10-year results are reported. However, one asset of the model is that it allows the effects of changing management to be determined on an annual basis.

The crop was seeded on May 15 and harvested on Sept. 28. Irrigation was applied biweekly on the clay loam and weekly on the sandy loam because of its lower water-holding capacity. The soil profile was not recharged with water at the end of the growing season, but a sufficient amount of water to recharge the profile was applied as a preplant irrigation the next season. The time and amount of rainfall during the fallow season were those recorded at CIMIS station #145, Madera, California, during the calendar year 2006, a relatively wet year that recorded 29 cm (11.4 in) total precipitation; the 10-year average for station #145 was 22 cm (8.7 in). The individual rain event numbers are reported below, in the Results section.

We chose a range of N input amounts for each combination of variables in order to determine how much N would be required to achieve maximum yield and what the relationship was between yield and application amount. The annual amount of N leached was computed for each case. The direction (upward or downward) and rate of water flow and N concentration in the soil water at the 100 cm depth, which represented the bottom of the root zone, were computed and plotted as functions of time. By combining water flow and N concentration, we were able to calculate the cumulative leaching amount at given times and the total amount of N leached during the year.

Results

The results from the organic N addition to the clay loam soil will be presented first. The relative yield (RY) and annual amounts of leached N are plotted as a function of the applied amount of organic N in figure 3 for AW/PET = 1.1 and in figure 4 for AW/PET = 1.42. Note that for higher water application rates, much greater applications of organic N are needed to achieve a given RY. The higher water application level resulted in more leaching of N (as depicted in figs. 3 and 4) and thus the fields required higher N applications in order to achieve a given yield. The grower is primarily interested in yields, but the amount of N leached is an important number when we are looking to prevent potential groundwater degradation from nitrate.

The model does not compute yield *per se*, but computes the relative N uptake (RN_{up}) — relative, that is, to the potential uptake of a plant that does not experience N deficiency. We then need to establish a relationship between RN_{up} and RY in order to convert our results to relative yield. Based on the results of Broadbent and Carlton (1979), this relationship for corn grown in the San Joaquin Valley is

$$RY = 1.7RN_{up} - 0.7RN_{up}^2 \qquad (3)$$

Because the relationship between yield and N uptake is not linear, the RN_{up} is less than RY for a given application.

Except for conditions of maximum yield, a reduction in the amount of N applied does not induce an equal reduction in the amount of N leached. For example,

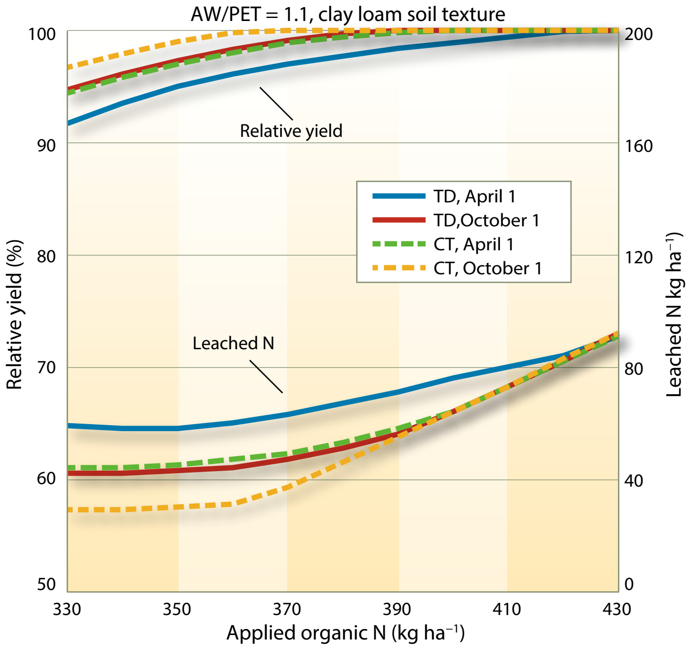

Fig. 3. Relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or Oct. 1; results for the clay loam soil and AW/PET = 1.1. The temperature is assumed constant (CT) for one set of data, and for the second set adjusted for temperature dependence (TD) for different times of the year.

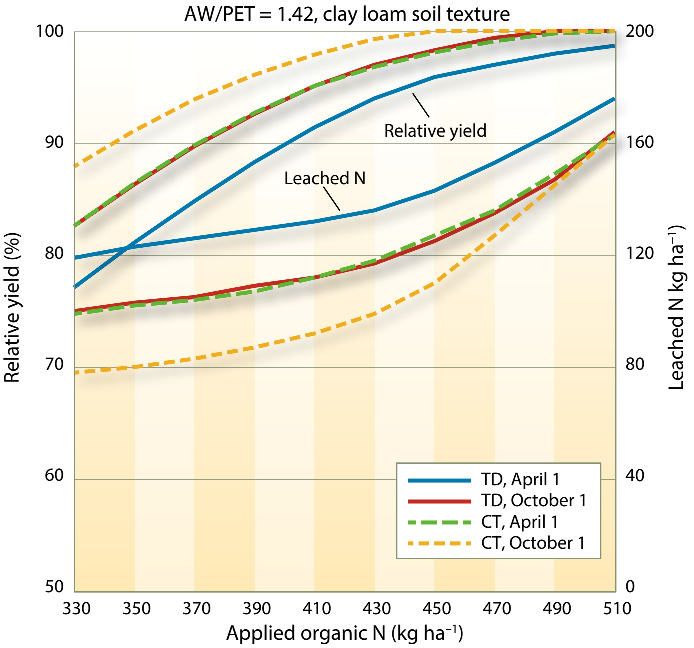

Fig. 4. Relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or Oct. 1; results for the clay loam soil and AW/PET = 1.42. The temperature is assumed constant (CT) for one set of data, and for the second set adjusted for temperature dependence (TD) for different times of the year.

for AW/PET = 1.1, reducing N application below 360 kg/ha did not reduce the leaching amount at all (fig. 3). For AW/PET = 1.42, a reduction of 100 kg/ha from 430 to 330 kg/ha in N application caused a reduction of only 20 kg/ha in leached N (fig. 4). Two factors contribute to this relationship. First, the reduction in N uptake from a given application is greater than the corresponding reduction in corn yield. The reduction in uptake increases the amount of N available for leaching. Second, and more important, the reduction in yield causes a reduction in ET, resulting in an increase of deep percolation, which is a major contributing factor in N leaching. This result emphasizes the importance of a proper understanding of the meaning of the phrase "excess N application" in this context. If "excess" is defined as application of more N than is removed from the root zone by the crop, without consideration of yield, a reduction in N application will not result in an equal reduction in the amount of N leached from the root zone. Indeed, there might be very little or no resulting reduction in leaching.

The date of application of organic N and whether or not any temperature effect adjustment is made to the rate of mineralization are important factors affecting the results. For the clay loam soil, application in October produced higher yields than application in April, and correcting for temperature effects resulted in lower yields (fig. 3). The greater time for mineralization from October to April made more mineralized N available for the crop season. However, this N would be subject to leaching from winter rains. As will be reported later, the rainfall pattern did not cause deep water percolation on this soil. The lack of consideration for the effects of low winter temperatures on mineralization resulted in an overestimate of yield and an underestimate of leaching in this case.

Results from the sandy loam soil are illustrated in figures 5 and 6. Note that the scale for leached N in sandy loam soil (figs. 5 and 6, ranging from 0 to 400 kg/ha) is twice that used for the clay loam soil (figs. 3 and 4, ranging from 0 to 200 kg/ha) and that the amounts applied to achieve maximum yield are greater. Organic N that was applied in April produced higher yields than that applied in October on the sandy soil, the opposite of the case with clay loam soil applications. This result reflects the greater degree of winter leaching on the sandy soil as compared to that of the clay loam soil. Coincidentally, temperature had very little effect on results on the sandy soil.

Figure 7 illustrates the effects of changes in the amount of water application on the N concentration and water flow at the bottom of the root zone at different times for the 370 kg/ha application of organic N on the clay loam soil. The same relationships are illustrated in figure 8 for the sandy loam soil. A negative water flux represents downward flow and a positive flux represents an upward flow at the bottom of the root zone (100 cm depth).

Considering the clay loam soil first, water flow at the 100 cm depth during the noncrop season is very low for both irrigation treatments. The AW/PET = 1.1 treatment caused only very low downward flow after preplant irrigation and at the latter part of the growing season. As expected, the AW/PET = 1.42 treatment resulted in more water flow at the bottom of the root zone. However, the flux was quite small until after about Aug. 1. Thereafter, peak flows were simulated biweekly, consistent with the dates of irrigation. The N concentration was fairly constant at all times, but was about 2.5 times higher for the AW/PET = 1.1 treatment than for the AW/PET = 1.42. Conversely, the amount of annual N leaching was about half as much for the AW/PET = 1.1 as for the AW/PET = 1.42 treatment because there was less leachate. These results clearly

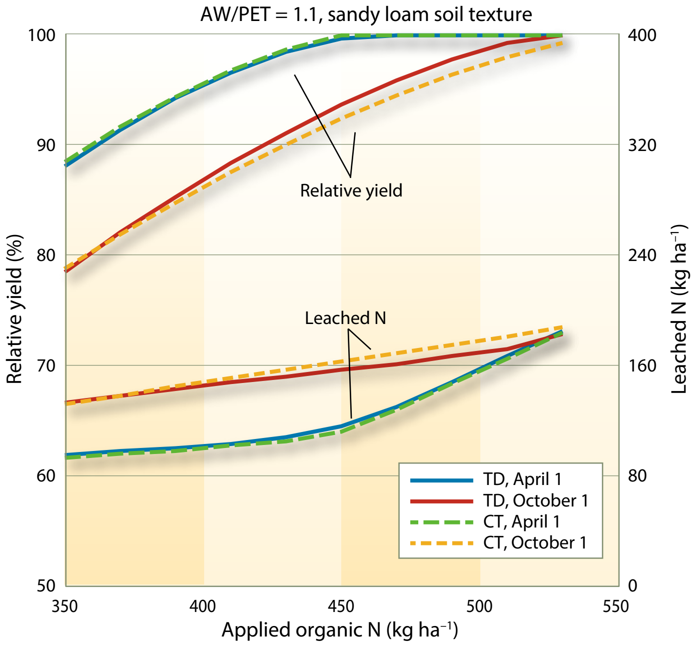

Fig. 5. Relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or Oct. 1; results for the sandy loam soil and AW/PET = 1.1. The temperature is assumed constant (CT) for one set of data, and for the second set adjusted for temperature dependence (TD) for different times of the year.

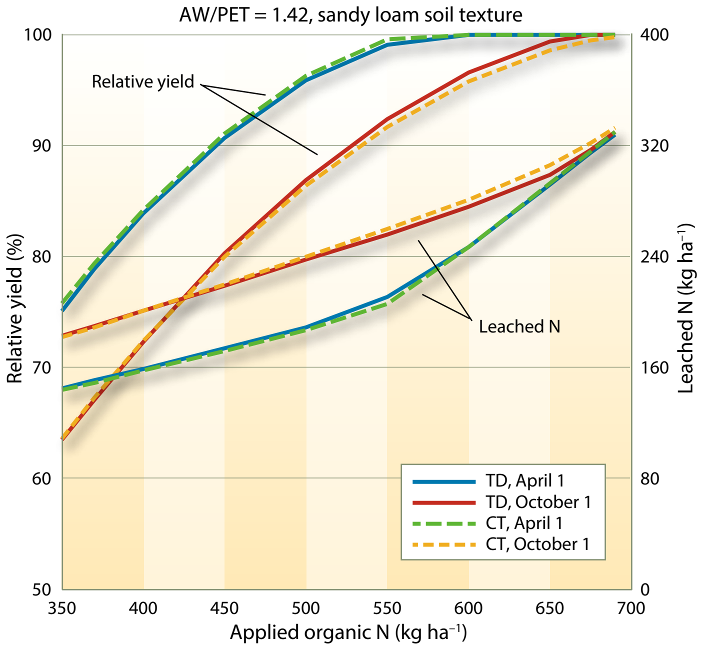

Fig. 6. Relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or Oct. 1; results for the sandy loam soil and AW/PET = 1.42. The temperature is assumed constant (CT) for one set of data, and for the second set adjusted for temperature dependence (TD) for different times of the year.

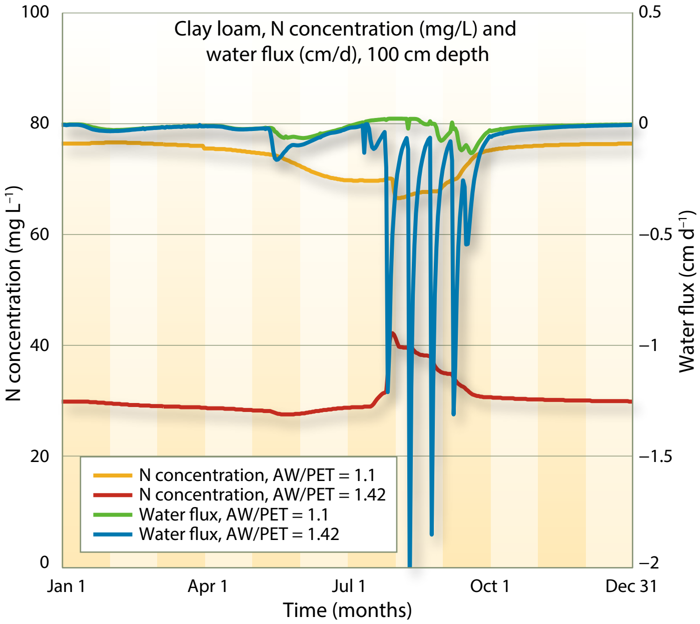

Fig. 7. N concentration and water flux in the clay loam soil at the bottom of the root zone at different times of year for the two water treatments. The results are for application of 370 kg/ha of organic N on April 1 (TD). A negative water flux represents downward water flow.

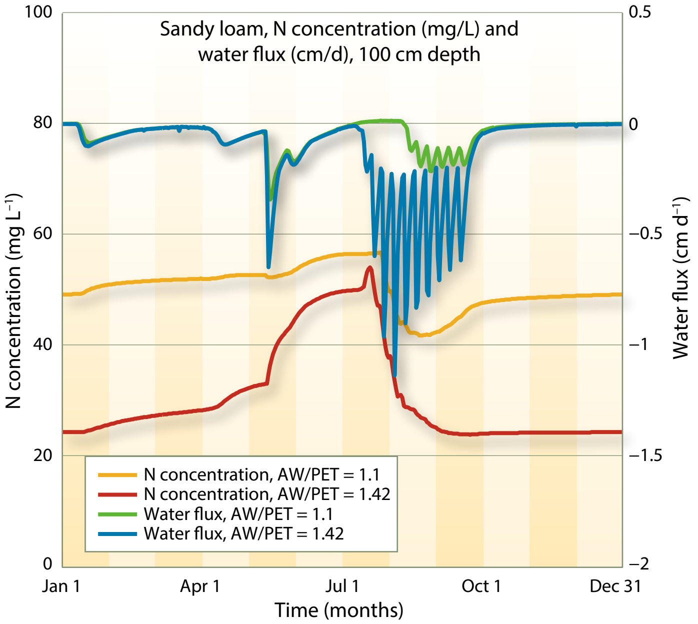

Fig. 8. N concentration and water flux in the sandy loam soil at the bottom of the root zone at different times of year for the two water treatments. The results are for application of 370 kg/ha of organic N on April 1 (TD). A negative water flux represents downward water flow.

demonstrate the problem with monitoring only the N concentration at the bottom of the root zone as an indicator that N is being leached from the crop. Besides being an expensive method, it can lead to erroneous conclusions.

The water flow pattern on the sandy soil differed from that on the clay loam soil, particularly in the non-crop season. The lower water-holding capacity of the sandy soil allowed the rain to penetrate deeper and create a downward flux at the 100 cm depth. This explains why the October application was less effective at producing yield than the April application. There is potential for a large amount of leaching to occur during the noncrop season. The amount of N leaching during the noncrop season is dictated by the soil properties, the total amount and distribution pattern of precipitation, and the depth of soil being considered, which is based on crop rooting patterns. The E-G model can be used to simulate leaching under any combination of these factors.

Because the sandy soil required weekly irrigation, the water fluxes during the latter part of the growing season reflect that irrigation schedule. As in the clay loam soil, N concentrations in the sandy soil remained fairly constant and were higher when there was less irrigation. In contrast, the amount of leached N was greater when there was more irrigation.

The cumulative amount of leached N and the amounts of irrigation or precipitation are shown in figure 9 for the case illustrated in figure 7. The rainfall pattern represents numerous small rain events during the winter, with the exception of two rains near Jan. 1 and one on May 21. The 7.2 cm event on May 8 was the preplant irrigation. The leaching pattern for both cases is chronologically consistent with the N concentrations and water fluxes shown in figure 7. The rate of N leaching was relatively low for AW/PET = 1.42 until the end of July, after which point the rate increased. This was concurrent with a period of high water flow. The N leaching was higher for the lower water application rate between Jan. 1 and Aug. 1. This was the result of higher N concentration in the soil water at the bottom of the root zone during that time period. Most of the yearly N leaching for AW/PET = 1.42 occurred during August and September, when large water flux events occurred and N concentrations were significantly lower than for AW/PET = 1.1.

Even though significantly more water was applied than lost through ET for the AW/PET = 1.42 treatment, the water flow at the bottom of the root zone was very low until the end of July. This result, though not anticipated, could be explained after observation. Note that in figure 9 the PET, and therefore the AW, continually increased until about Aug. 1. The amount of AW was intended to recharge the soil, based on potential ET since the previous irrigation. The "excess" water application prior to Aug. 1 would have been removed from the soil via ET (as shown by the higher ET numbers) after irrigation and would not have reached the 100 cm depth. After Aug. 1, the ET decreases with time, at which point the "excess" water would flow beyond the 100 cm depth and promote leaching, as observed.

All of the inorganic N treatment was applied on the seeding date of May 15, following the May 8 preplant irrigation. The RY and annual leached N results are graphed in figure 10. Far less inorganic N had to be applied to achieve maximum yield than was the case for organic N, and the smaller inorganic N application also resulted in less N leaching. Higher inorganic N applications were required to achieve maximum crop yield on the clay loam soil than on the sandy soil, and a higher level of leaching resulted. Higher applications and greater leaching were found for the larger water application on both soils. Detailed data on the water fluxes and concentrations are not presented here, but we noted that the soil concentrations were lower for the inorganic application than for the organic and the concentration was lower for the larger water application than for the smaller.

Unlike the organic treatment, which continues to produce mineral N after application, the inorganic N was applied near the surface each year only on the seeding date, and became entirely available to the plants then. Water percolating through the soil at that point would transport the N downward. However, corn takes up a large amount of N during the first half of the growing season, and in that way extracts the N from the soil and removes most of it before it can reach the bottom of the root zone. The smaller, more frequent water applications on the sandy soil would have reduced the depth of water penetration on the sandy soil and made the N more available to the crop. This could account for the sandy soil having less leached N than the clay loam soil.

Clearly, many complex interacting factors contribute to crop yield and the leaching of N from a field. The timing of water and N application and their amounts greatly affect the results. Proper management of organic N applications requires knowledge of the timing of mineralization, not just the total amount that will be mineralized during a given time period. Our results demonstrate the importance of converting the conventional data (decay series mineralization) into rate of mineralization as a function of time. We have also shown the importance of making adjustments to account for temperature.

Discussion of scientific findings as related to NHI

The Nitrogen Hazard Index (NHI) considers the crop, soil and irrigation system as critical factors in assessing the relative risk of groundwater degradation by nitrate. The following discussion of our results is in the context of these three factors.

The results we report here for corn differ in detail from the results one would see from other crops. Corn has an exceedingly high rate of N uptake over a short period of time and almost no uptake during the latter part of the season, when the crop still has a high transpiration rate and so requires irrigation (fig. 2). A crop with such a high maximum N uptake rate cannot possibly be fertilized solely with organic N if the goal is to meet peak demand without leaving excessive N in the soil before and after crop N uptake. Pang and Letey (2000) compared simulations of wheat and corn fertilization with organic N and found that wheat had higher yields and less leached N than corn. Even though both crops required the same total amount of N over the season, the N uptake for wheat extended over a longer period than for corn, and with lower peak rates. Crops with a low, continual N uptake demand are better suited to organic N fertilizers. Growing other plants in the field during the noncrop season facilitates the capture of the mineralized N that continues to enter the soil through the decay process. Feng et al. (2005) reported that a grass crop grown during the winter effectively reduced the leaching of N after a corn crop that had been grown on the same field and had been fertilized with dairy liquid waste.

The deep root system of corn is a positive feature, for our purposes. The crop can extract N over a considerable depth of soil before it leaves the root zone en route to groundwater. The rapid N uptake can be a positive feature for inorganic fertilizers that can be applied at high amounts near the soil surface. In that case, the N is rapidly taken up early in the crop season, leaving little in the soil for leaching later on. Corn has both positive and negative qualities with regard to potential groundwater degradation from nitrate, so we assigned the crop an intermediate hazard index number of 3. More important than the NHI number, though, is an understanding of the dynamic interactions that occur in a corn field.

Soil type significantly affects a field's potential for groundwater degradation.

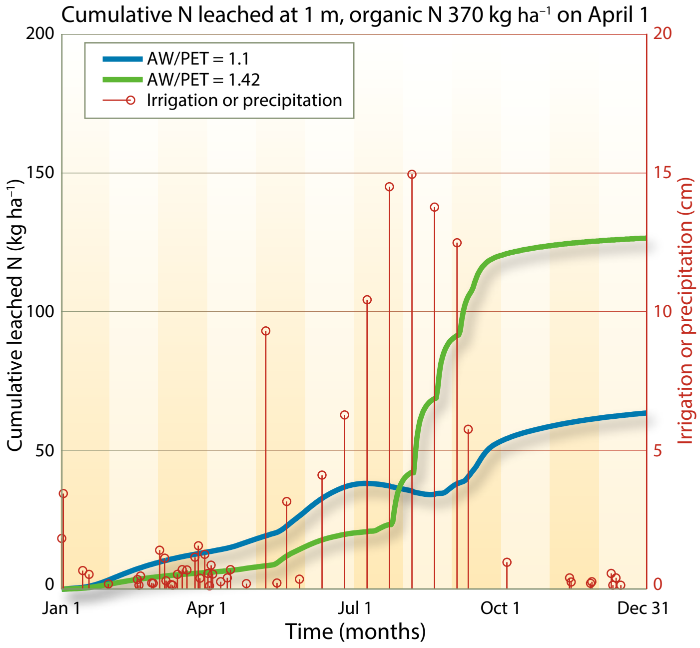

Fig. 9. Cumulative leached N and precipitation or irrigation amounts at different times of the year for the two water treatments. The results are for application of 370 kg/ha organic N on April 1 (TD).

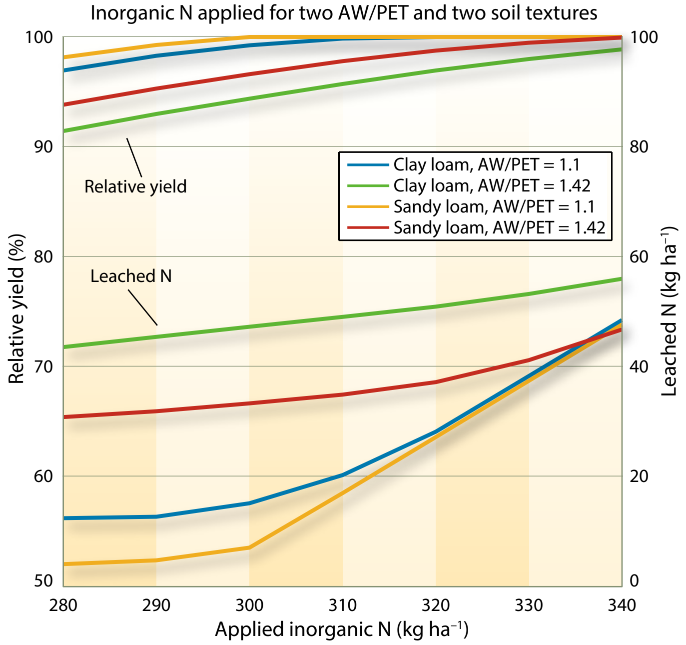

Fig. 10. Relative crop yield and amount of leached N for different amounts of inorganic N application for the two soils and two water treatments.

Under the conditions of the simulations reported here, the main effect of the sandy soil was to increase N leaching during the winter. The sandy soil's low water-holding capacity allowed precipitation water to move beyond the root zone, whereas the more capacious clay loam retained the precipitation water within its root zone depth.

Another major impact of soil type was not entirely manifested in the simulations. Soil type dictates how much water will infiltrate the soil using a surface irrigation system. Sandy soils have a high infiltration rate and commonly experience more water infiltration, whether the water comes from rainfall or a surface irrigation system. Our simulations used water scheduling so that the two AW/PET values would be the same for both soils. The AW/PET = 1.42 condition is far more likely to occur on sandy soils than on finer-textured soils. In every case, the higher AW/PET treatments induced lower yields and higher amounts of leached N than did the lower AW/PET treatments. This increased probability of N leaching is greater for the sandy soil than the clay loam, but we partially mitigated this factor by altering the irrigation schedule to apply smaller and more frequent irrigations in the sandy soil simulations than in the clay loam. This adaptation demonstrates that the impacts of soil type, when understood, can be compensated for through adjustments to management. The model does not include a provision for denitrification. Therefore, the leached N values represent the worst-case scenario for any soils that may induce denitrification. In a real-world situation, less denitrification would be expected on the sandy soil. The clay loam soil would be assigned an index number of 3 and the sandy loam soil a number of 5.

The irrigation system is the third factor included in the NHI. Surface irrigation systems allow little control over the amount and uniformity of irrigation. All pressurized systems allow control over the amount of application. Microirrigation systems also have potential for good uniformity. For our simulations, we assumed uniform irrigation. The uniform AW/PET = 1.1 can probably only be achieved with a well-designed and managed microirrigation system. Without fertigation, as simulated in this study, the index number would be 2. The AW/PET = 1.42 would be typical of surface irrigation that has an index number of 5.

Uniform irrigation (meaning that the same amount of water infiltration occurs at all locations in the field) is essential to accomplishing both high yield and low groundwater degradation. The extreme choices when irrigating a field with nonuniform water application are to overirrigate or underirrigate the entire field. Overirrigation causes groundwater degradation and underirrigation causes poor yields. An intermediate trade-off between the two is necessary. In principle, uniform irrigation allows both goals to be achieved.


Evett Kilmartin

Converting gravity flow systems to pressurized systems provides an opportunity to reduce deep water percolation and even the amount of fertilizer applied.

The findings in this simulation study are completely consistent with measurements made on 86 farm fields (Letey et al. 1977; Letey et al. 1979), which attests to the validity of the model. First, we see that the amount of N leached is more closely related to the amount of water percolating beyond the root zone than on the amount of N applied. Second, we see no correlation between the amount of N leached and the concentration of N in the water. The scientific evidence overwhelmingly indicates that the irrigation management decisions dictate what nitrogen management options are available for achieving high yield with low groundwater degradation.

Results in the context of track and report

None of the recommendations made by the State Water Resources Control Board (SWRCB) to the California Legislature with regard to nitrate in groundwater identifies water management as a potential controlling factor. The Board's recommendations emphasize development and implementation of an N mass balance tracking and reporting system to manage application of N fertilizer materials.

The law of conservation of mass specifies that, in one sense of the term, there is always mass balance. However, in a transient dynamic system in which there are several pools for N, the term "mass balance" lacks clear meaning. There are continual additions and deletions from each pool. If the identical management is continually followed, as is the case for our simulations, a steady-state condition develops when the cycle repeats itself on a temporal basis. Implicit in some usages of the term "mass balance" with regard to farm fields is the notion of a balance between the N added and the N removed by the crop. Sometimes N balance is defined as the ratio of N removed by the crop to the amount of N applied. This narrow definition ignores the several other pools and reactions present for N in the soil. For example, denitrification losses can be significant. In direct measurements in California agricultural fields, Ryden et al. (1979) found that in one field 51 kg/ha denitrified over a 123-day span when 335 kg/ha were applied (15% denitrified). Similarly, denitrification losses at seven study sites from three fields under vegetable production ranged from 95 to 223 kg N/ha/yr, or 14% to 52% of the applied N (Ryden and Lund 1979).

A reduction of leached N equal to the reduction of N application is a common assumption, by virtue of "mass balance." This assumption holds true if the higher N application is greater than is necessary to get maximum production, but it will not hold true if the reduced N application induces a reduction in crop yield. Indeed, reductions in N application can in some cases cause only very small reductions in the amount of N leached. Ignoring crop yield represents a major deficiency in the track and report approach that can lead to erroneous conclusions.

Tracking requires measurement. Because leaching of N is the culprit in this scenario, measuring the rate of leaching is vital. To accomplish this, one must measure the N concentration in the soil solution and the rate of water flow at the bottom of the root zone. An accurate measurement of this water flow at any particular time, however, is impossible. Furthermore, the flow rate can fluctuate greatly with time, as illustrated in figures 7 and 8. Because of all this, the leaching numbers are affected primarily by the water flow rate rather than by the concentration. Indeed, as it turned out, higher leaching of N was commonly associated with a lower soil solution concentration.

The measurement of nitrate concentrations in groundwater bodies provides valuable information. Concentrations measured today actually manifest the consequence of actions that took place decades ago. Whether the very high numbers we see are a result of excessive N application or of excessive irrigation is not important, though. What is important is that we improve present management practices in a way that will reduce future nitrate loads to the groundwater. It is true that a management change that decreases the load will not be manifest in groundwater concentrations for decades, but keeping water percolation beyond the root zone to a minimum is the most effective way to reduce the N load to groundwater. This decades-long feedback cycle keeps groundwater monitoring from being a reliable indicator of the effectiveness of present-day management practices. Still, proper irrigation management is essential to the effective implementation of more beneficial N management practices. Not only will a tracking and reporting system not achieve the goal, it could easily lead to the adoption of costly, ineffective management practices. In fact, tracking and reporting is only an attempt to monitor what is happening and has little immediate impact on reducing N loads.

Proper irrigation management is essential to the effective implementation of more beneficial N management practices.

Conclusions

The development of BMPs rather than a tracking and reporting regime is the effective, rational approach to reducing N loads. The NHI concept was proposed by the Nutrient Technical Advisory Committee (TAC), appointed in 1994 by the SWRCB as a resource for developing BMPs. Importantly, TAC proposed that fields with a low NHI number, which pose a low threat to groundwater degradation, should be exempt from a formal BMP so that resources could be focused instead on cases where they would more effectively reduce degradation. Additionally, the NHI identifies whether the major threat for each field comes from the soil, crop or irrigation system, or a combination of these. Using this approach, we would formulate a BPM tailor-made for each specific field's conditions. Although the SWRCB accepted the TAC report, the lack of available index numbers for the various soils and crops meant that the TAC recommendation was never implemented. Those index numbers are available today for many soils and crops, so it is time that the TAC recommendation and the SWRCB action of 1994 be reviewed.

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