JULY–SEPTEMBER 2013 • VOLUME 67 NUMBER 3

California Agriculture

Special issue:

Methyl bromide alternatives

Also:

Resurgence of
the bed bug

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

UC Cooperative Extension’s collaborations grow with the centuries

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In June, residents of Humboldt County climbed aboard a boat to learn how oysters are grown in Humboldt Bay. The next month, residents visited a local cattle ranch to learn about a grass-fed beef operation. These tours are the first of nine showcasing Humboldt County’s rich diversity and UC Cooperative Extension’s role in bringing science-based solutions to the community for the past 100 years.

Humboldt County was home to the first UC Cooperative Extension program, launched in 1913. Today, county residents are actively engaged in educational activities and events—like the tours—that celebrate 100 years of their partnership with UC Cooperative Extension.

May 2014 will mark the 100th anniversary of the Smith-Lever Act, the legislation that created Cooperative Extension, a nationwide system of community-based, applied research and education established as part of each state’s land-grant university. Cooperative Extension was started to help farmers, homemakers and youth use the latest university research to improve their lives. At first geared towards strengthening rural areas, Cooperative Extension became integral to suburban and urban communities as well.

In addition, UC Cooperative Extension created an innovative federal, state and county partnership between the land-grant institutions, the U.S. Department of Agriculture (USDA), the county government and the emerging Farm Bureau organization.

We continue to rely on those partnerships to solve local problems. For example, when the pathogen that causes sudden oak death was detected in Marin County in 1995, UC Cooperative Extension joined forces with USDA Forest Service and CAL FIRE to try to understand what was causing the unexplained tree death. When *E. coli* was traced back to leafy greens grown on the Central Coast, UC Cooperative Extension teamed up with the UDSA, California Department of Food and Agriculture and local growers and processors to develop better preventive measures.

This collaborative model has enabled California agriculture and communities to quickly address critical issues, to grow and to remain sustainable.

As communities have changed, Cooperative Extension has evolved its programs to meet their needs. The Expanded Food and Nutrition Education Program (EFNEP) offers free nutrition education classes in urban communities. City residents with poor access to fresh produce have benefited from programs on cultivating community and school gardens from Cooperative Extension’s Master Gardener Program. And workshops and advice in 4-H youth development programs encourage children to explore science and technology. Regardless of the population served, Cooperative Extension activities are grounded in university research and developed in partnership with local communities.

UC Cooperative Extension has evolved *how* its programs reach participants as well; today websites provide research-based information around the clock. State budget cuts since the 1980s have impacted advisor ranks, yet UC Cooperative Extension continues to maintain a presence in every California county to help address their unique problems and connect them with the trusted, science-based solutions provided by UC campuses.

Smith-Lever was signed into law by President Woodrow Wilson on May 8, 1914. One hundred years later, on May 8, 2014, UC Agriculture and Natural Resources (ANR) will observe the centennial of this legislation in every county of the state. Events will not only celebrate our first hundred years of service, but also will launch us into a second century of innovation. For when we consider the future needs of California, we must look beyond our borders. California’s exports of food, fiber and technology mean our work has global impact.

In April, UC ANR hosted the Global Food Systems Forum and webcast to listen to researchers, policymakers, producers and others discuss challenges and potential solutions for sustainably producing an adequate food supply to feed the world’s growing population. We continue to investigate how to best apply UC ANR’s research and extension to provide practical advice to California agricultural producers facing water shortages, climate uncertainty, environmental degradation, land use conflicts and invasive pests. We strive to improve the health of our families and communities through research and extension for better nutrition, youth development and economic development.

To do this, we are committed to rebuilding UC Cooperative Extension’s research and extension strength. Between the positions recently filled and those under recruitment, we are on track to increase the advisor and specialist ranks statewide—30 Cooperative Extension advisors and specialists have been hired since January 2012, and recruitment is either under way or will begin in 2014 for 43 more positions.

With the state’s economy recovering, our budget has stabilized and UC Cooperative Extension is on the rise. As we begin our second century of service, UC Cooperative Extension remains closely connected in California communities and committed to helping Californians enjoy a high quality of life, a healthy environment and economic success in a global economy.

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Methyl bromide alternatives

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E-Edition

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Correction: On page 109 of the April–June 2013 issue, the acknowledgements paragraph was missing from the end of the research article by Bruce R. Hoar et al. The text should read, "Funding for this research was provided by the Center for Produce Safety. The authors also thank Donna Henderson and Anita Claverie for their assistance."

About California Agriculture

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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.

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Methyl bromide primer and timeline

For decades, methyl bromide (MB) was agriculture's magic bullet. Injected into soil to a depth of 1 to 2 feet, this toxic and volatile fumigant would kill almost all microorganisms — nematodes, fungi, other pathogens, insects and weeds. It proved highly useful for many of California's signature crops, especially as a preplant treatment for sensitive annuals such as strawberries and tomatoes, or before replanting vineyards and orchard crops such as almonds and peaches. It boosted yields so effectively that researchers could not fully explain its benefits.

But in the early 1990s, atmospheric research revealed that MB was among the class of ozone-depleting substances (ODSs). Although MB occurred naturally, humans had added significant amounts to the stratosphere (the upper atmosphere, from 11 to 31 miles above the Earth's surface); the MB breakdown product, a bromine atom, thinned and destroyed the ozone layer, which otherwise protected humans and other life from damaging ultraviolet light.

Methyl bromide was scheduled for 100% phase-out by 2005 under the Montreal Protocol and the U.S. Clean Air Act. By that year, scientists had published prodigious amounts on alternatives, but in some specific situations growers still lacked clear, alternative production regimes. To be useful, new strategies had to be specific to different soils, climate conditions and crops over extended periods of time.

The bad news was that MB's remarkably consistent performance in controlling myriad pests could not be duplicated by any one replacement. Also, standard chemical alternatives were increasingly regulated due to concerns about air pollution and toxicity to workers and nearby populations.

The good news was that by 2006, the World Meteorological Organization (WMO) Scientific Assessment (and later assessments) reported a decrease in the atmospheric burden of ozone-depleting substances and early signs of stratospheric ozone recovery. The treaty was working — and helping to stem climate change as well.

At right is an abbreviated timeline of scientific findings and policy decisions.

— *Janet White*

1970

1974 UC findings: UC Irvine scientists Mario Molina and F. Sherwood Rowland publish findings that chlorofluorocarbons (CFCs, manufactured propellants in hair sprays, deodorants and so on) were migrating to the upper atmosphere and destroying the ozone layer.

1980

1985 Ozone hole detected: Atmospheric measurements reveal that the ozone layer over Antarctica is dramatically depleted and ozone levels are on a downward trend. By 1987, other measurements confirm that the Antarctic ozone hole is caused, in part, by CFCs and a breakdown product, chlorine.

1987 Montreal Protocol: The United States and 26 other countries sign an international treaty developed to protect the Earth from the detrimental effects of ozone stratospheric depletion. (By 2011, 196 countries, virtually the whole world, will sign.)

1990

1991 Methyl bromide depletes ozone: Scientists confirm that methyl bromide is a Class 1 ozone-depleting substance (ODS); it falls under the purview of the U.S. Clean Air Act and the Montreal Protocol.

1992 Copenhagen Amendment: Methyl bromide is listed as a controlled substance. Production and import (for any one developed country) are capped at 1991 levels. (Starting in 1994, the Protocol froze production at 1991 levels.)

1994 Clean Air Act mandates 100% phase-out by 2001: Initially the statutory maximum phase-out under the Clean Air Act calls for a 7-year timeline with 100% phase-out of methyl bromide by 2001.

1998 Phase-out schedule revised: U.S. Congress amends the Clean Air Act to synchronize it with the Montreal Protocol. The phase-out calls for developed countries to reduce production and import of methyl bromide by the following percentages of the 1991 baseline amounts: 25% in 1999, 50% in 2001, 70% in 2003 and 100% in 2005.

2000

2004 CUEs defined: On December 24, 2004, the EPA defines critical use exemptions as (1) based on the lack of methyl bromide for a specific use, for which this deficiency would result in significant market disruption or (2) based on the lack of alternatives that are technically feasible and cost effective, acceptable from the standpoint of environment and public health, and suitable to crops and circumstances.

2005 Methyl bromide 100% phase-out: Production and import are 100% phased out in developed countries; but in developing countries, the phase-out ends in 2015.

Regulations do not control use *per se*. There are permanent exceptions for quarantine and preshipment (QPS) purposes (interstate and international trade regulations) as well as temporary critical use exemptions (CUEs), granted yearly if there is no commercially or technically feasible alternative, or when a ban would lead to significant market disruption. The goal is zero exemptions by 2015.

2005 Phase-out schedule for CUEs in U.S.: For 2005, authorized CUEs equal 37% of baseline (1991 production level); by 2013, 2.2%; by 2014, 1.7%.

2006 Reliance on CUEs: California growers with critical use exemptions used 36% of the total U.S. CUEs, or about 3,200 tons.

2006 More research funded: USDA Agricultural Research Service (ARS) funds a new round of research focusing on the Pacific Northwest and Southeast — areas of the country where the needs for additional research on alternatives are greatest.

2006 Early signs of success: Scientific Assessment of Ozone Depletion: 2006 reports "There is clear evidence of a decrease in the atmospheric burden of ozone depleting substances (ODSs) and some early signs of stratospheric ozone recovery."

2010

2010 Protocol success linked to greenhouse gas reduction: "Most ODSs are potent greenhouse gases. The buildup of ODS abundances over the last decades contributes to global warming. The actions taken under the Montreal Protocol have reduced the substantial contributions these gases would have made to global warming." — *Scientific Assessment of Ozone Depletion: 2010.*

2013 California fresh strawberries: They remain one of the toughest cases for MB alternatives; they alone now use 73% of the total U.S. CUEs.

Methyl bromide terminology

Barrier films (low-permeability plastics): Gas-impermeable films that reduce fumigant emissions, increase fumigant retention and, in some cases, lower the dose needed for pest control. The traditional plastic tarp used in fumigation, HDPE, reduces fumigant emissions by about 50%. The recently developed virtually impermeable film (VIF) is more effective, and totally impermeable film (TIF) is the most effective.

Broadcast shank fumigation (or flat fumigation): Traditional strawberry field fumigation that began in the 1960s, in which growers applied MB combined with chloropicrin to entire fields, which are covered with polyethylene film to hold in the fumigant at concentrations needed to kill soil pests.

Buffer zones: Nonfumigated areas that separate the fumigated field from bystanders. Zones are designed to minimize exposure to people who are not directly associated with fumigant application (other agricultural workers and the general public). The size of the buffer zone is determined by fumigation method, field size and application rate. Large buffer zones, required for large fields or high application rates, complicate or prevent the treatment of some fields.

Chemigation: Irrigation applied with a fumigant, fertilizer or other water soluble agricultural input. Chemigation is used in a wide variety of crops and with different kinds of irrigation. For example, it is used to drip fumigate strawberry fields for the control of pathogens, nematodes and weed seeds. Because chloropicrin and 1,3-D are less volatile than MB, they can be applied to raised beds through drip systems and have been shown to be effective in controlling most soilborne pathogens and weed seeds, resulting in comparable strawberry yields.

Common acronyms

1,3-D: 1,3-dichloropropene
CUE: critical use exemption
DMDS: dimethyl disulfide
DFC: dynamic flux chamber
EVOH: ethyl vinyl alcohol resin vapor-barrier layer
HDPE: high-density polyethylene
ISCST3: Industrial Source Complex Short Term, version 3 Dispersion Model
MB: methyl bromide
MITC: methyl isothiocyanate
MTC: mass transfer coefficient (cm h^{-1})
MB + Pic: methyl bromide plus chloropicrin
MB:Pic: methyl bromide with chloropicrin (98:2, 67:33 or 50:50)
Pic: chloropicrin
Pic-Clor 60: fumigant product containing 60% chloropicrin and 39% 1,3-D
Pic-EC: chloropicrin emulsified formulation
QPS: quarantine and preshipment (exemption)
SF: sulfuryl fluoride
RABET: raised bed trough system
RED: Reregistration eligibility decision
TIF: totally impermeable film
VIF: virtually impermeable film

Critical use exemptions (CUEs): Allowances for production or import of MB in the absence of technically or economically feasible alternatives (see page 121).

Low permeability films: The traditional plastic tarp used in fumigation, HDPE, has much greater permeability than the newly developed films (VIF and TIF) and only reduces fumigant emissions by approximately 50%.

Non-attainment area (NAA): Any area that does not meet (or that contributes to ambient air quality in a nearby area that does not meet) the national primary or secondary ambient air quality standard for the pollutant. Such an area has air quality worse than the National Ambient Air Quality Standards as defined in the Clean Air Act Amendments of 1970. NAAs must have and implement a plan to meet the standard, or risk losing federal financial assistance. An area may be an NAA for one pollutant and an attainment area for others.

Ozone depleting substances (ODSs): In the United States, ODSs are regulated as Class I or Class II controlled substances. Class I substances have a higher ozone-depleting potential and have been completely phased out in the United States, except for exemptions allowed under the Montreal Protocol. They were subject to the first round of phase-out targets, have an ozone depletion potential (ODP) of 0.2 or higher, and include MB.

Phase-out of ODSs: EPA regulations issued under the Clean Air Act phase out the production and import of ODSs, consistent with schedules under the Montreal Protocol (see page 121).

Quarantine and preshipment exemptions (QPSs): Quarantine applications, with respect to MB, are treatments to prevent the introduction, establishment and/or spread of quarantine pests (including diseases), or to ensure their official control. Preshipment applications are those non-quarantine applications within 21 days prior to export to meet the official requirements of the importing country or the existing official requirements of the exporting country.

Reregistration eligibility decisions (REDs): In 2004, the EPA began reviewing the human health and environmental impact of fumigants that were registered prior to November 1984. REDs describe new or modified labeling requirements regarding fumigant rates, application methods, buffer zone requirements, neighbor notification and worker safety standards. One controversial aspect of these rules is the size of the required buffer zone around fumigated fields.

Stratosphere: Upper atmosphere, from 11 to 31 miles above earth's surface, where the ozone layer screens damaging ultraviolet light from the sun.

Totally impermeable (plastic) film (TIF): A relatively new barrier, TIF has been shown to be the most effective in fumigant retention. TIF is a multilayer film that includes one or more low-permeability layers, such as ethylene vinyl alcohol layers, as well as layers of standard polyethylene film.

Township cap/limit: The California Department of Pesticide Regulation (DPR) restricts levels of certain pesticides in ambient air within 36-square-mile areas known as townships. In California, 1,3-D is limited to 90,250 pounds per 36-square-mile township.

Troposphere: Lower atmosphere where air pollution develops, from the surface to 11 miles in altitude. Pollutants include ozone and particulate matter. VOCs contribute to the formation of some pollutants.

Virtually impermeable film (VIF): Although more permeable than TIF, VIF plastic film can reduce fumigant emissions and enhance their distribution in soil, in comparison with conventional polyethylene films. VIF differs from traditional high-density polyethylene tarps in that it has additional gas-impermeable layers, e.g., nylon or polyamides, between the polyethylene layers.

Volatile organic compounds (VOCs): Carbon-based compounds that contribute to formation of atmospheric photochemical smog. Under provisions of the U.S. Clean Air Act, the DPR must reduce agricultural emissions of smog-forming VOCs from soil fumigants and other pesticides. Regulations restrict fumigation from May 1 to Oct. 31 in NAAs.

(Information compiled from online sources; from authors Husein Ajwa, Greg Browne, Steve Fennimore and Jerry Weiland, and from Randy Segawa, Environmental Program Manager, Air and Ground Water Programs California DPR. — J. White)

For more information:

EPA Greenbook
http://www.epa.gov/oaqps001/greenbk/

EPA fumigant toolbox
http://www.epa.gov/pesticides/reregistration/soil_fumigants/

CDPR fumigant regulatory issues
http://www.cdpr.ca.gov/docs/emon/methbrom/fum_regs.htm

UNEP 2010
http://www.unep.org/annualreport/2010/

Specialty crops and methyl bromide alternatives: taking stock after 7 years

Greg T. Browne
Research Plant Pathologist, Crops Pathology and Genetics Research Unit, USDA-ARS, Department of Plant Pathology, University of California, Davis

Specialty crop farms and nurseries in California, Oregon and Washington provide local and world markets with abundant fruit, nut and vegetable crops and planting stock. These operations thrive due to dedicated human investment and the availability of precious combinations of soil, climate and water resources. California alone produces 99% of the U.S. almond and walnut crops and 90% of the strawberry crop, and it supplies 99% or more of U.S. almond, raisin, table grape and walnut exports. Combined, California, Oregon and Washington account for roughly 32% of the U.S. floriculture crop value, 44% of the nursery crop value and 78% of the fruit and nut crop value.

Pest-free nursery stock and productive soils are vital to efficient use of land, water, energy and fertilizer resources for specialty crops such as almonds and grapes. *Above*, an almond orchard in bloom.

We all have a large stake in the availability of specialty crops. Research increasingly documents their benefits to our health. They are a livelihood, directly or indirectly, for many of us. As a society, we have contributed collectively to key infrastructures, such as water resource developments for irrigation and the land-grant college system with its associated teaching, research and extension functions. Indisputably, ample food production, including specialty fruits, nuts and vegetables, is a key measure of national and global security.

California Agriculture journal thanks the faculty chairs for this special collection: Greg Browne, Research Plant Pathologist, USDA Agricultural Research Service (USDA-ARS) and Department of Plant Pathology, UC Davis, and Brad Hanson, Cooperative Extension Specialist, University of California, Davis. We also thank the USDA-ARS Pacific Area-Wide Pest Management Program for Integrated Methyl Bromide Alternatives for helping defray the cost of this issue and the upcoming October–December 2013 edition.

Yet specialty crop farming faces serious challenges. Especially in California, urban growth is removing farmland irreversibly. Also, water resources can be allocated away from agriculture, and some specialty crop pest management practices, such as soil fumigation, are requiring intensive regulation to ensure public safety.

In 2006, preplant soil fumigation with methyl bromide, an effective pest management practice used extensively in production of billions of dollars of high-value specialty crops annually, was being phased out due to its contributions to ozone depletion in the stratosphere. Further, the immediate alternatives to methyl bromide, mainly a few other soil fumigants, were on “shaky ground” due to their own environmental challenges.

That year, the U.S. Department of Agriculture (USDA) launched the Pacific Area-Wide Pest Management Program for Integrated Methyl Bromide Alternatives (PAW-MBA). The program drew growers, nursery representatives, regulatory officials and scientists from California, Oregon and Washington to work together as a multidisciplinary team in response to the methyl bromide phase-out. Scientists from the USDA Agricultural Research Service, University of California, California Department of Pesticide Regulation, Oregon State University and Washington State University, along with public and private stakeholders, all were vital to development and implementation of the program.

The PAW-MBA sought to: 1) optimize available “next-best” fumigant alternatives to methyl bromide soil treatments and 2) foster development of non-fumigant alternatives. Specific needs of the targeted production systems (i.e., perennial and annual nursery crops, strawberries, almonds and stone fruits, walnuts and grapes) as well as over-arching environmental challenges (e.g., human health and safety; air, soil and water quality; efficient use of environmental resources) would be accommodated.

In the absence of methyl bromide, specific needs varied among the different production systems. Field nurseries needed alternatives to manage weeds (effective herbicides were not available) and nematodes (certification requires nursery stock to be nematode-free) over 1- to 2-year plant production cycles, and there was little flexibility for non-fumigant alternatives. In contrast, orchardists had less need to control weeds and more pressing needs to manage soilborne pathogen complexes (including but not limited to nematodes) over 15- to 30-year production cycles. Compared to field nurseries, orchard, vineyard and strawberry producers had more flexibility to explore non-fumigant alternatives.

All of the PAW-MBA specialty crop systems shared the imperative to minimize non-target fumigant emissions to the atmosphere. Fumigants are hazardous, volatile, broad-spectrum biocides and are regulated accordingly at federal, state and county levels to keep bystanders safe and minimize environmental impacts. As the project teams formulated plans, soil fumigants were entering a re-registration process that involved extensive reviews of human and environmental risks and refinement of product labels to manage the risks. Also, in parts of California, regulations designed to remediate ground-level ozone unacceptable under the U.S. Clean Air Act were coming to bear on volatile organic compounds, including soil fumigants.

Crop- and emissions-management-centered project teams were formed to implement overall PAW-MBA goals while addressing specific production needs and common environmental concerns of the specialty crop systems. The resulting projects focused on optimizing reduced rates of fumigant alternatives to methyl bromide, testing plastic-tarp-based technologies to improve fumigant performance while reducing fumigant emissions, and examining non-fumigant approaches to soilborne pest management (e.g., use of herbicides, fungicides, soil heating, crop rotation, resistant rootstocks, etc.).

In this edition, *California Agriculture* presents the first of two special focus sections reporting results of PAW-MBA projects, including alternatives to methyl bromide for almonds and stone fruits (p. 128), strawberries (p. 139), forest nurseries (p. 153), and perennial fruit, nut and ornamental nurseries (p. 179). Fumigant emissions management research was an additional element of some of the crop-oriented projects (p. 147). Future articles will report findings on the use of GPS-controlled spot fumigation technology in orchards; efficacy of fumigant and non-fumigant alternatives in raspberry, sweet potato, and cut flower and ornamental nurseries; and efficacy of alternative fumigants for replanting of walnut orchards and grape vineyards. Although the PAW-MBA program is essentially completed, its outreach continues (for additional overviews of the past and ongoing efforts, visit http://ucanr.org/sites/PAWMBA/).


Diane Haase

Containerized seedling production in forest nurseries can reduce disease risk by starting seeds in a clean, protected environment such as a greenhouse. *Above*, Styroblock container production of spruce seedlings in Moscow, ID.


Steve Fennimore

Non-fumigant approaches to managing soilborne pathogens and weeds in strawberry beds include steam treatment, *above*, in which soil is heated to temperatures higher than 150°F.


Husein Ajwa

Researchers with the PAW-MBA studied the use of plastic tarp technologies such as totally impermeable film (TIF) to improve fumigant performance while reducing emissions. *Above*, broadcast shank fumigation under TIF, Salinas, CA.

It became clear from results of most PAW-MBA projects that soil fumigation currently plays a critical role in specialty crop production and efficient use of land, water, energy and fertilizer resources in the process. But what about the future of soil sanitation strategies for specialty crops, given our need to reduce dependence on soil fumigation? This question has recently been considered formally by a scientist-stakeholder group assembled by the California Department of Pesticide Regulation. The group's members recently developed a Non-Fumigant Strawberry Production Action Plan (http://www.cdpr.ca.gov/docs/pestmgt/strawberry/work_group/action_plan.pdf), which outlines specific challenges and opportunities for development of non-fumigant production methods. Although the action plan is focused on strawberry production, it is relevant to non-fumigant-based production of other specialty crops. The state plan called for basic and adaptive research, small and large-scale field testing and demonstration, and related educational and infrastructure support. It includes scientific focus areas as diverse as soil microbiology, plant genetics, horticulture, economics and information technology, and recognizes the need for long-term public and private collaboration.

The development of viable long-term methyl bromide alternatives remains among many important issues facing specialty crop agriculture and the public it serves. Most of us would prefer to preserve our prime specialty-crop farmland and have access to its healthful produce rather than see it converted irreversibly into competing non-agricultural uses. Yet achieving this preference will require commitment and creativity from us all.

The author wishes to express deep gratitude to all PAW-MBA team and stakeholder members and to the staff of *California Agriculture* for their dedication and support of the program and this special issue.

Researchers develop alternatives to methyl bromide fumigation

Time is running out for California growers who still use methyl bromide. This soil fumigant is just short of a miracle for pest management — a single treatment before planting controls nematodes, diseases and weeds. But methyl bromide is also a health and environmental hazard, and is being phased out under an international ban. To help growers make the inevitable transition, UC and U.S. Department of Agriculture (USDA) researchers just spent 5 years testing methyl bromide alternatives for key western crops with a $5 million grant from the USDA. The program's research is presented in the current and the coming October–December issue of *California Agriculture*.

"One goal of the program was to identify methyl bromide alternatives that were immediately useful and economically feasible," says Greg Browne, a USDA plant pathologist at UC Davis who was project coordinator for the research program. "Another was to foster development of non-fumigant strategies for managing soilborne pests."

Growers have used methyl bromide since the 1960s to effectively sterilize fields before planting. But this toxic gas is so volatile that more than half of the amount injected into soil can eventually end up in the air. When methyl bromide rises high in the atmosphere, it contributes to thinning of the ozone layer (the layer that shields us from ultraviolet radiation). In 2005, developed countries banned methyl bromide under the Montreal Protocol, an international treaty signed in 1987 to protect the stratospheric ozone layer.

Even so, the treaty still allows limited use of methyl bromide in certain cases today. These include critical use exemptions for strawberries, almonds and other crops that lack alternatives that are both effective and affordable, as well as quarantine and preshipment exemptions for rootstock, bulbs and other nursery crops that could spread pests to new places. This authorized use shrinks each year, however, and will soon end. In the United States, recent methyl bromide use is down sharply from the 1991 baseline of 28,000 tons. The nationwide exemption for 2013 is 2.2% of baseline, or about 620 tons, and in 2014 this will drop further to 1.7% of baseline, or about 480 tons. The exemption for 2015, if any, is unknown. For comparison, California alone used 3,550 tons of methyl bromide in 2004, the year before it was banned.

Brad Hanson

Alternative fumigants such as 1,3-D may be the best option in the short term for nursery stock, which must be completely nematode-free to meet California's phytosanitary certification requirements.

Other restrictions on methyl bromide use include seasonal bans to cut air pollution, and the requirement of buffer zones to protect people's health. While methyl bromide depletes the protective ozone in the stratosphere, it adds to ground-level ozone or smog. Thus, its use is prohibited during the warm months in parts of the state with poor air quality, including the San Joaquin Valley and Ventura County. Moreover, methyl bromide–free buffers are required around sites that are hard to evacuate, such as schools, hospitals and jails, because high concentrations of this fumigant can cause lung, eye and skin damage as well as respiratory and central nervous system failure.

Finding alternatives

Most of the dwindling U.S. methyl bromide allotment goes to California and Florida, so the USDA Agricultural Research Service launched twin research initiatives to help find alternatives for growers in these regions. "The programs focused on the most important needs in the west and southeast," says Browne. "The crop mixes were based on the views of growers and other stakeholders." The western program, called the Pacific-Area Wide Integrated Methyl Bromide Alternatives Program, includes production crops such as grapes, strawberries and tree nuts as well as nursery crops such as cut flowers, forest trees and sweet potatoes. The South Atlantic Area Extension Program for Methyl Bromide Alternatives, the southeast program, includes crops such as strawberries, tomatoes, cucumbers and peppers.

Finding alternatives is a challenge because methyl bromide sterilizes soil so well. "Methyl bromide is a one-shot control. It does so much that it's hard to find a true replacement," says Brad Hanson, a UC Cooperative Extension (UCCE) weed specialist at UC Davis. In addition, the best alternative varies, depending partly on the primary benefit a particular crop gets from methyl bromide. For example, the biggest problems for production crops may be diseases or weeds. But the biggest problem for nursery stock is nematodes, tiny worms that can damage plants by eating them and by spreading diseases. Nursery stock must be completely nematode-free to receive the certification required by the state of California.

Another challenge is that while other fumigants can be substituted for methyl bromide, only a few are approved, and their use is also restricted. Like methyl bromide, alternative fumignats have seasonal bans and buffer requirements. Moreover, alternative fumigants can also have tight limits on total use. These restrictions are likely to increase, intensifying the urgency to find non-fumigant solutions.

Optimizing other fumigants

Despite their drawbacks, alternative fumigants may be the best option — at least in the short term — for many crops with methyl bromide exemptions. This is particularly true for nursery products. "They have a higher bar because they have to get phytosanitary certification," says Hanson, who led a team that focused on bareroot rose, tree and vine nursery stock grown in the ground. "If any nematodes are found, growers have to destroy the whole block of plants," he adds. Losses can reach 20,000 plants and, for trees and vines, can exceed $50,000 per acre. Perennial nursery stock is vital to California's fruit, nut and vineyard industries, and supplies more than 60% of the rose plants and fruit and nut trees sold nationwide.

Methyl bromide is a small molecule that spreads quickly even in soil with fine pores, which means it controls nematodes even in soil that is wet or full of clay. In contrast, other fumigants are less forgiving of soil conditions. "We asked how we could make them work better," Hanson says. The team tested an alternative fumigant called 1,3-dichloropropene (1,3-D) which controls nematodes well in sandy soil but often doesn't spread evenly enough in clay. "In less than ideal conditions, it can leave pockets of untreated soil," Hanson says. In addition, 1,3-D doesn't control weeds as well as methyl bromide, so growers will have to incur the extra expense of additional tillage, hand weeding or herbicides. Another disadvantage is that this alternative fumigant may not control soil diseases as well as methyl bromide.

That said, the researchers showed that 1,3-D can control nematodes effectively in fine soil as long as it has been properly prepared. This includes tilling deeper to dry and pulverize the soil, injecting the fumigant deeper, and using tarps to keep more of the fumigant in the soil. When allowed by county regulations, the team also recommends combining 1,3-D with other fumigants called chloropicrin and metam sodium. "Although this is not a simple solution, now growers will have information on how to use these alternatives once their methyl bromide exemptions expire," Hanson says.

Reducing emissions

Because using fumigants is unavoidable for nursery stock in the short term, Hanson was also on a team that focused on reducing their emissions from the soil. Besides lessening their environmental impact, keeping these volatile gases out of the atmosphere will help growers meet the tighter air quality regulations expected in the future. This will help extend the agricultural use of fumigants until effective non-fumigant alternatives are found.


Brad Hanson

Workers sort and grade bareroot nursery stock. California supplies most of the rose plants and fruit and nut trees sold nationwide.

The emissions reduction team tested a new kind of tarp that has five or more layers to help keep fumigants in the soil. This multi-layer tarp, called totally impermeable film (TIF), traps 90% of the fumigant. Over time, the trapped fumigant breaks down or is degraded into harmless compounds by microbes. TIF also boosts the fumigant's concentration in soil and helps it spread through the field better, making this treatment more effective. "This might cut fumigant use by about half, which would solve a lot of problems," says Suduan Gao, a USDA soil scientist in Parlier who led the team.

The high-tech tarp also has a potential downside, though. A spike of toxic gas is released if the TIF is cut open for planting before the fumigant has broken down, which can take two weeks or more depending on the soil conditions, and the application method and rate. "We're now working on safe use," Gao says. "The goal is to keep the fumigant under the tarp long enough that there won't be a surge in emissions."

Targeted injection

Another way of using less fumigant is to apply it only where needed, rather than on an entire field or all along the length of each row. Almond and other stone fruit growers use methyl bromide primarily to control Prunus replant disease, a soilborne disorder that stunts the trees' early growth. This greatly diminishes crop yields — and profits — over the life of the orchard. Almonds alone are valued at close to $4 billion a year, and were California's number two commodity in 2011. Before replanting an orchard, growers typically inject methyl bromide in a continuous swath down each row.

But it turns out that the entire row doesn't have to be fumigated to control Prunus replant disease. The USDA's Browne led a team that tested spot treatments, which entail injecting alternative fumigants only into the sites where trees would be planted. "We wanted to see how little we could use," he says. To target spot treatments to future tree sites, a GPS-based system was developed under the direction of Shrini Upadhyaya, a professor in the Department of Biological and Agricultural Engineering at UC Davis.

While almond and other stone fruit growers currently fumigate about half of an orchard's area before replanting, spot treatments can decrease that to about a tenth or a fifth. “Spot treatments provided adequate control of Prunus replant disease and may be very helpful to growers needing to use less fumigant for costs savings or regulatory restrictions,” Browne says. He is now working to develop almond and stone fruit rootstocks that resist Prunus replant disease. Ultimately, this could help these growers stop using fumigants altogether, as long as their orchards don’t have nematode problems.

However, nematodes are a problem in about a third of California’s almond and stone fruit orchards. These pests eat the roots of trees, stunting their growth, and populations can build over the lifetime of an orchard, reducing yields. Growers with nematode problems currently fumigate continuously down the entire row. However, as long as they use nematode-resistant rootstock, they could use the intermittent spot treatment instead.

Fumigation not needed?

While many production systems with methyl bromide exemptions are likely to switch to other fumigants, the researchers found one that may not need fumigation at all. Sweet potato growers have two production systems: commercial fields, and hotbeds where they raise their own transplants. Growers had already begun using an alternative fumigant on commercial fields due to the cost of methyl bromide. But, when the study began, they still used methyl bromide to prepare hotbed soil. Sweet potatoes, which were the number five commodity in Merced County in 2011, needed an alternative fast because their exemption was set to end in 2012.

“The presumption was that it would be a disaster, with rumors of 75% crop loss,” says Scott Stoddard, a UCCE farm advisor in Merced County who led a team that focused on sweet potato hotbeds. “But no one had ever tested what methyl bromide was actually doing, or not doing, in this system,” he adds. The team found that even with no treatment, plant diseases were not a problem. Likewise, nematodes were not a problem, presumably because hotbed production is during the early spring when populations of this pest tend to be low.

However, without methyl bromide, sweet potato hotbeds did have a lot of weeds. But the team found that these can be controlled with herbicides, showing that fumigation is not needed in hotbeds. “We found an alternative that everyone’s happy about — it’s less expensive, works and has no use restrictions,” Stoddard says. “This approach has been rapidly adopted by the industry.”

Beyond fumigants

Likewise, the strawberry research team focused on ways to avoid fumigation altogether. This could allow strawberry production on prime growing land that is too close to urban areas for fumigation. “Strawberries like the same climate as people do,” says Steve Fennimore, a UCCE weed specialist in Salinas who led a team that focused on strawberries. “They do best within a few miles of the ocean, which is also where a lot of people live.”

Methyl bromide is used on about a third of California’s strawberry acreage, where soilborne pathogens are high. “Strawberries are incredibly susceptible to disease,” Fennimore says. “They turn brown and die.” Valued at nearly $2 billion per year, strawberries were the state’s number six commodity in 2011. While strawberries can be grown with other fumigants, these are also so heavily regulated that growers are struggling to replace the methyl bromide currently being used. Ultimately, strawberry growers may have to use a mix of fumigant and non-fumigant treatments.

At the request of the California Strawberry Commission, the team explored non-fumigant alternatives including production without soil. For example, strawberries are grown in substrates such as peat moss or coconut hull fiber in Europe. These systems are challenging, however, requiring irrigation and fertilization several times a day.

The team also tested controlling soil pathogens with steam sterilization. “Instead of understanding soil, we’ve just been fumigating it,” Fennimore says. “Using physical tools is a different approach.” The team tested a steam rig that heats soil to 160°F in just 90 seconds and keeps it hot for 20 minutes, long enough to kill soil pests as effectively as methyl bromide. The rig can treat an acre in 15 hours, and the team is working to bring that down to 4–8 hours.

To give strawberry growers more non-fumigant options, the team also tested controlling soil pests and weeds with mustard seed meal. This natural material contains a compound called allyl isothiocyanate that sterilizes soil but is not toxic to people. So far, a combination of mustard seed meal and steam treatment is promising.

Another natural approach is to control diseases and possibly weeds with the anaerobic microbes that live in soil. Called anaerobic soil disinfestation, this method entails increasing anaerobic microbe populations by feeding them a carbon source such as rice bran, and then making the soil anaerobic by covering it with plastic and keeping it wet. Short-term findings on small plots suggest that anaerobic microbes may control strawberry diseases nearly as well as fumigation.

Program website

The research teams documented their findings in a 100-page website (http://ucanr.edu/sites/PAWMBA/), which will help growers find the methyl bromide alternatives that work best for them. “We wanted to give them a place to find out what to expect when they make the switch,” says project coordinator Browne. By identifying alternatives that are both effective and economical, this research will help ease the transition to post–methyl bromide production of key crops in California. — *Robin Meadows*


Raquel Serohijos

Strawberries growing in coir, a soil-free substrate that does not need fumigation.

RESEARCH ARTICLE

Managing the almond and stone fruit replant disease complex with less soil fumigant

by Greg T. Browne, Bruce D. Lampinen, Brent A. Holtz, David A. Doll, Shrinivasa K. Upadhyaya, Leigh S. Schmidt, Ravindra G. Bhat, Vasu Udompetaikul, Robert W. Coates, Bradley D. Hanson, Karen M. Klonsky, Suduan Gao, Dong Wang, Matt Gillis, James S. Gerik *and* R. Scott Johnson

As much as one-third of California's almond and stone fruit acreage is infested with potentially debilitating plant parasitic nematodes, and even more of the land is impacted by Prunus replant disease (PRD), a poorly understood soilborne disease complex that suppresses early growth and cumulative yield in replanted almond and peach orchards. Preplant soil fumigation has controlled these key replant problems, but the traditional fumigant of choice, methyl bromide, has been phased out, and other soil fumigants are increasingly regulated and expensive. We tested fumigant and nonfumigant alternatives to methyl bromide in multiple-year replant trials. Costs and benefits were evaluated for alternative fumigants applied by shanks in conventional strip and full-coverage treatments and applied by shanks or drip in novel spot treatments that targeted tree planting sites. Short-term sudangrass rotation and prudent rootstock selection were examined as nonfumigant approaches to managing PRD. Trial results indicated that integrations of the treatments may acceptably control PRD with relatively little soil fumigant.

Leigh S. Schmidt

Rootstocks for almonds and stone fruits were tested for their resistance to the Prunus replant disease complex near Parlier, CA. Shown are a plot of PRD-affected rootstocks in nonfumigated replant soil, *left*, and a plot of relatively healthy rootstocks grown in soil preplant fumigated with 1,3-D:Pic 63:65 (Telone C35), *right*.

Approximately 1 million acres of California's best agricultural land are devoted to production of almonds and stone fruits (USDA 2011), and sustained high production from this land requires that the orchards be replanted every 15 to 25 years, depending on the production system. Research has documented myriad problems that can suppress growth and productivity in such replanted orchards (Bent et al. 2009; Browne et al. 2006; Larsen 1995; McKenry 1996, 1999; Westerdahl and McKenry 2002). Abiotic soil factors related to previous crop production, such as compaction, salinity, suboptimal pH, nutritional imbalances and herbicide residues, can compromise the performance of replanted orchards, but many of these problems can be avoided or remedied without great difficulty or expense.

Biotic replant problems, including plant parasitic nematodes and Prunus replant disease (PRD), can pose more of a challenge. Plant parasitic nematodes infest as much as one-third of California's almond and stone fruit acreage (McKenry and Kretsch 1987) and have the potential to compromise all phases of an orchard's productive life by inflicting root damage. Several rootstocks for almonds and stone fruit have shown genetic resistance to root knot nematodes, but little resistance has been demonstrated against the other two major nematode pests affecting these crops, the ring nematode and the root lesion nematode (McKenry 2007). PRD, which is much more widespread than nematode damage on almonds and stone fruits, is a poorly understood soilborne disease complex that suppresses early growth and cumulative yield in replanted almond and peach orchards (Bent et al. 2009; Browne et al. 2006). It afflicts successive generations of almonds and stone fruit planted at the same location and is associated with poor health of the trees' fine roots and incidence of several plant-parasitic fungi and oomycetes. The severity of the disease varies greatly among orchards, but it is observed most commonly on loam, sandy loam, and sand soil textures in California. PRD can occur on its own or in combination with other replant problems.

Preplant soil fumigation has been an effective means of control for biological replant problems, but fumigant usage today is being challenged on several fronts, including the phase-out of methyl bromide (US EPA 2012), township caps on the use of the fumigant 1,3-dichloropropene (1,3-D) (Carpenter et al. 2001), volatile organic compound regulations under the

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U.S. Clean Air Act (Cal-DPR 2012), and increasingly restrictive buffer zones (see pages 122–127 for explanation and more details on each of these topics). Due to required buffer zones (to protect bystanders from unintended exposure), many fields have large areas that cannot be treated using conventional fumigation.

Reducing dependence on fumigation

Over the long term, breeding of rootstocks that broadly resist or tolerate soilborne pathogens and development of cultural practices that effectively remediate replant problems may remove dependence on soil fumigation. In this article we report on the effectiveness of options currently available for control of the most widespread almond and stone fruit replant problem, PRD. We examine the potential contributions of optimized soil fumigation methods, crop rotation and rootstock selection to the integrated management of PRD and reduced fumigant use.

Almond replant trials

As part of our research, we established two almond replant trials in Madera County focused on fumigant-based options for control of PRD. The trials were designed to help optimize soil fumigation practices by identifying fumigant formulations that are particularly effective for control of the disease complex and by determining the effectiveness of different fumigant rates and novel fumigant delivery methods. Regarding the latter emphasis, GPS-based software and hardware systems were developed recently to deliver spot fumigation treatments by tractor to tree planting sites (Coates et al. 2007; Udompetaikul et al. in press). The new spot treatment system was designed for planning, mapping and treating all tree sites in a replacement orchard and is considered to be much safer and faster than spot fumigation treatments applied with a hand-held probe. Spot treatment can reduce the amount of fumigant required to treat an orchard acre by 50% to 90%, but evaluations of the GPS-controlled tractor application system were needed.

Two orchards in California, one near Firebaugh and the other near Madera, were selected for replanting experiments. The Firebaugh trial included soils of Dinuba fine sandy loam, El Peco fine sandy loam and Fresno fine sandy loam, whereas the Madera trial included El Peco, Fresno, and Lewis sandy loams and Tujunga loamy sand. Lands for the Firebaugh and Madera replant trials were cleared of old almond orchards grown on 'Nemaguard' rootstock in the summers of 2006 and 2007, respectively, using conventional practices. After removal, the old trees were chipped (the removed tree residue was ground up by a tub grinder and hauled away for energy generation or other uses). To reduce soil compaction, the cleared lands were ripped to a depth of 5 to 6 feet and then smoothed. In preparation for soil fumigation, the lands were then sprinkler irrigated with about 1.5 inches of water to reduce the potential for fumigant emissions to escape into the atmosphere.

Fumigants were applied to the soil in October 2006 for the Firebaugh trial and October 2007 for the Madera trial. The fumigant formulations were:

- methyl bromide (MB), 98%; chloropicrin (Pic), 2%, as a warning agent (MBC Concentrate, TriCal Inc.)
- 1,3-D, 98% (Telone II)
- chloropicrin (Pic), 99% (Tri-Clor)
- mixtures of 1,3-D:Pic, including 63:35 (Telone C35) and 39:60, (Pic-Clor 60)
- iodomethane (IM):Pic 50:50 (Midas)

In each orchard, all preplant soil fumigation treatments were applied by TriCal Inc. (Hollister, CA) to plots that would accommodate a width of three tree rows (66 feet) and a length of 10 tree spaces (140 to 170 feet). The MB treatments were applied with a conventional MB rig (TriCal Inc.), and the system injected fumigant at soil depths of 18 to 20 inches through two shanks spaced 60 inches apart; one pass was made for each tree row, effectively treating a 10-foot-wide strip. The other fumigant treatments were applied with a Telone rig (TriCal Inc.), which also injected fumigants at soil depths of 18 to 20 inches, but through three or five shanks (depending on the treatment). The shanks were spaced 20 inches apart and tipped with horizontal "wing" attachments. Fumigant was released from two points 8 inches apart, one behind each wing tip. The rig was used to apply three types of treatments: single-pass strip treatments, in which fumigant was

Optimized soil fumigation, crop rotation and rootstock selection are valuable components for integrated management of PRD.


Greg Browne

First-year impact of Prunus replant disease at the Firebaugh replant trial; stunted trees in the foreground row were planted in plot of nonfumigated replant soil, while trees in the background rows were planted in preplant fumigated soil.

applied only to 8.3-foot-wide strips centered over future tree rows; full-coverage treatments, in which the entire area of a replicate plot received fumigant; and spot treatments, in which either 8.3-foot-wide by 8-foot-long (Firebaugh trial) or 5-foot-wide by 7-foot-long (Madera trial) rectangular areas centered over future tree sites were treated.

The spot treatments were administered via a Telone rig retrofitted with GPS-based software and hardware to rapidly turn shank injections off and on as the tractor traveled down the future tree rows with the shanks remaining in the soil (Coates et al. 2007; Upadhyaya et al. 2009; Udompetaikul et al. in press). Before the spot applications began, the software was used to create a virtual map of each orchard's future tree sites according to desired row and tree spacings and planting patterns (rectangular and diamond planting patterns were used in the Firebaugh and Madera trials, respectively), and the desired width and length of the zones to be fumigated around each mapped tree planting site were selected.

The control plots were ripped with Telone rig shanks but received no fumigant. Each treatment was applied to several replicate plots (six at Firebaugh and five at Madera). The plots were randomized in a complete block design.

The Firebaugh trial was replanted in January 2007, and the Madera trial in January 2008. In each replicate plot, a center row was replanted to 'Nonpareil' almond and the two adjacent rows were replanted to other varieties selected for cross-pollination. In all cases, the rootstock for 'Nonpareil' was 'Nemaguard' peach. Efficacy of the treatments was assessed according to the percentage of incident photosynthetically active radiation (PAR) intercepted by the 'Nonpareil' tree canopies in midsummer and nut yields collected starting in the third growing season and annually thereafter. To measure the PAR interception, we used a new mobile platform that provides a good estimate of the yield potential of tree canopies (Lampinen et al. 2012).

Almond replant trial results

In both the Firebaugh and Madera trials, most of the preplant soil fumigation treatments showed enhanced canopy growth through the first and second yield years (the third and fourth growing seasons after planting, respectively) when compared to the nonfumigated control (table 1; $P = 0.002$ to < 0.0001 for effect fumigant treatment).

At Firebaugh, compared to the control, preplant strip treatments with MB and 1,3-D boosted PAR interception by 20% and 39%, respectively, in yield year 1 (table 1). Thereafter, these fumigation treatments had little effect on PAR interception. Other fumigant treatments at Firebaugh, including Pic and combinations of Pic with 1,3-D or IM, were generally more effective than the MB and 1,3-D treatments, boosting mean PAR interception by 56% to 97% in yield year 1 and 11% to 22% in yield year 2 compared to the control. By yield year 3 (the fifth growing season after planting), however, none of the treatments affected PAR interception (table 1; $P = 0.24$).

In the Madera trial, PAR responses to fumigation were generally more similar among the treatments than in the Firebaugh trial (table 1). At Madera, increases in PAR interception due to preplant fumigation ranged from 34% to 68% in yield year 1 and 35% to 69% in yield year 2 compared to the nontreated control (table 1). The increases in PAR interception between yield years 1 and 2 were generally less at Madera than at Firebaugh. Pressure bomb readings taken in yield years 1 and 2 at Madera suggested that tree water stress was responsible for the lesser growth.

In both trials, using the assumption of a net price (i.e., the price after subtraction of nut hauling, hulling and marketing costs) of $2 per pound of nut meats, increases in PAR interception translated into profitable yield increases for all treatments except MB (table 1). The high cost of the MB treatment was not offset by the relatively poor yield increases it generated. By yield year 2, the MB treatment reduced cumulative net returns by $1,120 and $552 per acre in the Firebaugh and Madera trials, respectively, compared to the control. The full-coverage treatment with 1,3-D:Pic 63:35 resulted in the second greatest and greatest cumulative nut yields over the harvests monitored in the Firebaugh and Madera trials, respectively, but the high cost of the treatment kept the net returns relatively low compared to several other MB-alternative treatments (table 1).

Across both trials, the strip treatments with Pic and combinations of 1,3-D:Pic (63:35 and 39:60) generally afforded greater net returns than other treatments. Although the GPS-controlled spot treatments generated lower net returns than some of the strip treatments, the spot treatments provided greater returns than the strip treatment with 1,3-D alone, which has been an almond and stone fruit industry standard. In terms of dollars of net revenue per pound of fumigant, the spot treatments were generally more efficient than strip or full-coverage treatments (table 1). When a net price of $1.70 per kernel pound was assumed (instead of $2 per pound, for the sake of comparison), all of the MB-alternative treatments


Greg Browne

First-year impact of Prunus replant disease at the Madera replant trial; stunted trees in the foreground were planted in plot of nonfumigated replant soil, while larger trees in the background of the same row were in plot of preplant fumigated soil.

still increased net crop revenues, but the returns were again negative for the MB treatment and relatively low for the 1,3-D:Pic 63:35 full-coverage treatment. We intend to continue annual PAR and yield measurements in the Madera and Firebaugh trials. Yields have not converged among the treatments, suggesting that their economic value will continue to sort out over time.

Soil sampling from all replicate plots of the control, MB strip and 1,3-D:Pic 63:35 broadcast treatments detected negligible to small nematode populations in 2009 and 2012. Specifically, in 2009 at Firebaugh, we detected one ring nematode per half pint (250 milliliters) of soil from one MB-treated plot, and no lesion, ring or root knot nematodes from other plots; at Madera, there were three lesion nematodes per half pint (250 milliliters) of

TABLE 1. Results summary, almond replant trials in Madera County

						Photosynthetically active radiation (PAR) absorbed			Cumulative yield			Cumulative net revenue gain†		Fumigant efficiency	
Trial	**Fumigant***	**Coverage**	**Fumigant rate**		**Cost of treatment**	**Yield year 1**	**Yield year 2**	**Yield year 3**	**Yield year 1**	**Yield year 2**	**Yield year 3**	**Yield year 2**	**Yield year 3**	**Yield year 2**	**Yield year 3**
			lb/treated acre	*lb/orchard acre*	*$/acre*	.... *%*			...... *lb kernels/acre*			.... *$/acre*		*net $ gain/ lb fumigant*	
Firebaugh	Control	None	0	0	0	16	46	59	161	856	3,024	0	0	—	—
	MB	Strip (45%)	400	180	1,962	19	46	54	455	1,277	3,366	(1,120)	(1,279)	(6.22)	(7.10)
	1,3-D	Strip (38%)	340	129	393	22	50	58	547	1,517	3,997	929	1,552	7.19	12.01
	Pic	Strip (38%)	400	152	871	29	54	61	932	2,088	4,676	1,593	2,433	10.48	16.01
	Pic	Strip (38%)	300	114	677	28	51	56	975	2,129	4,726	1,870	2,727	16.40	23.92
	Pic	Strip (38%)	200	76	482	32	54	61	979	2,308	4,929	2,422	3,328	31.87	43.79
	1,3-D:Pic (63:35)	Strip (38%)	550	209	882	30	56	62	905	2,260	5,113	1,926	3,296	9.22	15.77
	1,3-D:Pic (39:60)	Strip (38%)	550	209	829	31	55	60	1,123	2,502	5,540	2,462	4,202	11.78	20.11
	1,3-D:Pic (39:60)	Strip (38%)	400	152	667	30	53	59	834	2,132	4,765	1,885	2,814	12.40	18.51
	IM:Pic (50:50)	Strip (38%)	400	152	—	30	57	62	948	2,120	5,107	—	—	—	—
	Pic	Spot (17%)	400	68	441	26	51	58	811	1,939	4,673	1,725	2,857	25.37	42.01
	1,3-D:Pic (63:35)	Spot (17%)	550	94	447	25	51	59	778	1,844	4,484	1,530	2,473	16.37	26.45
	1,3-D:Pic (63:35)	Full (100%)	550	550	2,169	31	55	61	941	2,285	5,364	688	2,511	1.25	4.57
	Value of *P*:					**<0.0001**	**0.002**	**0.24**	**<0.0001**	**<0.0001**	**<0.0001**				
	95% confidence interval values:					**± 4**	**± 4**	**± 4**	**± 240**	**± 277**	**± 473**				
Madera	Control	None	0	0	0	25	30	—	274	973	—	0	—	—	—
	MB	Strip (45%)	400	180	1962	36	45	—	380	1,678	—	(552)	—	(3.07)	—
	1,3-D	Strip (38%)	340	129.2	393	35	42	—	405	1,496	—	653	—	5.05	—
	Pic	Strip (38%)	400	152	871	39	45	—	562	2,028	—	1,239	—	8.15	—
	Pic	Strip (38%)	300	114	677	40	47	—	516	1,930	—	1,237	—	10.85	—
	Pic	Strip (38%)	200	76	482	34	42	—	407	1,494	—	558	—	7.34	—
	1,3-D:Pic (63:35)	Strip (38%)	550	209	882	38	46	—	512	1,884	—	938	—	4.49	—
	1,3-D:Pic (39:60)	Strip (38%)	400	152	667	36	42	—	514	1,724	—	834	—	5.48	—
	IM:Pic (50:50)	Strip (38%)	400	152	—	43	51	—	517	2,185	—	—	—	—	—
	Pic	Spot (11%)	400	44	319	39	46	—	454	1,690	—	1,115	—	25.34	—
	1,3-D:Pic (63:35)	Spot (11%)	550	60.5	322	34	40	—	443	1,552	—	835	—	13.81	—
	1,3-D: Pic (63:35)	Full (100%)	550	550	2,169	42	50	—	485	2,300	—	483	—	0.88	—
	Value of *P*:					**0.0003**	**0.0002**		**<0.0001**	**<0.0001**					
	95% confidence interval values:					**± 5**	**± 6**		**± 64**	**433**					

* Abbreviations indicate the following fumigants (and formulations): MB = methyl bromide 98%, chloropicrin 2% (MBC Concentrate, TriCal Inc.); 1,3-D = 1,3-dichloropropene 98% (Telone II, Dow AgroSciences); Pic = chloropicrin 99% (Tri-Clor, TriCal Inc.); 1,3-D:Pic 63:35 = 1,3-dichloropropene 63% + chloropicrin 35% (Telone C35, Dow AgroSciences); 1,3-D:Pic 39:60 = 1,3-dichloropropene 39% + chloropicrin 60% (Pic-Clor 60, Dow AgroSciences); and IM:Pic = methyl iodide 50%, chloropicrin 50% (Midas, Arysta Life Sciences Inc.).

† Based on a net kernel price (i.e., the price after subtraction of nut hauling, hulling, and marketing costs of $2.00 per lb.).

soil from one control plot, and no lesion, ring or root knot nematodes from other plots. In 2012 at Firebaugh, we detected no lesion, ring or root knot nematodes; at Madera, we detected 164 and 348 lesion nematodes per half pint (250 milliliters) in two respective control plots, and no lesion, ring or root knot nematodes in other plots. These results suggest that PRD was the dominant replant problem in these trials, but it is possible that plant parasitic nematode populations will build and have future economic impacts.

Despite the long-term uncertainties, our trials indicate that effective preplant soil fumigation can be an essential step in maximizing net revenues in replanted almond orchards, at least when 'Nemaguard' rootstock is used in the replanted orchard and PRD is active. Furthermore, our findings suggest that at orchard sites at risk for PRD and not infested with plant parasitic nematodes, growers can increase net revenues by using strip treatments with Pic or mixtures of Pic with 1,3-D instead of treatments with 1,3-D alone. Finally, the efficacies and efficiencies of GPS-controlled spot fumigation treatments indicate that they may have important applications where site or air quality sensitivities permit use of only very low rates of fumigant per acre.

Microplot replant trials

We conducted microplot trials to explore the potential of fallowing and crop rotation to remediate PRD. It was found in replanted apple orchards in Washington state that preplant rotation with wheat as a green manure lessened the severity of apple replant disease (Mazzola and Gu 2000; Mazzola and Mullinix 2005). Also, certain crops such as 'Piper' sudangrass have been recommended during fallow periods for suppression of nematode populations (Westerdahl et al. 2010). We investigated the potential for using short-term crop rotation and fallowing to reduce the severity of PRD in California.

For this purpose, microplots were constructed at the San Joaquin Valley Agricultural Sciences Center (SJVASC), U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS), Parlier. The microplots consisted of sections of concrete pipe (24 inches in diameter by 48 inches long) inserted vertically into soil, with the rims protruding approximately 8 inches above the soil surface. The microplots were spaced 3 feet apart, edge to edge, and were filled with Hanford sandy loam soil that had been excavated from 0.3- to 2.5-foot depths in an adjacent peach orchard where trees had expressed PRD.


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To test plant response to different soil treatments including preplant crop rotation, researchers established soil microplots by installing 4-foot lengths of 24-inch-diameter concrete pipe vertically into the soil and filling the pipes with soil from a nearby orchard affected with Prunus replant disease.

The soil in the microplots was planted with trees on 'Nemaguard' rootstock to maintain PRD induction potential, and the plants were watered with drip irrigation. Soil assays indicated that the soil did not have significant numbers of damaging plant parasitic nematodes.

Eight different treatments were imposed on the microplots in a randomized complete block design; there were five replicate microplots per treatment. The treatments were chosen to simulate remediation options of potential interest to almond and stone fruit growers during orchard replanting (table 2). For example, growers may choose to schedule orchard replacement to accommodate dry fallowing of the land for several months or years before replanting, or, alternatively, to replant quickly, without an extended fallow period. Also, whether or not fallowing is involved, growers typically have the option to fumigate the soil or leave it untreated before replanting. Fallowing and fumigation options were represented in treatments 1 to 4 (table 2). When an orchard-free period is observed before replanting, a rotation crop may be used. We selected treatments 5 to 8 to test some of the crop rotation options (table 2).

Treatment options 1 and 2 have the potential to be completed without losing a season of almond or peach production. Treatments 3 through 8 would typically require the loss of a crop cycle, unless a spring-harvested stone fruit variety was being replaced. If potted trees were to be used for the orchard replanting, it would be possible to complete the rotation with wheat alone (treatment 7) without loss of an almond or stone fruit cropping cycle (potted trees can be planted in late spring). Planting bareroot trees after the wheat rotation would require an undesirable delay. Unless kept in cold storage, bareroot trees are optimally planted by early February.

Details of the microplot trials were as follows: Three separate (repeat) experiments were completed. All three experiments had the same treatments, but the experiments were started successively, one year apart. In each experiment, the summer and fall portions of treatments 1 through 8 were imposed beginning in June of the year the experiment began (nearly 1 year before the microplots would be replanted with 'Nemaguard' peach plants.) The summer and fall portions of treatments 1 through 8 were continued until the following November, 4 months before replanting (table 2). During this period, the treatments involved maintaining growth of trees on 'Nemaguard' rootstock, dry fallowing (the soil was kept bare by hand-weeding) or growing hybrid corn or 'Piper' sudangrass (table 2). The 'Nemaguard,' corn and sudangrass plants were drip-irrigated to meet evapotranspiration needs, but the fallowed plots were not irrigated. All plots (including those fallowed) were fertilized periodically with equal amounts of ammonium sulfate fertilizer.

Near the end of the preplant period, in early November, the scions of trees on 'Nemaguard' rootstock (in treatments 1 and 2) and the tops of the sudangrass plants (treatments 6 and 8) were removed and then discarded outside the microplots. Also, the corn stalks (treatment 5) were chopped into pieces 2 to 3 inches long and kept within the microplots. The 'Nemaguard' and sudangrass root system residues and the corn roots and stubble were turned into the top foot of soil in their respective plots using a shovel to simulate thorough disking. Soil in all other plots was turned in the same manner, and the wheat was planted in its plots (treatments 7 and 8). In mid-November, the soil fumigation treatments were imposed on the appropriate plots using a microfumigation rig; MB plus Pic (50:50 formulation) was injected at 400 pounds per acre at 1 foot below the soil surface. At the end of the winter-spring period, soil in all plots, including those with wheat, was turned over repeatedly to a depth of 1 foot with a shovel to simulate disking.

In each of the three repeat experiments, we assessed efficacy of the preplant remediation treatments by replanting the microplots with 'Nemaguard' peach seedlings in the following March (i.e., for each experiment, nearly a year after the experiment's beginning) and measuring accumulated shoot weights of the seedlings the following November. The 'Nemaguard' seedlings were watered by drip irrigation to meet evapotranspiration demand and fertilized periodically with ammonium sulfate. All plots received the same irrigation and fertilization schedule, except in cases where soil moisture became excessive due to reduced water use by PRD-affected plants; in such cases, irrigation was briefly withheld from overly wet plots until soil moisture levels were similar among all plots.

Microplot replant trial results

In the three successive microplot trials (fig. 1, experiments 1, 2 and 3), several relatively consistent effects emerged, including the following:

- Preplant fumigation with MB plus Pic (50:50) consistently improved growth of replanted 'Nemaguard' peach seedlings, with or without extra preplant fallowing (fig. 1, treatments 1–4).
- The extra 5 months of preplant fallowing alone (fig. 1, treatment 3) did not significantly improve 'Nemaguard' growth, compared to the nonfallowed, nonfumigated control (treatment 1).
- A summer rotation with 'Piper' sudangrass (fig. 1, treatment 6) significantly improved growth of replanted 'Nemaguard,' as compared to fallowed and non-fallowed controls (treatments 1 and 3), but the degree of benefit did not consistently match that achieved by fumigation.
- Rotations involving corn or wheat (fig. 1, treatments 5, 7 and 8) were sometimes beneficial, as compared to the controls (treatments 1 and 3).

These results suggest that some crop rotations, and particularly a summer rotation with 'Piper' sudangrass, may help

TABLE 2. Preplant treatments applied to Parlier microplots filled with soil from a peach orchard affected by Prunus replant disease

	Treatment sequence		
Treatment number	Preplant cropping status in summer/fall (Jun–Nov)	Fumigation treatment (Nov)	Preplant cropping status in winter/spring (Nov–Mar)
1	'Nemaguard' rootstock	None	Bare fallow
2	'Nemaguard' rootstock	MB + Pic, 400 lb/ac†	Bare fallow
3	Bare fallow	None	Bare fallow
4	Bare fallow	MB + Pic, 400 lb/ac	Bare fallow
5	Corn hybrid N8214*	None	Bare fallow
6	'Piper' sudangrass	None	Bare fallow
7	Bare fallow	None	'Penewawa' wheat‡
8	'Piper' sudangrass	None	'Penewawa' wheat

* Syngenta Seeds, NK Brand, Western Ag Services, Clovis, CA.
† Methyl bromide and Pic mixture (50:50, w:w).
‡ Lake Seed Inc., Ronan, MT.

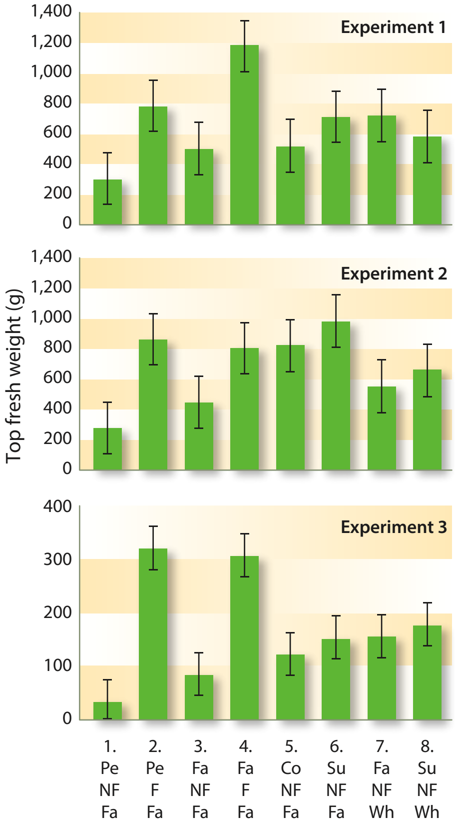

Fig. 1. Effects of preplant fallowing, crop rotation and fumigation on growth on 'Nemaguard' peach rootstock in microplot trials near Parlier. Experiments 1, 2 and 3 above were started in June of three successive years (2002, 2003 and 2004). For each experiment, treatment numbers are shown in the top row of *x*-axis labels; the second row of labels represents the corresponding cropping status of the treatments from June to November (Pe = peach, Fa = fallow, Co = corn, Su = sudangrass); the third row of labels indicates subsequent fumigation treatment (NF = nonfumigated, F = fumigated) and the fourth row of labels indicates subsequent cropping status from November to March (Fa = fallow, Wh = wheat). Vertical bars are 95% confidence intervals.

growers reduce the severity of PRD and thereby reduce the need for soil fumigation. Orchard validation of some of the microplot findings was completed in a peach replant trial, as described below.

Peach replant trial

Favorable responses to spot and strip fumigation treatments in the almond orchard replant trials and to crop rotation in the microplot trials led to validations in a peach orchard replant trial. For the experiment, plums on 'Nemaguard' rootstock were removed from a block at the SJVASC in early July 2007. The land was ripped to a depth of 2 to 3 feet, leveled, pre-irrigated and divided into five main plots, each of which was split in half. Each half of the five main plots measured 72 feet by 140 feet. One half was kept fallow (i.e., maintained relatively weed-free by a combination of cultivation and post-emergence herbicide treatments), while the other half was planted to 'Piper' sudangrass as a green manure crop. The sudangrass was grown for 2 months under sprinkler irrigation, then shredded and disked into the ground; the disking operation was extended across the whole field in preparation for preplant soil fumigation treatments.

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In the first growing season of the peach replant trial near Parlier, peach trees planted in preplant fumigated plots grew well (***above***, **shown are trees in plot strip treated by shank injection of 1,3-D:Pic 63:35), while the peach trees planted into nonfumigated control plots grew poorly due to the PRD complex,** ***below*****.**

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Soil fumigation treatments were applied in late October 2007. The treatments were assigned randomly to 20-foot-wide by 144-foot-long strip plots that ran across both halves of each main plot (i.e., the halves that had been cropped with sudangrass and those that were fallowed). Each of the fumigation treatment plots was centered over a single future tree row; the rows were to be spaced 20 feet apart.

The treatments included a nontreated control, a 10-foot-wide strip shank treatment with MB, an 8.3-foot-wide strip treatment with 1,3-D:Pic 63:35, spot shank treatments with 1,3-D:Pic 63:35 and Pic (each applied to 5-foot by 6-foot areas centered on tree planting sites), and a drip-applied emulsified 1,3-D:Pic 61:35 (Inline, Dow Agrosciences) (applied to points centered under tree sites, as described below).

The shank treatments in the peach trial were applied in the same manner as in the almond replant trials, using the MB rig for the MB treatment and the Telone rig for the other shank treatments. As in the almond trials, the GPS software and hardware systems were used to map tree sites and administer the shank spot treatments. The drip spot treatment was applied through a single 1-gallon-per-hour emitter per tree site; the emitter was connected to a tube that discharged the fumigant formulation 20 inches beneath the soil surface, as described previously (Wang et al. 2009).

In February 2008, all of the plots were planted with bareroot 'Burpeach 7' peach trees on 'Nemaguard' rootstock (Burchell Nursery, Oakdale, CA). Each replicate strip plot (i.e., the plots that received control and fumigation treatments) included 12 trees planted 12 feet apart in a row. Six of the 12 trees were in the half of the strip plot that had been planted to sudangrass, and six of the trees were in the half of the strip plot that had been fallowed. Efficacy of the treatments was assessed using methods described for the almond replant trials.

Peach replant trial results

Strong positive vegetative growth responses to all soil fumigation treatments were observed in the peach replant trial (e.g., photos, p 134) and led to profitable yield responses (table 3).

All preplant fumigation treatments greatly improved annual and cumulative yields, but the greatest yield increases were in the strip treatment with 1,3-D:Pic 63:35 (table 3). There were highly significant effects of preplant soil fumigation treatment on peach yields in each cropping year from 2009 through 2012 (data not shown) and for the cumulative yields across all 4 years (table 3, $P < 0.0001$).

The preplant rotation with sudangrass significantly improved annual peach yields in the second and fourth years of harvest ($P = 0.03$ and 0.02, respectively) and cumulative peach yields across all years ($P = 0.03$) (table 3). There was no significant interaction between soil fumigation and crop rotation in annual or cumulative yields ($P > 0.39$).

Fruit size was affected by fumigation treatments in the first and third years of harvest ($P < 0.0001$ and 0.003, respectively) and in the cumulative yield ($P = 0.05$), but not in the second or fourth harvests ($P = 0.08$ to 0.18). In the cumulative yield, mean fruit weight for both the MB and 1,3-D:Pic 63:35 strip treatments was 0.39 pound per fruit (95% confidence interval [CI] ± 0.01 pound), whereas fruit weight in all other preplant fumigation and control treatments was 0.37 pound per fruit (± 0.01 pound). Preplant rotation with sudangrass improved fruit size only in 2009 ($P = 0.007$) and did not affect fruit size in the cumulative yields ($P = 0.11$). There was no significant interaction between soil fumigation and crop rotation that affected fruit size in annual or cumulative yields ($P > 0.66$).

Because stone fruit prices can vary greatly depending on time of harvest, changing markets, industrywide crop abundance and many other factors, economic value of the preplant treatments in the peach replant experiment was evaluated here assuming a range of net fruit prices (i.e., gross fruit returns minus harvest, packing, sales and marketing costs) of 24, 12, 6 and 3 cents per pound. Due to the relatively small effect of preplant treatments on fruit size in cumulative yields, fruit size effects on fruit price were not considered. Because there was no significant interaction between preplant

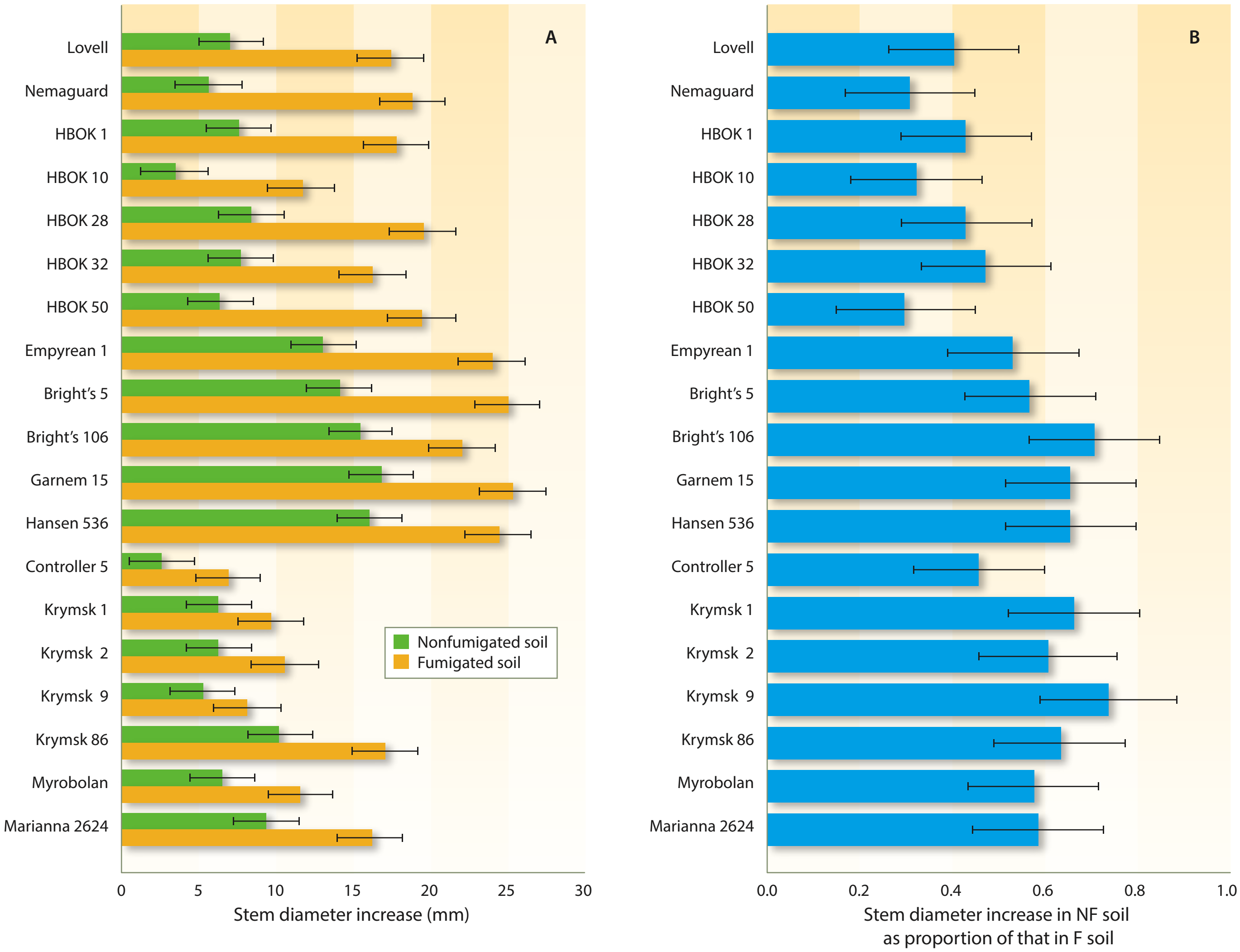

Fig. 2. Susceptibility of clonal almond and stone fruit rootstocks to Prunus replant disease complex. The rootstocks were transplanted into nonfumigated (NF) and fumigated (F) plots of soil. Stem diameter growth increases were measured from the time of planting in April 2011 to October 2011. (A) Actual stem diameter increases, and (B) stem diameter increases in NF plots expressed as proportions of the increases in F plots (NF/F stem diameter increase proportions). There were eight replicate three-tree plots per treatment combination. Vertical bars are 95% confidence intervals.

fumigation and crop rotation treatments, only the main treatment effects of the treatments were considered, unless stated otherwise.

Compared to the nonfumigated control, net returns were increased by all preplant fumigation treatments at all fruit return prices (24, 12, 6 and 3 cents per pound), except that at the lowest fruit price, MB fumigation reduced net returns (table 3). Increases in net revenues due to strip fumigation with 1,3-D:Pic 63:35 ranged from $13,465 to $754 per acre, depending on fruit pricing (table 3). The shank and drip spot treatments were less cost effective, generating returns that ranged from $8,958 to $480 per acre. Among the spot treatments, the shank-applied Pic resulted in the greatest net returns, followed by the spot treatments with 1,3-D:Pic via shank and drip (table 3). At a net fruit return price of 24 cents per pound, the cumulative net revenue increase due to spot treatment with Pic ($8,958) was similar to that associated with the MB treatment ($9,067, table 3). At lower fruit prices all spot treatments remained economical, whereas the MB treatment became uneconomical.

In terms of efficiencies per pound of fumigant applied, the spot treatments held an advantage over the strip treatments. For example, increases in pounds of fruit yield per pound of fumigant applied were as follows: MB in shanked strips, 236; 1,3-D:Pic 63:35 in shanked strips, 262; 1,3-D:Pic 63:35 in shanked spots, 487; 1,3-D:Pic 61:33 in dripped spots, 832; and Pic in shanked spots, 785. Spot treatments also were more efficient than strip treatments in terms of dollars of net revenue increase generated per pound of fumigant; the increase in efficiency was apparent across the range of net fruit prices we considered (24 to 3 cents per pound of fruit) (table 3).

Since the effect of sudangrass rotation was statistically the same across all fumigation treatments (including the nonfumigated control), we first evaluated the returns that it generated on average, across the fumigation treatments (table 3). In this case, the sudangrass rotation increased net returns at all fruit prices considered, but as fruit price returns dropped from 24 to 3 cents per pound, the net return generated from the rotation dropped from $1,911 per acre to $51 per acre (table 3). When the sudangrass rotation was evaluated only in the context of the nonfumigated treatment, using only fruit yield data from those plots, the net return from sudangrass rotation ranged from $5,826 at fruit return prices of 24 cents per pound to $541 at fruit return prices of 3 cents per pound (data not shown).

Our peach orchard replant trial results documented the value of a sudangrass rotation in managing PRD over a broad range of fruit prices, even when the rotation was restricted to a 2-month period. Further work is needed, and justified, to optimize the use of sudangrass rotation; for example, a several-month rotation may have done more good, but this was not tested. The economic efficacy of the spot treatments in the peach trial, although not as great as in the comparable strip treatment, confirms almond replant trial results that indicated spot treatments may have a valuable niche where site sensitivity or grower preferences require the use of little fumigant.

Evaluating rootstock resistance

While seedling rootstocks are very important and useful in California almond and stone fruit production, new propagation technologies are facilitating improvement and use of clonal rootstocks. Several new, diverse clonal rootstocks have become available for almond and stone fruit production, but there is relatively little detailed information on their resistance to the PRD complex, an important consideration for growers wanting to use them for

TABLE 3. Results summary, peach replant trial near Parlier

Treatment*						**Net fruit prices and net revenue gain†**				**Net fruit price and fumigant efficiency**	
Fumigant	**Treated area**	**Fumigant rate**		**Cost of treatment**	**Cumulative yield**	**$0.24/lb**	**$0.12/lb**	**$0.06/lb**	**$0.03/lb**	**$0.24/lb**	**$0.03/lb**
		lb/treated acre	*lb/orchard acre*	*$/acre*	*lb/acre*	*$/acre*				*net $ gain/lb fumigant*	
Control	None	0	0	0	45,850	0	0	0	0	—	—
MB	Row strip (42%)	400	200	2,272	93,097	9,067	3,398	563	(854)	45.34	(4.27)
1,3-D:Pic (63:35)	Row strip (50%)	550	231	1,062	106,378	13,465	6,201	2,570	754	58.29	3.27
1,3-D:Pic (63:35)	Tree spot (13%)	550	69	460	79,349	7,580	3,560	1,550	545	110.25	7.93
1,3-D:Pic (61:33)	Tree spot (5%)	550	28	207	68,727	5,283	2,538	1,166	480	192.12	17.45
Pic	Tree spot (13%)	400	50	457	85,080	8,958	4,251	1,897	720	179.16	14.41
Value of *P*:					**< 0.0001**						
95% confidence interval values:					**± 10,130**						
No rotation with sudangrass				0	75,320	0	0	0	0	—	—
Preplant rotation with sudangrass				214	84,174	1,911	849	317	51	—	—
Value of *P*:					**0.03**						
95% confidence interval values:					**± 6,576**						

* The 1,3-D:Pic 61:33 treatment was applied by drip, whereas the other fumigants were applied by shank. Because there was no significant interaction between preplant fumigation and crop rotation treatments, only main treatment effects are shown; fumigation effects are averaged across preplant crop rotation treatments and vice versa.

† Reflects change in net revenue relative to control treatment. Values in parentheses are net losses.

replanting of second- and later-generation orchards. Conceivably, rootstocks that resist or tolerate PRD could reduce or eliminate dependence on soil fumigation.

A field experiment was established at the SJVASC to evaluate resistance to PRD in 19 clonal almond, stone fruit and experimental rootstocks (table 4). The test site had been cleared from almonds on 'Nemaguard' rootstock in summer 2010. In October 2010, soil plots 350 feet long were shank-fumigated with 1,3-D:Pic 63:35 (540 lb/ac) or shanked without fumigant (control). There were eight replicate soil plots per soil treatment, arranged in randomized complete blocks. The soil treatment plots were subdivided into three-tree subplots that were randomly assigned to individual rootstocks.

The rootstocks were planted in April 2011 from pots. The trees were drip-irrigated and fertilized periodically with urea ammonium nitrate. Resistance was assessed in October 2011 for each rootstock, block by block, by dividing rootstock stem diameter increase (measured from the time of planting) in the nonfumigated (NF) plot by the stem diameter increase in the fumigated (F) plot (i.e., the NF/F stem diameter increase proportion). A repeat experiment was established in 2012 in an adjacent block using similar methods, except that the rootstocks were planted in May instead of April, and there were five replicate plots per soil treatment.

TABLE 4. Rootstocks included in 2011 and 2012 evaluations of resistance to Prunus replant disease complex

Rootstock	Type*	Genetic background†	Compatible crops*
'HBOK1'	Pe	*HB × OK peach*	Pe
'HBOK 10' ('Controller 8')	Pe	*HB × OK peach*	Pe
'HBOK 28'	Pe	*HB × OK peach*	Pe
'HBOK 32' ('Controller 7')	Pe	*HB × OK peach*	Pe
'HBOK 50' ('Contoller 9.5')	Pe	*HB × OK peach*	Pe
'Lovell'	Pe	*P. persica*	Al, Pe, Ap, Pl, Pr
'Nemaguard'	Pe	*P. persica × P. davidiana*	Al, Pe, Ap, Pl, Pr
'Empyrean 1' ('Barrier 1')	Pe	*P. persica × P. davidiana*	Pe, Al
'Bright's Hybrid 5'	Pe × Al	*P. persica × P. dulcis*	Al
'Bright's Hybrid 106'	Pe × Al	*P. persica × P. dulcis*	Al
'GxN 15' ('Garnem')	Pe × Al	*P. dulcis × P. persica ('Nemared')*	Al
'Hansen 536'	Pe × Al	*[Okin. × (P. davidiana × 'Pe PI 6582')] × alm.*	Al, Ap, Pe
'Controller 5' (= 'K146-43')	Pl hybrid	*P. salicina × P. persica*	Pe
'Krymsk 1' ('VVA 1')	Pl hybrid	*P. tomentosa × P. cerasifera*	Pl, some Pe
'Krymsk 2'	Pl hybrid	*P. incana × P. tomentosa*	Unknown
'Krymsk 9'	Pl hybrid	*P. armeniaca × P. ceracifera*	Unknown
'Krymsk 86' ('Kuban 86')	Pl hybrid	*P. persica × P. cerasifera*	Al, Pe, Pl
'Myrobalan'	Pl hybrid	*P. ceracifera*	Ap, Pl, Pr
'Marianna 2624'	Pl hybrid	*P. munsoniana × P. cerasifera*	(Al), Ap, Pl, Pr

* Al = almond, Ap = apricot, Pe = peach and nectarine, Pl = plum, Pr = prune. Parentheses indicate that not all varieties of the crop are compatible with the rootstock. Growers should check with UC farm advisors and nursery representatives for rootstock details and updates.

† *HB × OK* = 'Harrow Blood' × 'Okinawa'.

Results of rootstock evaluations

In the 2011 experiment, all rootstocks grew less in nonfumigated soil than in fumigated soil, but the severity of the growth reductions varied by rootstock (fig. 2A and 2B). The rootstock–soil treatment interaction was highly significant ($P < 0.0001$). Most rootstocks with only peach parentage were relatively susceptible to the PRD complex in nonfumigated soil. For example, calculated NF/F stem diameter increase proportions for 'Harrow Blood' × 'Okinawa' clones (HBOK 1, 10, 28, 32 and 50), 'Lovell' and 'Nemaguard' peach ranged from 0.31 to 0.50 (fig. 2B). 'Empyrean 1,' also a peach, was the least susceptible of rootstocks with this parentage, with an NF/F stem diameter increase of 0.53. The hybrid rootstocks that combined peach and almond parentage were less susceptible than most peaches; for example, 'Bright's Hybrid' clones 5 and 106, 'Garnem,' and 'Hansen 536' had NF/F stem diameter increase proportions of 0.57 to 0.71. Rootstocks with plum parentage, including 'Controller 5,' 'Krymsk' clones 1, 2, 9 and 86, 'Marianna 2624,' and 'Myrobalan,' varied in susceptibility to the complex in nonfumigated soil (NF/F stem diameter increase proportions of 0.46 to 0.74).

Although some of the most vigorous rootstocks (e.g., the peach × almond hybrids and 'Empyrean 1') were also the least impacted by PRD, overall there was not a significant correlation between the magnitude of stem diameter increase values in fumigated plots (one measure of the inherent vigor of the rootstocks) and NF/F stem diameter increase proportions (our measure of PRD resistance) ($P = 0.98$). Also, genetic dissimilarity of the tested rootstocks with 'Nemaguard,' the rootstock used for the previous stone fruit orchard, was not a consistent predictor of the impact of PRD on rootstock growth. For example, 'Empyrean 1' (a peach, as is 'Nemaguard') was no more impacted by PRD than the rootstocks with plum parentage.

Evaluations of the rootstocks in the repeat (2012) trial are not complete but tend to confirm the results in the first (2011) trial. Overall, PRD severity in the repeat trial has been less than in the first trial, but NF/F stem diameter increase rankings were similar between the experiments. For example, in the repeat trial in September 2012, the rootstocks with peach parentage exhibited NF/F stem diameter increase proportions of 0.53 to 0.60, except for 'Empyrean 1,' which had an NF/F stem diameter increase proportion of 0.83. The peach × almond hybrids were less suppressed than most peach rootstocks by the absence of fumigation (NF/F stem diameter increase proportions of 0.72 to 0.90), and the rootstocks with plum parentage were variable (NF/F stem diameter increase proportions of 0.45 to 0.83).

As in the 2011 experiment, the rootstock–soil treatment interaction was significant in the 2012 experiment ($P = 0.0004$). As in the first trial, in the repeat trial there has not been a significant overall correlation between the magnitude of stem diameter increase values in fumigated plots (inherent vigor) and NF/F stem diameter increase proportions (PRD resistance) ($P = 0.30$), although some of the most vigorous rootstocks were among those most resistant to PRD.

The results of the rootstock trials suggest that judicious development and selection of rootstocks will contribute strongly to PRD management and reduce dependence on soil fumigation. Nevertheless, growers should carefully consider the horticultural suitability of prospective rootstocks to all of the demands of a site before choosing a rootstock. For example, due to their other susceptibilities, some peach × almond hybrid rootstocks are known as poor choices for replanting at sites subject to the ring nematode–bacterial canker complex or subject to poor drainage or problems with crown and root rot due to *Phytophthora*. UC farm advisors and fruit and nut nursery workers are valuable resources in rootstock selection.

Meeting the replant challenge

This report, although not exhaustive in scope, highlights the potential for integrated management of a key replant problem, PRD, with minimal dependence on soil fumigation. Optimized soil fumigation, crop rotation and careful rootstock selection all are valuable components for integrated management of PRD. Our almond and peach replant trials demonstrated that, when trees are at risk for PRD but not nematode damage, strip treatments with Pic or combinations of Pic and 1,3-D are likely to be more economical than strip treatments with 1,3-D alone, which is the current standard, or full-coverage treatments with 1,3-D:Pic 63:35. However, depending on the time of treatment, Pic application may require use of a tarp covering.

The trials also demonstrated the practical potential of GPS-controlled tree spot shank fumigation treatments, which made efficient use of limited amounts of fumigant to control PRD. Spot fumigation treatments may have great value for orchard replant sites where fumigant rates must be kept very low due to site regulatory restrictions. Microplot data suggested, and an orchard replant trial confirmed, that short-term rotations with 'Piper' sudangrass before orchard replanting can reduce subsequent PRD severity and thereby improve crop returns.

The sudangrass rotation improved net crop returns with or without preplant fumigation and across a wide range of profitable fruit prices, suggesting that the rotation is a prudent practice when it can be fit into stone fruit replanting schedules.

Finally, in a typical stone fruit replanting situation following removal of trees on 'Nemaguard' rootstock, we identified diverse replacement rootstocks (i.e., certain peach × almond, peach, and plum hybrid selections) with relatively low sensitivity to the resident PRD complex. In some situations, the rootstocks with reduced PRD sensitivity may markedly reduce the need for soil fumigation. Nevertheless, all site and scion cultivar factors should be considered carefully in choosing an orchard's rootstock(s). Continued selection and breeding of rootstocks will be essential in reducing dependence on soil fumigation.

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RESEARCH ARTICLE

TIF film, substrates and nonfumigant soil disinfestation maintain fruit yields

by Steven A. Fennimore, Raquel Serohijos, Jayesh B. Samtani, Husein A. Ajwa, Krishna V. Subbarao, Frank N. Martin, Oleg Daugovish, Dan Legard, Greg T. Browne, Joji Muramoto, Carol Shennan *and* Karen Klonsky

A 5-year project to facilitate the adoption of strawberry production systems that do not use methyl bromide initially focused on fumigant alternatives and resulted in increased use of barrier films that reduce fumigant emissions. The focus shifted in year 3 to evaluating and demonstrating nonfumigant alternatives: soilless production, biofumigation, anaerobic soil disinfestation (ASD) and disinfestation with steam. In the 2010-2011 strawberry production season, fruit yields on substrates were comparable to fruit yields using conventional methods. Anaerobic soil disinfestation and steam disinfestation also resulted in fruit yields that were comparable to those produced using conventionally fumigated soils. Additional work is in progress to evaluate their efficacy in larger-scale production systems in different strawberry production districts in California.

Steve Fennimore

In a multi-year study of strawberry production systems, the use of nonfumigant alternatives such as heat treatment with steam resulted in fruit yields comparable to those produced using conventional fumigants. *Above*, steam application to strawberry beds prior to planting near Camarillo, CA.

California's coastal districts, where 86% of the nation's strawberries are produced on 38,600 acres, are the most productive strawberry-growing areas in the United States (CSC 2011; NASS 2011). To achieve this level of productivity, California strawberry producers need effective soil disinfestation, productive varieties and cultural practices such as polyethylene mulch and drip irrigation (Strand 2008). Strawberries are very sensitive to soil pathogens, and growers with these highly productive systems have become dependent on preplant fumigation. Traditionally, they used methyl bromide plus chloropicrin (MB + Pic) as the basis for soil pest control. Fumigation with these chemicals controls soilborne pathogens such as *Verticillium dahliae*, *Phytophthora* species, *Pythium* species, *Rhizoctonia* species, *Fusarium oxysporum* and *Cylindrocarpon* species, as well as nematodes, soilborne insects and weed seeds in the soil seedbank (Wilhelm and Paulus 1980). In 1992 methyl bromide was classified as a Class I stratospheric ozone-depleting chemical. Since 2005, under the Montreal Protocol, the use of methyl bromide for fumigation in the United States has been permitted only through critical use exemption (Anbar et al. 1996; USDS 2008). The methyl bromide phase-out and other regulatory limitations make research on alternative pest control measures essential.

Currently, some California strawberry fields can still be treated with methyl bromide under the critical use exemption, which is subject to annual review by the parties of the Montreal Protocol.

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However, methyl bromide costs have been increasing, and its use in strawberry production has been decreasing (CADPR 2011). Alternative fumigants being used are 1,3-dichloropropene (1,3-D) and chloropicrin (Pic). In traditional fumigation of California strawberry fields, beginning in the 1960s and continuing until recently, growers applied methyl bromide plus chloropicrin to the total field area. This process was called flat fumigation; the entire field was covered with polyethylene film to hold the fumigant at the concentration needed to kill soil pests (Wilhelm and Paulus 1980). In the last decade, a sizable portion of the strawberry acreage has been treated with fumigants applied to the strawberry bed by drip fumigation (USDS 2008).

The major alternatives to methyl bromide such as 1,3-D and chloropicrin are heavily regulated due to the potential for adverse health effects to workers and nearby populations, which has complicated the transition away from methyl bromide. In California, 1,3-D use per 36-square-mile township is limited to 90,250 pounds, called a township cap, which severely limits its availability in numerous key strawberry production areas (Carpenter et al. 2001). A 2008 strawberry critical use nomination indicates that "township caps currently limit the use of 1,3-D on 40% to 62% of total strawberry land" (USDS 2008). Chloropicrin is capped at a use rate of 125 pounds near sensitive sites such as day-care centers, and in some counties it cannot be used within one-quarter mile of such sites. Consequently, considerable methyl bromide use continues in California because restrictions on alternative fumigants leave few other options for much of the strawberry acreage.

Fruit yields in the steam treatments and the anaerobic soil disinfestation treatments were comparable to those in the Pic-Clor 60 application.

Currently about 68% of the California strawberry acreage is fumigated with alternatives to methyl bromide, primarily drip-applied mixtures of 1,3-D plus chloropicrin (InLine, Pic-Clor 60) or chloropicrin emulsified formulation (Pic-EC) (CADPR 2011). Drip fumigation with these products costs less than broadcast shank fumigation with methyl bromide plus chloropicrin. However, there are limits to how much of the remaining 32% of the strawberry acreage can be converted from methyl bromide to alternative fumigants. Fumigants are difficult to apply evenly by chemigation on hilly fields where beds are not formed along contour lines. Also, all fumigant applications are restricted or not allowed within one-quarter mile of a sensitive site, such as a hospital, jail, school or day-care facility (VCAC 2011).

The public has shown less and less tolerance toward agricultural fumigant use, and regulators have been forced to look for solutions that meet the demands of the public yet allow growers to farm. One strategy to reduce the potential for fumigant exposure from off-site movement of volatile fumigants is the use of barrier films, which trap the fumigant in the field.

Fumigants and barrier films

A gas-impermeable film can minimize fumigant emissions, increase fumigant retention over time and reduce the amount of fumigant needed for effective pest control (Wang et al. 1999). Compared to standard 1-mil polyethylene films or uncovered soil, virtually impermeable film (VIF) can greatly reduce fumigant emissions and enhance retention of the fumigant in the upper soil layer (Chellemi and Mirusso 2002). VIF differs from traditional single-layer high-density polyethylene tarp because VIF has at least one gas-impermeable layer (such as nylon or polyaminides) between polyethylene layers (Wang et al. 1997).

Higher concentrations of 1,3-D and chloropicrin were measured under VIF than under standard film 1 to 4 days after drip fumigation (Desaeger and Csinos 2005). Improved retention of fumigants under VIF provides more opportunity for fumigants to degrade in the soil instead of being released into the atmosphere (Wang and Yates 1998). Researchers have found that VIF can reduce the amount of 1,3-D plus chloropicrin needed for effective soil disinfestation by 50% (Medina et al. 2006). Santos et al. (2005) found that reducing methyl bromide plus chloropicrin rates by 50% under multilayer VIF controlled nutsedge similarly to full-rate (350 pounds per acre) methyl bromide plus chloropicrin applied under standard single-layer films.

A relatively new barrier film, totally impermeable film, or TIF, has been shown to retain fumigant better than VIF (Fennimore and Ajwa 2011). TIF is a five-layer film with two ethylene vinyl alcohol layers embedded in three layers of standard polyethylene film (Fennimore and Ajwa 2011). Fumigant-use regulations in Ventura County allow the application of twice as many pounds of chloropicrin per 48-hour period where TIF is used than under standard 1.25-mil film (VCAC 2011). Fennimore and Ajwa (2011) found that TIF was effective at trapping fumigants, improving weed control and boosting strawberry yields. By trapping the fumigant under TIF, higher fumigant concentrations kill a greater percentage of the weed seeds and soil pathogens, thus improving soil pest control and yields.

Field evaluation of VIF

We conducted field trials near Salinas at the USDA Agricultural Research Service (USDA-ARS) Spence Farm and near Watsonville at the Monterey Bay Academy research facilities during the 2007–2008 season. Fumigants were applied at Monterey Bay Academy on Oct. 11, 2007, and at Spence Farm on Oct. 24, 2007. The fumigants tested were 1,3-D plus chloropicrin (InLine, 200 pounds per acre; and Pic-Clor 60, 150 pounds per acre), methyl bromide plus chloropicrin (50/50 drip formulation, 200 pounds per acre), and chloropicrin (150 pounds per acre). The efficacy of each treatment was compared to methyl bromide plus chloropicrin (67/33 formulation, 300 pounds per acre) applied by drip fumigation. Each fumigant was applied under two types of film: 1.25-mil VIF (Bruno Rimini, London, UK) and 1.25-mil standard polyethylene tarp.

Approximately 4 weeks after fumigation, the bareroot strawberry variety Albion was transplanted. Beds were 54 inches wide, center to center, and two lengths: 30 feet long at Monterey Bay Academy and 100 feet long at Spence Farm. Due to differences in the land available at the two sites, final harvest plot size was 20 feet long at Monterey Bay Academy and 35 feet long at Spence Farm. Treatments were arranged in a split plot

Mass transfer coefficient

The mass transfer coefficient is a measurement of the ability of an agricultural film to block fumigant flow through the film. Every fumigant is different, but using chloropicrin as an example, a standard film would have a mass transfer coefficient in the range of 0.7 to 2.3 cm h^{-1}. A VIF or TIF film would have a mass transfer coefficient in a range of 0.0016 to 0.000 cm h^{-1} (Qian et al. 2011).

design, with film as the main plot and fumigant as the subplot, and replicated four times at each site. Conventional tillage practices were followed for strawberry production in each area.

Fruit yield was evaluated once or twice weekly and sorted into marketable fruit and culls. Fruit yield data were analyzed using SAS version 9.3 (SAS Institute, Cary, NC). Data were analyzed for the effects of film on season-long fruit yields, and mean separation was performed using Fisher's protected LSD. The emissions data were analyzed in EXCEL (Microsoft, Redmond, WA) using a student's *t*-test.

The permeability of the two films to 1,3-D, chloropicrin, iodomethane and methyl bromide vapors was monitored using procedures described by Papiernik et al. (2001). Film samples were taken before and after installation, and the average measurement of the flow rate of fumigant through the film (the mass transfer coefficient, MTC, centimeters per hour [cm h^{-1}]) determined. For each fumigant, the before and after coefficients varied less than 10%, which means that installation did not damage the impermeable layer (Ajwa, unpublished). Across all fumigants, the coefficients varied between 2.7 and 16.9 cm h^{-1} for the 1.25-mil standard polyethylene tarp but less than 0.01 cm h^{-1} for VIF, a significant difference for all fumigants (data not shown). The average mass transfer coefficient of VIF was less than 1% of the average coefficient of the standard tarp. The effect of film on fruit yields was not significant (data not shown).

The work with VIF suggested that it does indeed trap fumigants but does not necessarily improve fruit yields. Recent work with TIF indicated different results. Compared with 1-mil single-layer standard films, TIF resulted in higher fumigant concentrations under the film, higher strawberry fruit yields and better weed control (Fennimore and Ajwa 2011). The work with VIF reported above used a three-layer film with only one impermeable layer; it was a first-generation barrier film. The TIF film, a second-generation film, tested in subsequent studies was a five-layer film with two impermeable layers. The extra impermeable layer in the TIF film may have resulted in greater tolerance to stretching, and thus fewer breaks in the film and better pest control.

Soilless production, no fumigants

Presently registered alternative fumigants such as 1,3-D, chloropicrin, and 1,3-D plus chloropicrin combinations have been tested and are effective at controlling soil pests in strawberry (Fennimore et al. 2003). However, as described above, regulations limit the use of these products (Carpenter et al. 2001; VCAC 2011). Given the challenges to fumigant use in California, the options for growing strawberries without fumigants must be thoroughly explored. One such option is soilless production.

Strawberry crops can be produced on clean soilless substrates. This production method is commonly used in Europe and does not require methyl bromide. In 2003, 2,815 acres (1,140 hectares) of strawberries were produced using soilless culture in Belgium, the Netherlands, U.K., France and Italy (Lieten, Longuesserre, Pivot 2004). Soilless production of strawberry crops is also being evaluated in Florida (Hochmuth and Hochmuth 2003). Soilless production traditionally used coir, peat or other soilless substrates enclosed in bags under plastic covers, that is, high tunnels (Lieten, Longuesserre, Baruzzi et al. 2004). However, concerns about bag disposal have led to more-sustainable systems, including the raised bed trough system.

Raised bed trough system (RABETS). The bed is made like a typical strawberry bed, with the exception that troughs are cut into it and lined with fabric designed to permit moisture penetration but not allow root penetration. The troughs are filled with clean planting material, steam-treated soil or soilless media; drip tape is installed, and the beds are tarped in the same way as conventional strawberry beds.

The primary justification for using this system is that strawberry crops can


Dan Legard

In a raised bed trough system, troughs are cut into each bed and lined with fabric that permits moisture penetration but not root penetration. The troughs are then filled with clean substrate materials. Here at Mar Vista Berry, Santa Maria, yields surpassed those from standard fumigation plots.


Dan Legard

Once the troughs are filled with substrate (left), the beds are covered with film. The beds can be left in place for several crop cycles. No fumigant is used.


Dan Legard

Strawberries planted in substrate at Mar Vista Berry, Santa Maria. One of the main concerns in soilless strawberry production is the maintenance of a favorable pH, EC and nutrient supply to the growing plants.

be produced without fumigation (Lieten, Longuesserre, Pivot 2004); although if the soilless media could be disinfested and recycled, instead of discarded at the end of each cropping cycle, it would, in theory, represent a more sustainable system. Additional advantages include the ease of attracting harvest labor due to the high fruit yield per linear foot of bed row, and the ability to leave the beds in place for several crop cycles. One of the disadvantages is that coir and peat substrates are expensive and of limited quantity. However, composted wood fiber and composted pine bark have shown good results as substrates and are available locally and are generally less expensive (Lieten, Longuesserre, Baruzzi et al. 2004). Logistical issues such as substrate costs and the delivery and installation of large amounts of substrate material have yet to be addressed in U.S. systems.

RABETS field trials. Field trials of a raised bed trough system were carried out at Monterey Bay Academy, near Watsonville, and at Mar Vista Berry, near Santa Maria, from fall 2010 to summer 2011. The studies were set up in randomized complete block designs consisting of five treatments replicated four times. The treatments were 100% coir (coconut hull fiber), a 70:30 peat and perlite mixture, an amended soil mix of 50% steamed soil plus 25% rice hulls and 25% coir, a standard fumigation treatment (MB + Pic), and an untreated, nonfumigated control. Harvesting was done from April 28 to Sept. 15, 2011 (Monterey Bay Academy), and April 13 to Oct. 4, 2011 (Mar Vista Berry, Santa Maria). The fruit was sorted into marketable berries and cull (nonmarketable). Periodic collection of substrate samples was done to monitor pH, electrical conductivity (EC), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N) and available phosphorus (P). All data were subjected to analysis of variance (JMP version 8; SAS Institute, Cary, NC), and Fisher's protected LSD at 0.05 was used to compare means.

Table 1 shows the plant diameters and yields of strawberry crops grown in the plots at Monterey Bay Academy and Mar Vista Berry. There were highly significant differences in plant diameter and yield (marketable, cull and total) of strawberries grown at Monterey Bay Academy. The widest plant diameter (10.46 inches) was from plants grown in the peat and perlite system. The three substrate treatments (coir, peat and perlite, and steamed soil with amendments) did not significantly differ in marketable yield. The untreated, nonfumigated control treatment had the smallest plant diameter and lowest marketable yield. The marketable yield of the coir, peat and perlite, and steamed soil with amendments treatments was 27%, 29% and 13% higher, respectively, than the yield from the standard fumigated treatment.

At Mar Vista Berry (Santa Maria), the widest plant diameters were in the steamed soil with amendments plots (10.25 inches) and the peat and perlite substrate plots (9.86 inches). However, the substrate treatments did not affect the marketable fruit yield. Significant differences were noted only on the cull yield. The highest cull yield was observed in the steamed soil with amendments; this was the case at both Mar Vista Berry and Monterey Bay Academy, and it could be attributed to the very low pH and high EC (electrical conductivity) of this substrate.

One of the main concerns in soilless strawberry production is the maintenance of a favorable pH, EC and nutrient supply to the growing plants. For most of the sampling periods at the experimental sites, different substrate and soil treatments had significantly different levels of pH, EC, nitrate nitrogen, ammonium nitrogen and available phosphorus.

At both sites, the pH of the coir and the peat and perlite treatments was lower in the early sampling periods but increased with time, reaching the targeted value of 5.7 after 3 to 4 months (data not shown); this slow rise in pH to the target value was attributed to the high nutrient adsorptive capacity of the soilless substrates. The pH of the amended soil treatments at both sites was generally low at all sampling periods, and the target value was not reached during the production cycle.

With the exception of the initial sampling period, the EC of the substrate treatments at Monterey Bay Academy was generally low (< 2.0 mS/cm). In contrast, the EC in the Mar Vista Berry beds was consistently high, which could be due to the higher amount of salts in the irrigation water. The EC of the steamed soil with amendments treatment at Mar Vista Berry was also consistently high throughout the growing season.

The soilless substrates are low in nutrients; thus, fertilization is one of the key issues in these systems. Surprisingly, the initial nitrate nitrogen of the coir and the peat and perlite mixture was higher at both sites, and the target value of 100 ppm was maintained in the beds through the season except for the latter stages of plant growth (table 2). The standard fumigated

TABLE 1. Strawberry plant diameter and yield at Monterey Bay Academy and Mar Vista Berry, as affected by different substrates, 2010-2011

Treatment	Plant diameter	Yield			Percentage of relative yield
		Marketable	Cull	Total	
	inches	·········· *lb/plant* ··········			
Monterey Bay Academy					
Coir	9.63b*	3.26a	1.52bc	4.77a	127a
Peat and perlite	10.46a	3.26a	1.65ab	4.91a	129a
Steamed soil with amendments	9.18bc	2.89ab	1.72a	4.61a	113ab
Standard fumigation	8.56c	2.57b	1.38c	3.95b	100b
Untreated control	7.40d	0.90c	0.72d	1.62c	35.3c
Probability > *F*	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Mar Vista Berry					
Coir	9.61bc	1.93	1.21bc	3.14	100
Peat and perlite	9.86ab	1.91	1.26ab	3.18	99
Steamed soil with amendments	10.25a	1.83	1.33a	3.16	95
Standard fumigation	9.24c	1.94	1.14cd	3.08	100
Untreated control	8.66d	1.91	1.10d	3.01	99
Probability > *F*	< 0.0001	0.6710	0.0006	0.2467	0.7505

* Mean values within a column followed by the same letter(s) or without letters were not significantly different according to Fisher's LSD test ($P > 0.05$).

beds had generally low nitrate nitrogen. At all sampling periods, the ammonium nitrate was lower than the RABETS target value of 14 ppm (data not shown).

The RABETS target of 30 ppm available phosphorus was maintained in all of the media treatments at both sites (data not shown).

TABLE 2. Nitrate nitrogen values* in Monterey Bay Academy and Mar Vista Berry substrate trials, 2010-2011

	Monterey Bay Academy				Mar Vista Berry			
Treatment	**Nov 18 2010**	**Mar 11 2011**	**June 16 2011**	**Sep 9 2011**	**Nov 12 2010**	**Mar 8 2011**	**Jun 14 2011**	**Sep 8 2011**
Coir	145.9a†	135.0a	39.5b	25.9b	160.4b	112.0b	141.8a	29.3
Peat and perlite	92.2b	152.5a	68.7a	37.8a	210.9a	177.4a	155.1a	33.4
Steamed soil with amendments	32.4c	70.5b	12.6c	32.1ab	94.3c	49.6c	145.0a	29.8
Standard fumigation	15.0d	4.7c	1.2c	27.7b	38.5d	7.1d	21.2b	38.5
Untreated control	15.0d	5.0c	0.9c	23.0b	39.6d	4.4d	7.3b	37.4
Probability > *F*	< 0.0001	< 0.0001	< 0.0001	0.0328	< 0.0001	< 0.0001	< 0.0001	0.4975

* Nitrate nitrogen target value is 100 ppm.

† Mean values within a column followed by the same letter(s) or without letters were not significantly different according to Fisher's LSD test ($P > 0.05$).

Anaerobic soil disinfestation

Anaerobic soil disinfestation (ASD), a nonchemical alternative to methyl bromide, was developed in Japan (Momma 2008) and the Netherlands (Blok et al. 2000) to control soilborne pathogens and nematodes in strawberries and vegetables. Anaerobic soil disinfestation integrates the principles of solarization and flooding in situations where neither method alone is effective or feasible. Anaerobic soil conditions are created by incorporating readily available carbon sources into topsoil, covering the soil with plastic tarp and irrigating to field capacity. The tarp is left in place to maintain soil moisture above field capacity and to sustain anaerobic conditions. Anaerobic decomposers respire using the added carbon, which results in a buildup of anaerobic byproducts that are toxic to pathogens (Katase et al. 2009). These byproducts degrade rapidly once the tarp is removed or holes are punched through the tarp for planting.

Studies were conducted during 2008 to 2011 in an attempt to optimize anaerobic soil disinfestation for California strawberry and Florida vegetable production systems. Overall, it was very effective in suppressing *Verticillium dahliae* in soils, and it resulted in 85% to 100% of the marketable fruit yield observed with fumigated controls in coastal California strawberries when 9 tons per acre of rice bran was preplant incorporated and 3 to 4 acre-inches of irrigation was applied in sandy loam to clay loam soils (Shennan et al. 2011).

In the semitropical climate of Florida, when composted broiler litter (to improve the water-holding capacity of Florida's sandy soil) and heavy blackstrap molasses were incorporated as substrate, anaerobic soil disinfestation treatments provided good control of nutsedge and excellent control of grasses, broadleaf weeds, *Phytophthora capsici* and *Fusarium oxysporum* f. sp. *lycopersici* (Rosskopf et al. 2010). In the cooler conditions of the Central Coast, however, anaerobic soil disinfestation may not provide effective control of many weed species (unpublished data).

To ensure consistency of pest suppression across varying locations, the effects of soil temperatures and treatment length and the mechanisms of pest suppression by anaerobic soil disinfestation are being further elucidated. Its integration with other nonfumigant approaches may also have promise. For example, a combination of anaerobic soil disinfestation and mustard seed meal application is currently being tested (Shennan and Muramoto, unpublished).

Soil disinfestation with steam

Heat treatment with steam can be used for soil sterilization or pasteurization (Samtani et al. 2012). Studies have shown that most plant pathogens, insects and weeds will die when moist soils are heated to temperatures higher than 150°F (65°C) for 30 minutes (Baker and Roistacher 1957). The duration and amount of steam needed to raise the soil temperature to 150°F depend on various soil factors, including texture, type and moisture content. Minuto et al. (2003) found that soil could be heated most rapidly at a moisture content between 8.5% and 12% in a sandy loam and between 6% and 7% in a sandy soil. Steam applied to field soil that raised the temperature to 158°F for 20 minutes resulted in weed control comparable to methyl bromide (Samtani et al. 2012).

In addition to pest control, an advantage of steaming is that it lacks the negative environmental and worker health issues associated with chemical fumigants. Some have reported that steaming has little or no lasting negative impact on soil quality or soil microbial communities (Jäderlund et al. 1998; Zackrisson et al. 1997) as opposed to the known potential impact of methyl bromide fumigation on both soil quality and microbes (Ibekwe et al. 2001; Yamamoto et al. 2008). Other studies have reported a more significant change in soil microbial activity due to steam sterilization (Tanaka et al. 2003; Yamamoto et al. 2008). Differences among steam studies may be related to duration of steam application and soil temperatures attained during steam treatments as well as the soil organic matter content.

Steam has also been shown to increase crop growth and yields (Moyls et al. 1994). Previous work found that strawberry fruit yields from steam-treated soils were similar to those from soils fumigated with methyl bromide plus chloropicrin (Samtani et al. 2012).

Biofumigants

Natural products such as mustard seed are being evaluated as biofumigants. Recent studies found that mustard seed meal amendment can suppress root infection by *Rhizoctonia solani* (Mazzola 2006). We have been testing mustard seed meal (BioFence, Green Envy) in strawberry beds at rates of 500 to 4,000 pounds per acre incorporated into the soil. Mustard meal alone does not consistently produce high fruit yields or control weeds (Samtani et al. 2011). One possible method to enhance solarization is to use combinations of mustard meal, chloropicrin, and metam sodium treatments (Chellemi and Mirusso 2006). By heating the soil with solarization or steam, the pest control activity of metam sodium, chloropicrin or mustard meal may be higher than at ambient soil temperatures.

ASD, mustard seed meal and steam

A field study was conducted at Monterey Bay Academy from October 2010 to September 2011 to evaluate anaerobic soil disinfestation and steam with and without mustard seed meal application prior to planting strawberry beds. Treatments included a control; Pic-Clor 60 at 300 pounds per acre as a standard; mustard seed meal at 3,000 pounds per acre; anaerobic soil disinfestation with rice bran at 9 tons per acre; anaerobic soil disinfestation with rice bran at 7.5 tons per acre and mustard seed meal at 3,000 pounds per acre; steam; and steam plus mustard seed meal at 3,000 pounds per acre.

Trial design. The trial was arranged in a randomized complete block design with four replicates. Anaerobic soil disinfestation was initiated Oct. 7 to create a saturated condition. The plots were maintained above field capacity with intermittently applied irrigation water (total of 2.5 acre-inches) from Oct. 8 to Nov. 3, 2010. Steam was applied via spike injection from a stationary steam generator for a sufficient time to raise the soil temperature to 158°F for 20 minutes on Oct. 13 and 14, 2010. Weed densities were measured in 25-square-foot sample areas covered with clear tarp, on Dec. 15, 2010, Jan. 21, Feb. 23 and April 6, 2011. Strawberry fruit was harvested weekly from April 28 to Sept. 15, 2011. Fruit was sorted as marketable and cull (nonmarketable) at each harvest date. Data were subjected to analysis of variance and means were separated using Fisher's protected LSD.

Trial results. Overall, the steam treatment and the steam treatment with mustard seed meal were as effective as Pic-Clor 60 in providing weed control (table 3). Anaerobic soil disinfestation plus rice bran suppressed weed densities, but it was less effective than Pic-Clor 60. No


Joji Muramoto

In preparation for anaerobic soil disinfestation, rice bran is applied to the planting field. This nonchemical alternative to methyl bromide was developed in Japan and the Netherlands.


Joji Muramoto


Joji Muramoto

Rice bran can be incorporated before or after strawberry beds are formed. Shown are broadcasting, *left*, or bed top, *right*, application methods.


Joji Muramoto

Listing of beds after incorporation of rice bran at Salinas, CA. Drip irrigation tape and then tarp will be installed so that the beds are ready to irrigate to create anaerobic conditions.


Joji Muramoto

Water is applied to the covered strawberry beds to create anaerobic conditions prior to planting. Anaerobic soil disinfestation was very effective in suppressing *Verticillium dahliae* in soils, and it resulted in 85% to 100% of the marketable fruit yield observed with fumigated controls in coastal California strawberries.


Steve Fennimore

Steam is applied to strawberry beds with a stationary steamer at a commercial field near Watsonville. Raising the soil temperature to 158°F for 20 minutes produces soil pest control comparable to fumigants.

strawberry plant injury was observed in any of the treatments (data not shown).

Marketable yields data collected from April 28 to Sept. 15, 2011, indicate that strawberry fruit yields in the steam treatments and the anaerobic soil disinfestation treatments were comparable to those in the Pic-Clor 60 application (table 3). These data, along with data from our prior studies, show that steam is as effective as chemical fumigation; and that anaerobic soil disinfestation also produces yields equivalent to Pic-Clor 60 but may need to be combined with herbicide use in severely weed-infested sites.

The costs of the anaerobic soil disinfestation treatments with rice bran, and with rice bran plus mustard seed meal, were $1,632 and $3,093 per acre, respectively, including material, spreading, incorporation and irrigation (fig. 1). The cost of steam was $10,440 per acre, compared to $1900 per acre for Pic-Clor 60. Therefore, although the yields and gross revenues were comparable across treatments, the net returns after treatment and harvest costs were highest for the Pic-Clor treatment, followed by the anaerobic soil disinfestation with rice bran. The lowest net revenue was for the steam plus mustard seed meal treatments due to the high cost of the steam treatment.

TABLE 3. Treatment effect on weed density and strawberry yield April 28 to Sept. 15, 2011

Treatment	Weed density	Fruit yield
	no. per 25 square feet	*lb/plant*
Pic-Clor 60	93.5c*	2.53a
Mustard seed meal	635.7ab	1.60b
Steam	118.7c	2.44a
Steam + mustard seed meal	93.5c	2.53a
ASD + rice bran	495.7b	2.39a
ASD + rice bran + mustard seed meal	568.7ab	2.53a
Untreated control	701.6a	1.60b

* Mean values within a column followed by the same letter(s) or without letters were not significantly different according to Fisher's LSD test ($P > 0.05$).

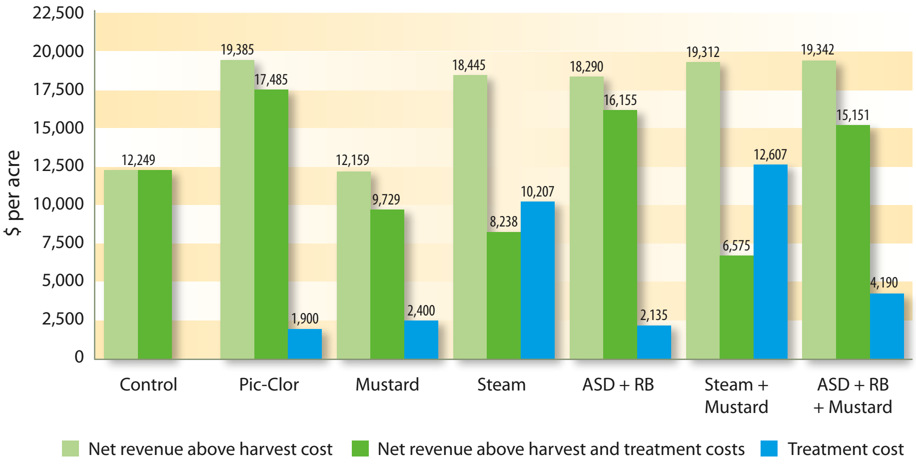

Fig. 1. Cost and returns per acre for an untreated, nonfumigated control; a standard Pic-Clor 60 fumigation treatment; and various nonfumigant soil treatments at Monterey Bay Academy, 2010–2011. Mustard = mustard seed meal. ASD = anaerobic soil disinfestation. RB = rice bran.

The cost data showed a critical need for more-efficient steam injection systems before steam can be adopted commercially. Recent advances with steam application equipment can reduce the cost of steam treatment to less than $5,500 per acre with the potential for further cost reductions (Fennimore et al. 2012). Since 2011 we have used an automatic mobile steam applicator in our research, which lowers the labor costs relative to those reported here by approximately 50% to 70%. It mixes steam with soil, allowing soil to be heated from 60˚F to 160˚F in 90 seconds — much more rapidly than the steam application system used here (Fennimore et al. 2012).

Future options

The phase-out of methyl bromide has proven to be a daunting task for the California strawberry industry. Not only are strawberry producers faced with the likelihood that methyl bromide will no longer be available to them by 2015, but they also must deal with increasing regulatory stringency on the use of all soil fumigants. While fumigants face an uncertain future in California, barrier films can help trap fumigants in the soil and reduce the likelihood of environmental or health impacts associated with fumigants in the atmosphere. It appears very likely in the near future that barrier films will be the only type of film approved for use with fumigants in California.

Potential methods of strawberry production that do not use fumigants include growing plants in substrates and using steam treatments or anaerobic soil disinfestation. All of these systems are being evaluated on a much larger scale, from 1 to 10 acres, with different soil types, to determine commercial feasibility and cost effectiveness. It is not likely, nor is it desirable from a pest management perspective, that one nonfumigant system will dominate on a large percentage of the strawberry acreage. Multiple production systems, using fumigants and nonfumigants, would allow producers to rotate treatments to suppress soil pests.

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Fumigant emission reductions with TIF warrant regulatory changes

by Husein Ajwa, Michael S. Stanghellini, Suduan Gao, David A. Sullivan, Afiqur Khan, William Ntow *and* Ruijun Quin

With methyl bromide's phase-out, most growers have turned to alternative fumigants, particularly 1,3-dichloropropene (1,3-D) and chloropicrin. These alternatives are tightly regulated because they are classified as toxic air contaminants and volatile organic compounds; the latter combine with other substances to produce ground-level ozone (smog). Two ambient air monitoring studies were conducted to evaluate the potential of totally impermeable film (TIF) to reduce emissions from shank applications of chloropicrin and 1,3-D. In 2009, a study demonstrated that TIF reduced chloropicrin and 1,3-D peak emissions by 45% and 38%, respectively, but TIF did not reduce total emissions when it was cut after 6 days. In 2011, increasing the tarp period from 5 to 10 days decreased chloropicrin and 1,3-D peak emissions by 88% and 78%, and their total emissions by 64% and 43%, respectively. Concurrent dynamic flux chamber results corroborated the ambient air monitoring data. These studies provide regulatory agencies with mitigation measures that should allow continued fumigant use at efficacious application rates.


Mike Stanghellini

Recent studies demonstrate that totally impermeable film (TIF) can significantly reduce peak and total emissions of chloropicrin and 1,3-D when tarping periods are extended from 5 days to 10 days. *Above*, TIF application at Lost Hills, Kern County.

As the availability of methyl bromide diminishes, the use of products containing chloropicrin and 1,3-dichloropropene (1,3-D; Telone II) are becoming the new standard fumigant treatments. Various formulations of them are injected into the soil at depths of 8 to 24 inches using tractor-mounted injection shanks, or they are applied via chemigation, in a drip irrigation system.

1,3-D is an excellent nematicide with some broad-spectrum activity, and it is often applied as the sole active ingredient for crops that are primarily subject to nematode infestation. It is commonly combined with chloropicrin to enhance control of soilborne pathogenic fungi.

Chloropicrin has excellent fungicidal properties with some broad-spectrum activity, and it can be applied as the sole active ingredient for crops that are primarily under disease pressure. Chloropicrin is most often combined with either methyl bromide or 1,3-D to enhance control of other soil pests, such as nematodes and weeds.

1,3-D is regulated in California on a township cap basis (see page 122). Chloropicrin use, since December 2012, is restricted by U.S. Environmental Protection Agency (US EPA) buffer zone regulations; and all fumigants are limited by the California Department of Pesticide Regulation (DPR) in designated areas with air pollution problems. As part of the 2008 Reregistration Eligibility Decision (RED) for chloropicrin, the US EPA (2009) proposed substantial label changes for chloropicrin to mitigate potential exposure resulting from soil fumigation. The new requirements, which took full effect in December 2012, implement nationwide buffer zones for all chloropicrin products. Buffer zones are setback distances between a treated field and any occupied structure, designed to mitigate potential bystander exposure to peak emissions. Also in 2008, the California EPA (Cal EPA) Department of Pesticide Regulation (DPR) issued a series of regulations regarding volatile organic compound (VOC) emissions and subsequent limitations on how, when and where certain fumigants can be used (CDPR 2009). The DPR VOC regulations address cumulative amount of fumigant emissions over several days, rather than the highest emission value from treated fields; some fumigant VOC emissions react with nitrous oxide compounds (generated by vehicles, industrial processes, etc.) and contribute to ground-level ozone, a pollutant that affects the air quality in several air basins in California such as the Sacramento Valley, San Joaquin Valley, Southeast Desert, South Coast, and Ventura County. The regulations on

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fumigant-use patterns in these VOC nonattainment areas (NAAs) will continue to limit fumigant use in the NAAs.

Field trials conducted in the last few years have evaluated various surface sealing methods or treatments to reduce fumigant emissions during soil fumigation. These include different application methods, organic and chemical soil amendments, different tarping materials and supplemental irrigation (water seals) (e.g., Cabrera et al. 2011; Fennimore and Ajwa 2011; Gao et al. 2009, 2011). While several strategies effectively reduce fumigant emissions, some of them are impractical (e.g., lack of water precludes the use of water sealing) or may come at the expense of reduced efficacy if they impede the soil dispersion potential of the fumigant (Hanson et al. in press; Jhala et al. 2012).

The most promising and practical strategy, to date, appears to be the adoption of low-permeability tarps, collectively called virtually impermeable films (VIFs). Traditional VIFs contain a nylon vapor-barrier layer; a relatively new type of low-permeability film, totally impermeable film (TIF), contains an ethyl vinyl alcohol (EVOH) resin vapor-barrier layer.

We collected field data from two trials to help regulatory agencies make decisions on the adoption of TIF for soil fumigation. We recorded peak emission levels, which are used to set buffer zones, and total emission levels, which relate to the VOC regulations. The trials included broadcast applications of chloropicrin, 1,3-dichloropropene (1,3-D) and mixtures of the two (coformulated end-use products).

The significant emissions reductions obtained when using TIF should allow regulatory agencies to provide relief to growers.

Materials and methods

We conducted two field trials to evaluate the potential of TIF to reduce fumigant peak and total emissions: the first in 2009 near Oxnard, Ventura County, and the second in 2011 near Lost Hills, Kern County. Both sites were located in air basins designated by DPR as VOC nonattainment areas (NAAs), where fumigant use is restricted (see page 122).

All fields were prepared in accordance with the product-labeled mandatory good agricultural practices (GAPs), which are a suite of application guidelines on proper soil preparation, appropriate soil moisture, weather considerations, application parameters and other factors. The test field plots were chosen to reflect representative sandy loam California fumigated soils, typical seasons of application and typical application equipment.

In both trials, chloropicrin and 1,3-D emissions from the broadcast fields were determined by measuring ambient air concentrations in 8 to 16 directions (depending on field size and shape) surrounding the field. Measurements were recorded for 6-hour periods for the first 48 hours, then every 12 hours for the remainder of the study except during tarp cutting and removal, when the sampling reverted to 6-hour intervals.

Air was pumped through ANASORB CSC (coconut charcoal; SKC tube 226-109) and XAD-4 solid sorbent tubes to capture any 1,3-D and chloropicrin, respectively, in the air at each sampling period. Chloropicrin and 1,3-D were extracted from the respective sorbent tubes using analytical methods developed by the CDFA, and both were analyzed by gas chromatography using a micro electron capture detector. The Industrial Source Complex (ISCST3) Dispersion Model was used to determine chloropicrin and 1,3-D flux values using the analytical results coupled with concurrent meteorological data that were collected during air monitoring. On-site meteorological stations collected relevant data, including wind speed, wind direction, ambient air temperature, relative humidity, solar radiation and precipitation.

Fumigant permeation through TIF was also determined using the dynamic flux chamber method, whereby flow-through chambers were placed directly on top of the TIF. A constant air flow through the chamber swept the air above the tarp, allowing fumigant emissions passing through the tarp to be trapped at the chamber outlet using XAD-4 resin sampling tubes; these tubes were later extracted and analyzed using gas chromatography with a micro electron capture detector. The dynamic flux chamber was operated continuously, with 3- to 6-hour intervals between exchanging sampling tubes.

Flux was calculated based on fumigant concentration captured in the chamber, sampling area, sampling time and flow rate. Detailed chamber methodology information can be found in Gao and Wang (2011). The dynamic flux chamber method monitors fumigant emissions at ground


David Miller

To monitor fumigant emissions at ground level, researchers used dynamic flux chamber equipment, *above*, to confirm and interpret the ambient air monitoring data.

level (the tarp-air interface) and was used to help confirm and interpret the ambient air monitoring data — in particular, it increased our confidence in data collected from large fields.

The polyethylene tarp used was a standard commercial broadcast tarp (1-mil high-barrier film by Cadillac Products Packaging Company, Troy, MI) that complied with the methyl bromide tarp permeability requirements of Title 3, California Code of Regulations, Section 6450(e). The TIF, VaporSafe, was manufactured by Raven Industries (Sioux Falls, SD). In the 2009 trial, the TIF used was an experimental 10.5-foot-wide film. In 2011, the TIF was a 13-foot-wide commercially viable film.

TABLE 1. Broadcast shank application scenarios in ambient air monitoring field trials in Oxnard 2009 and Lost Hills 2011

Location	Field	Soil sealing method	Days to tarp cut	Injection depth	Formulated product* application rate
				inches	*lb/acre*
Oxnard	1	Polyethylene	6	12	Pic-Clor 50 281.2
Oxnard	2	TIF	6	12	Pic-Clor 50 275.0
Lost Hills	1	TIF	16	12	Pic-Clor 60 571.3
Lost Hills	2	TIF	10	12	Pic-Clor 60 547.0
Lost Hills	3	TIF	5	12	Pic-Clor 60 593.6

* Pic-Clor 50 is a 50:50 mixture of chloropicrin and 1,3-D. Pic-Clor 60 is a 60:40 mixture of chloropicrin and 1,3-D.

2009 Oxnard trial

Two broadcast application fields, approximately 1 acre each, were separated by several miles to prevent cross-contamination. Air sampling was conducted at the beginning of each application (Sept. 10) and continued for 13 days (Sept. 23). Tarp cutting occurred 6 days after application (Sept. 16). An experimental 50:50 mixture of chloropicrin and 1,3-D was applied in both fields via broadcast shank at a 12-inch injection depth and at a rate of 281.2 pounds of product per acre in Field 1 and 275.0 pounds per acre in Field 2. Field 1 was tarped with 10.5-foot-wide, 1-mil, clear polyethylene film. Field 2 was tarped with 10.5-foot-wide, 1-mil, clear TIF (table 1).

A certified applicator applied the fumigants using a closed, pressurized, winged shank injection system (Noble plow). Soil type in Field 1 (polyethylene tarp) was a Hueneme sandy loam (coarse loamy, mixed, superactive, calcareous, thermic Oxyaquic Xerofluvents). Soil type in Field 2 (TIF) was a Metz loamy sand (sandy, mixed, thermic Typic Xerofluvents).

2011 Lost Hills trial

This study was designed to determine the effectiveness of TIF in reducing emission rates and total mass loss of chloropicrin and 1,3-D and to show the extent that peaks associated with tarp cutting change as a function of tarp deployment period. Comparative emissions data were generated from three 12-inch-deep broadcast shank applications of a 60:40 chloropicrin and 1,3-D co-formulated end-use product (Pic-Clor 60). The three fields were in close proximity to one another to enable concurrent air monitoring and to ensure that meteorological and soil conditions were similar.


Husein Ajwa

Data from the Oxnard trial indicate that a longer tarp-covering period than the standard 5 days is needed to reduce emissions associated with tarp cutting. *Above*, broadcast shank fumigation under TIF, Oxnard, Ventura County, September 2009.

The applications were made on one 8-acre field (Field 1) and two 2-acre fields (Fields 2 and 3) near Lost Hills on June 4. The two 2-acre fields were separated by approximately 830 feet to prevent cross-contamination. The 8-acre field was at least 4,900 feet from the other fields. Air monitoring was conducted concurrently at each field starting at the beginning of application and continuing until 48 hours after the time of tarp cutting in each field. All fields had the same application scenario: Pic-Clor 60 applied via broadcast shank at a 12-inch injection depth with a target rate of 588 pounds of product per acre (equivalent to 350 pounds chloropicrin per acre plus 238 pounds 1,3-D per acre).

Soil type in all three fields was Milham sandy loam (fine loamy, mixed, superactive, thermic Typic Haplargids) except for one corner of Field 1, which contained Kimberlina fine sandy loam (coarse loamy, mixed, superactive, calcareous, thermic Typic Torriorthents).

The only major difference between the three fields was the duration of tarp deployment. Field 1 was tarped for 16 days, Field 2 for 10 days, and Field 3 for 5 days (table 1).

Oxnard trial results

Background samples collected at both fields indicated that no cross-contamination occurred during the monitoring. For Field 1 (polyethylene tarp) and Field 2 (TIF), the chloropicrin peak flux rates were 8.31 μg/m^2/second at 162 to 168 hours after the start of application, and 4.62 μg/m^2/second at 0 to 6 hours after the start of application, respectively (fig. 1A). Total mass loss of chloropicrin was 10.8% in Field 1 and 14.1% in Field 2 (fig. 1B). Field 2's total mass loss may have been affected by the numerous holes inadvertently punched into the tarp during air monitoring by unknown personnel working in adjacent fields.

The 1,3-D peak flux rates in Field 1 were 38.28 μg/m^2/second at 30 to 36 hours after the start of application; and in Field 2, they were 28.53 μg/m^2/second at 144 to 150 hours after the start of application (fig. 1C). Total mass loss of 1,3-D was 43.24% in Field 1 and 42.9% in Field 2 (fig. 1D).

Emission flux and cumulative loss estimated using dynamic flux chambers were reported in Qin et al. 2011. Emission flux of chloropicrin and 1,3-D from Field 2 (TIF) was substantially lower than from Field 1 (polyethylene film) during tarp covering. Total through-film emission loss during the 6-day covered period was < 1% for chloropicrin and 2% for 1,3-D in Field 2 compared to 12% for chloropicrin and 43% for 1,3-D in Field 1. The greater retention of 1,3-D under the TIF (Field 2) resulted in an emissions peak after tarp cutting, which did not occur with the polyethylene film (Field 1). Chloropicrin emissions were fairly low in both fields, regardless of the tarp type.

Overall, the dynamic flux chamber data were similar to the ambient monitoring data in figure 1, which show there was no difference between the TIF and polyethylene tarped fields in terms of total emission loss. The data clearly indicate that a longer tarp-covering period than the standard 5 days would be needed to reduce emissions associated with tarp cutting.

These results demonstrate that while in place and intact (and in comparison to polyethylene tarp), TIF can significantly reduce the peak emissions rates of chloropicrin and 1,3-D. However, longer tarping periods are needed to achieve optimal reduction in total emissions of 1,3-D.

Lost Hills trial results

No cross-contamination between fields occurred during the air sampling periods. For Field 1 (tarped with TIF for 16 days), the chloropicrin peak emissions rate was 6.46 μg/m^2/second at approximately 48 to 60 hours after the start of the application (fig. 2A); for Field 2 (TIF for 10 days), it was 5.12 μg/m^2/second at approximately 72 to 84 hours after the start of the application; and for Field 3 (TIF for 5 days), it was 41.53 μg/m^2/second at approximately 126 to 132 hours after the start of the application (fig. 2A). The total mass loss

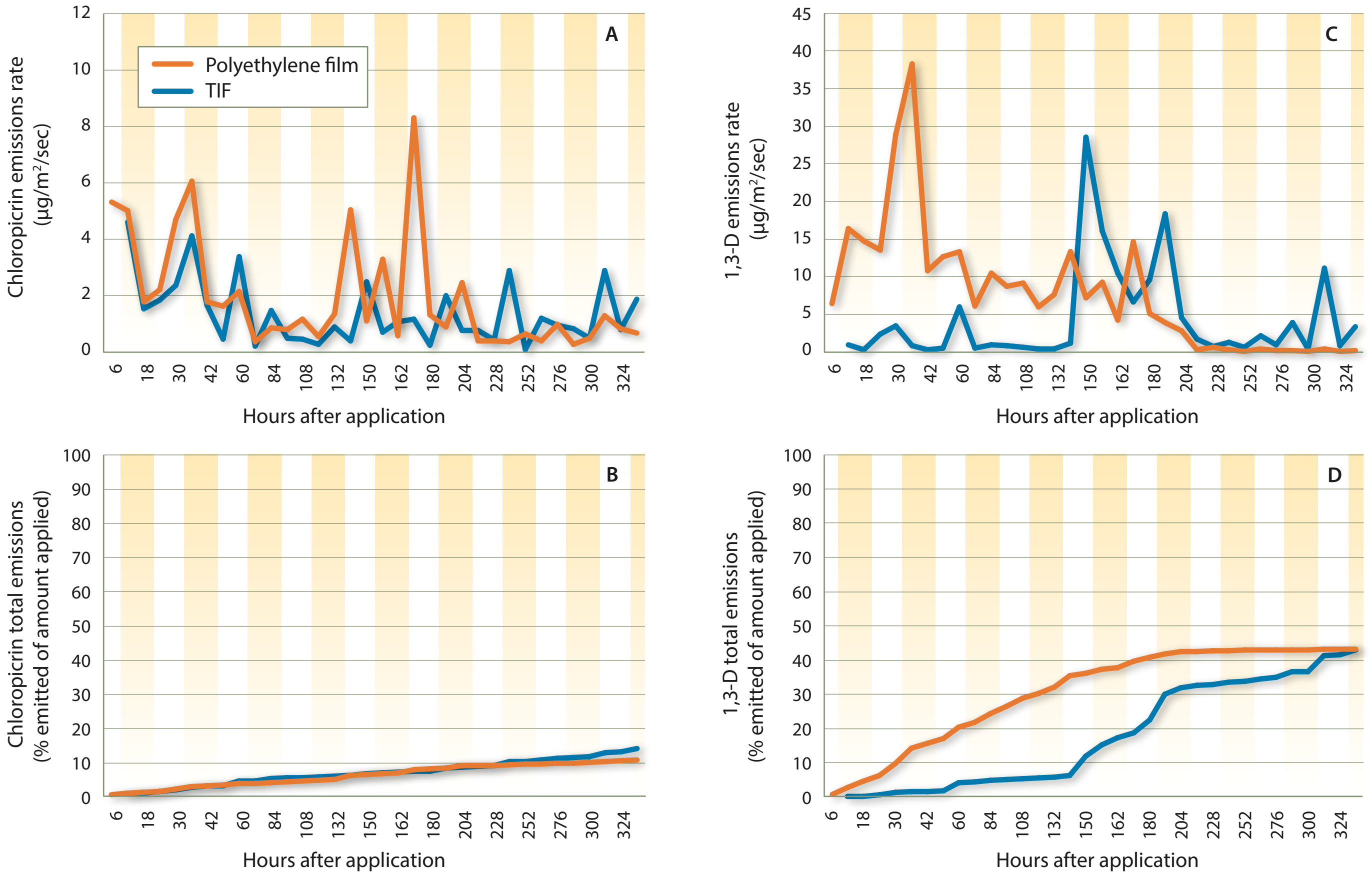

Fig. 1. Peak and total emissions from the Oxnard 2009 trial as measured by ambient air monitoring. (A) Chloropicrin emissions rate; (B) Chloropicrin total emissions; (C) 1,3-D emissions rate; and (D) 1,3-D total emissions.

for chloropicrin was 4.5% (Field 1), 3.6% (Field 2) and 10.0% (Field 3) (fig. 2B).

For Field 1 (TIF for 16 days), the 1,3-D peak emissions rate was 6.49 μg/m^2/second at approximately 30 to 36 hours after the start of the application (fig. 2C); for Field 2 (TIF for 10 days), it was 10.63 μg/m^2/second at approximately 246 to 252 hours after the start of the application; and for Field 3 (TIF for 5 days), it was 47.29 μg/m^2/second at approximately 126 to 132 hours after the start of the application (fig. 2C). The total mass loss for 1,3-D was 10.2% (Field 1), 10.9% (Field 2) and 19.1% (Field 3) (fig. 2D).

Emission flux and total emission loss measured in Field 1 by the dynamic flux chamber method are shown in figure 3 (A-D). Over the 16-day tarp period, cumulative emission losses before tarp cutting were 5.7% for chloropicrin and 7.4% for 1,3-D, respectively (fig. 3B, 3D). A much smaller emissions rate was measured after tarp cutting on this 16-day tarped field than was measured in the 2009 trial, where the TIF was cut after 6 days. Emission losses resulting from tarp cutting in the 2011 trial were 2.1% for chloropicrin and 5.6% for 1,3-D, respectively. The total measured emission losses from Field 1 in the 2011 study were 7.8% for chloropicrin and 13.1% for 1,3-D. These measurements generally support the ambient monitoring results (4.5% loss of applied chloropicrin and 10.2% loss of applied 1,3-D).

The results of the Lost Hills study demonstrated that peak and total emissions of chloropicrin and 1,3-D under TIF are significantly lower when tarp cutting is extended from 5 days to 10 days. The differences in total emissions when tarps were cut at 10 days versus 16 days after application were negligible.

Significant emission reductions

While in place and intact (deployed in the field), TIF significantly reduces fumigant emissions by retaining fumigants under the tarp. These studies corroborate and provide field-scale validation of earlier laboratory work showing the emissions reduction potential of this film technology. For fumigants like chloropicrin with short soil half-lives (1 to 2 days), a tarping period of 5 to 6 days should be sufficient for application rates of less than 200 pounds per acre. However, for higher application rates and for fumigants with longer soil half-lives, such as 1,3-D, longer tarp periods are needed to maximize the emissions reduction potential of TIF use.

These results show that peak and total emissions arising from high rates of chloropicrin and 1,3-D applications can be effectively mitigated if the tarping duration of TIF is extended to 10 days. Only nominal benefits would be achieved by extending the tarping period from 10 to 16 days. Although TIF has the ability to retain 1,3-D in the soil for a few weeks, the degradation half-life of 1,3-D under field conditions is 5 to 7 days (Ajwa et al. 2003, 2010), and a very small residual concentration, if any, is found in the soil when TIF is removed from the field after 10 days. Also, the final degradation products of 1,3-D are nontoxic (mainly carbon dioxide,

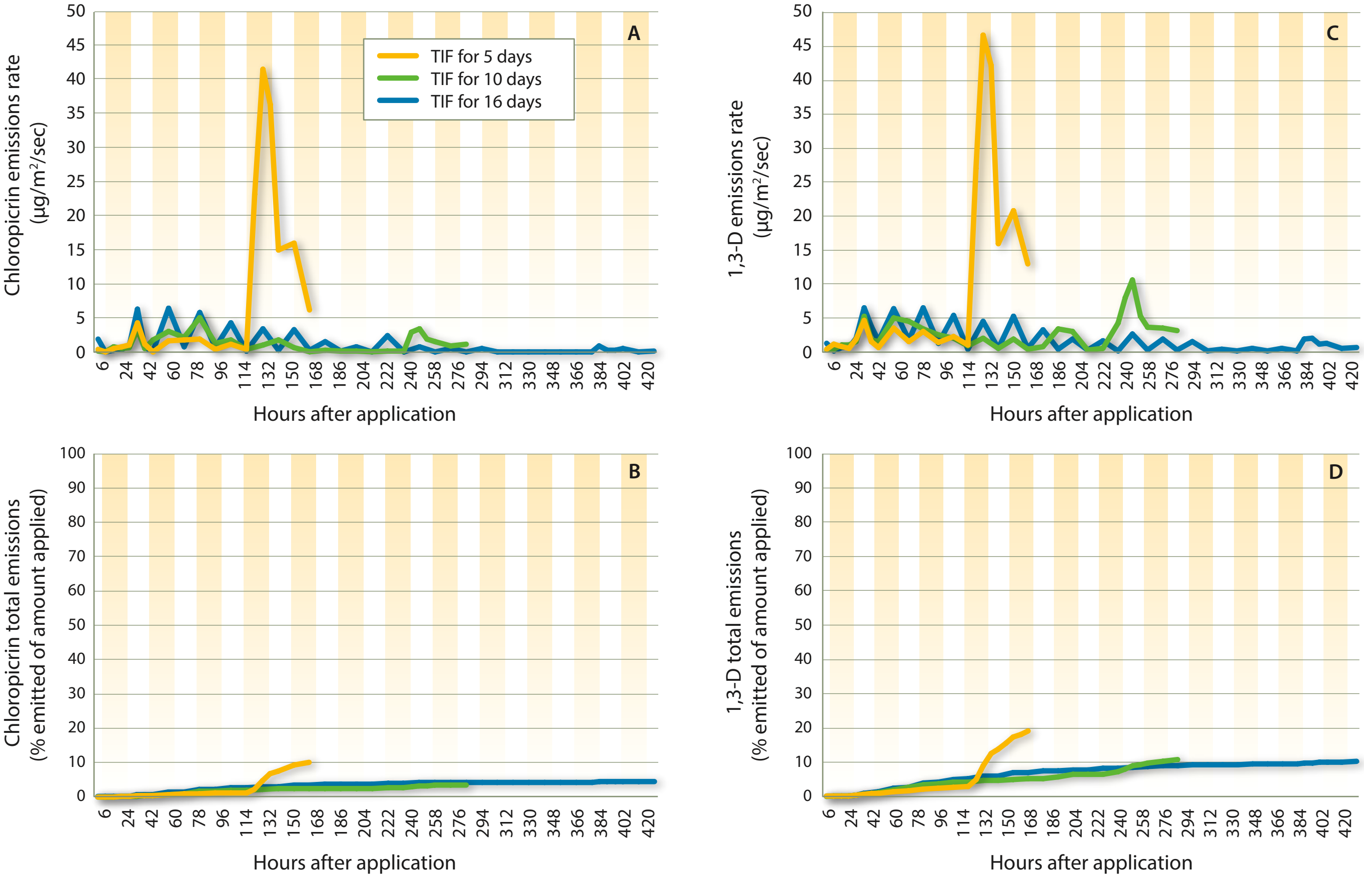

Fig. 2. Peak and total emissions from Lost Hills 2011 trial as measured by ambient air monitoring. (A) Chloropicrin emissions rate; (B) Chloropicrin total emissions; (C) 1,3-D emissions rate; and (D) 1,3-D total emissions.

water and chlorine) and do not pose risk to humans and the environment (Dungan and Yates 2003).

Emission data obtained from dynamic flux chambers agree with and strongly support the ambient monitoring data. The significant emissions reductions obtained when using TIF should allow regulatory agencies to provide relief to growers by implementing smaller buffer zones, increasing the volume of fumigant use and providing growers with greater flexibility in areas with spatially or temporally-based fumigant restrictions where total emissions are of concern.

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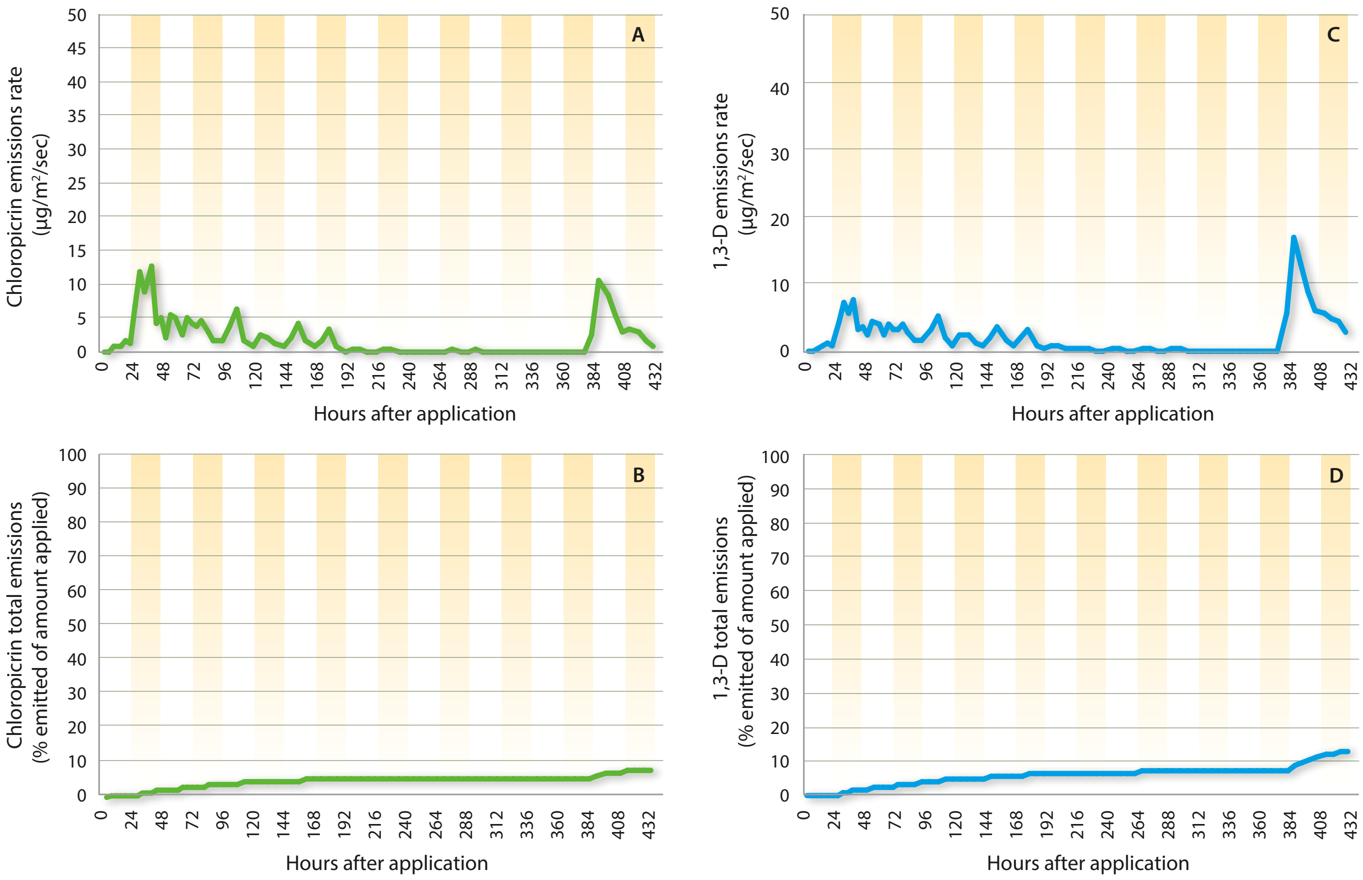

Fig. 3. Peak and total emissions from Field 1 (16 days) of Lost Hills 2011 trial as measured by the dynamic flux chamber. (A) Chloropicrin emissions rate; (B) Chloropicrin total emissions; (C) 1,3-D emissions rate; and (D) 1,3-D total emissions.

REVIEW ARTICLE

Forest nurseries face critical choices with the loss of methyl bromide fumigation

by Jerry E. Weiland, Will R. Littke *and* Diane L. Haase

Forest nurseries in the western United States have relied for decades on methyl bromide to control soilborne pests. Numerous studies have investigated alternative fumigants, alternative application methods and nonfumigant approaches for their ability to reduce soilborne pest populations and produce quality, disease-free seedlings. We review the recent studies and identify where research is needed to assist the industry's transition away from methyl bromide. For the immediate, foreseeable future, an integrated approach combining nonfumigant and fumigant methods will provide the best strategy. Nevertheless, the industry may need to transition completely to container production if fumigant regulations become more restrictive.


Jerry Weiland

Suburbs have encroached onto land adjacent to some forest seedling nurseries, which significantly restricts growers' use of fumigants.

The forest nursery industry in the western United States produces tree seedlings that are primarily used for reforestation. Many states in the region require that forest lands that have been harvested or destroyed by fire, diseases or insects be replanted with seedlings. Oregon and Washington lead the western states in the number of seedlings that are replanted each year. In Washington, approximately 50 million seedlings were planted in 2011 (pers. comm., J. Trobaugh, Webster Nursery, Olympia, WA); similar numbers were planted in Oregon (OFRI 2008). Using average planting densities of 150 to 350 seedlings per acre (0.4 ha), we estimate that 143,000 to 333,000 acres (58,000 to 135,000 ha) of forest land were planted in each state during the 2011 planting season.

To meet demand for seedlings, nurseries in the western states of California, Idaho, Montana, Oregon and Washington produced approximately 200 million seedlings in 2011, over half of which were 1- or 2-year-old conifer species (industry survey, Weiland 2011, of 16 of the largest forest nurseries in those states). Approximately 75% of these seedlings (150 million) were sold as bareroot stock, with the remaining 25% sold as containerized stock. Bareroot seedlings, grown in the field and shipped without soil surrounding their roots, have historically been favored because they are generally larger in size than containerized seedlings, and can be produced in greater numbers, at lower cost.

During the last decade, the industry suffered a series of nursery closures, particularly of state- and federally-funded operations. In June 2011, for example, California closed its last state nursery, in Magalia, due to state budget reductions (CalFire 2011). This followed the closing of its container seedling production facility in Davis in 2003. Some closures were due to the decreased demand for seedlings during the recent economic recession. However, much of the long-term reduction in demand has been driven by a downward trend in annual timber harvests since 1989 (Adams et al. 2006).

When seedling production is limited, demand can suddenly outstrip supply, as often occurs after catastrophic forest fires. Seedlings can sometimes be procured locally, but often they must be purchased from out-of-state (industry survey, Weiland 2011). Imported seedlings must meet phytosanitary certification requirements, but new weeds, pathogens and quarantine pests may be introduced accidentally.

Current methyl bromide use

Pest management is a significant issue for forest nurseries. For decades, the industry has relied on methyl bromide (MB) in combination with chloropirin (Pic) to manage soilborne insects, weeds and pathogens (Enebak 2007). The general practice in the Pacific Northwest has been to fumigate in fall with methyl bromide plus chloropicrin (67:33 at 350 pounds per acre), crop for 2 years and finish with a year of bare fallow (in which fields are not planted and kept weed free) before repeating the cycle (Weiland et al. 2011).

In the absence of soilborne pest control, nurseries can experience significant losses in seedling yield and quality. Some weeds, such as yellow nutsedge (*Cyperus esculentus*), are of particular concern because they are quarantine pests in Oregon and Washington. Many growers are also

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concerned about the introduction of nonnative pathogens, especially after the discovery of *Phytophthora ramorum*, the causal agent of sudden oak death, in the ornamental nursery trade.

Methyl bromide application in bareroot forest nurseries has continued under critical use exemptions (CUEs) and quarantine and preshipment exemptions (QPSs). Many nurseries initially used CUEs to continue methyl bromide application while alternative fumigants were evaluated. However, as the amount of methyl bromide available to U.S. forest nurseries under CUEs decreased from 192.5 tons in 2005 (UNEP 2010b) to 34.2 tons in 2012, some nurseries switched to QPSs (Enebak 2007). From 2008 to 2009, there was an almost 75% increase in QPS methyl bromide consumption in the United States, part of which was attributed to the switch from CUEs (UNEP 2010a).

Currently, almost all surveyed private bareroot nurseries in the Pacific Northwest continue to use methyl bromide, under QPS exemption, as the main method of soilborne pest control (industry survey, Weiland 2011). In contrast, federal nurseries have turned almost exclusively to dazomet (Basamid), because of federal pressure to use the least toxic materials and also because these nurseries are in the more-arid regions of the western United States, where spring fumigation can be carried out more easily. Private nurseries located west of the Cascades receive abundant rain in the winter and spring, which makes spring dazomet application infeasible due to seedling phytotoxicity (James 2002).

Of the 14 largest nurseries (including state, federal and private nurseries) in the western region that include some bareroot production, approximately 70% rely on methyl bromide for soilborne pest control (industry survey, Weiland 2011). In 1993, Smith and Fraedrich reported that 80% of the nurseries in the region relied on the fumigant; and in 1981, the figure was 90% (Landis and Campbell 1989). Regardless of the decrease in use, the pressure to further reduce methyl bromide for soil fumigation continues. Given the amount of attention that the QPS issue has received (UNEP 2010a, 2010b), growers should expect that the QPS exemptions will end in the near future.

Recent changes to fumigant application regulations and pesticide labels have significantly limited the use of methyl bromide and other fumigants in forest nurseries. In particular, buffer zone requirements affected nurseries near new suburban growth. Even with buffer zone reduction credits, the new restrictions implemented in 2012 will place restrictions on bareroot forest nursery production, and in all likelihood, growers will eventually lose methyl bromide as a pest management tool.

Fortunately, a large number of reviews and independent studies have addressed methyl bromide alternatives. This review will focus on what has been learned from research over the last decade or so, primarily from the western region.


Jerry Weiland

Application of virtually impermeable film (VIF) over a reduced rate of iodomethane plus chloropicrin. Glue (red strips) is released from the spray nozzle before the film unrolls (*insert*).

Alternative fumigants

Most of the emphasis in the forest nursery industry has been placed on alternative fumigant chemistries as replacements for methyl bromide. As of April 2013, the Environmental Protection Agency (EPA 2013) listed five fumigant alternatives (and no nonfumigant alternatives) for the industry: dazomet, metam sodium (Vapam, Busan), chloropicrin (Pic), dimethyl disulfide (DMDS), and 1,3-dichloropropene (1,3-D), and two combinations of these: 1,3-D and chloropicrin (Telone, Pic-Clor 60) and metam sodium and chloropicrin. Each of the five EPA-listed alternative fumigants have been used with mixed results in nursery trials.

The EPA lists propargyl bromide and sodium azide as alternatives under development, but these are not yet registered for use in forest nurseries. Unfortunately, iodomethane (methyl iodide), an effective methyl bromide alternative, was pulled from the U.S. market in March 2012 by Arysta Life Sciences in response to poor sales due partly to its higher cost (Weiland et al. 2011) and partly to the number of environmental restrictions that were being implemented (EPA 2013).

Dazomet, metam sodium. Early conifer nursery studies focused on methyl isothiocyanate (MITC)–producing agents (dazomet, metam sodium) and their efficacy (Tanaka et al. 1986). Rates varied from 250 to 350 pounds per acre for dazomet and 50 to 100 gallons per acre for metam sodium. These and later results (Littke et al. 2002) identified serious operational inconsistencies in chemical incorporation, water application and disease control efficacy. MITC agents require water activation to achieve efficacy, and this reaction is sensitive to temperature (must be above 50°F). This limits their use to summer and fall applications; severe phytotoxicity can result from incomplete chemical volatilization during spring.

Other research showed that tarping with high-density polyethylene (HDPE) plastic, virtually impermeable film (VIF) or totally impermeable film (TIF) increased weed and disease control. Currently, metam sodium remains a viable component in alternative fumigant mixes with chloropicrin; it is more easily incorporated uniformly as a liquid than the dazomet granular formulation.

Chloropicrin. Chloropicrin formulated with methyl bromide (98:2, 67:33 or 50:50

Nonfumigated plot shows disease and weed pressure, right foreground. Fumigated plot is in background.

Closeup of nonfumigated plot shows disease and weed pressure, *top*; fumigated plot shows healthy Douglas-fir seedlings, *above*.

MB:Pic) has been part of the operational fumigant standard for decades in most industrial forest nurseries. Chloropicrin is an effective soil disease control agent when used alone at 100 to 300 pounds per acre. However, broad-spectrum weed control is generally lacking.

In the southeastern United States, where lighter sandy soils prevail, 300 pounds per acre chloropicrin was comparable to methyl bromide with chloropicrin (MB:Pic) over three pine seedling crop rotations, provided an effective herbicide regime was used to control weeds (Cram et al. 2007; South et al. 1997).

Our experience in the western United States suggests that chloropicrin does not penetrate as well as methyl bromide into heavier soils, thus requiring more emphasis on proper soil preparation prior to fumigation. As a spring fumigant, chloropicrin lingers in the soil and increases the risk of phytotoxicity to newly transplanted seedlings. Chloropicrin regulations currently require concentrations above 20% in fumigant mixtures to comply with safety standards, and buffer limitations curtail the high doses of chloropicrin required for its stand-alone use as a fumigant.

Today, chloropicrin is used effectively as an alternative fumigant when paired with other fumigant agents — iodomethane:chloropicrin (50:50 at 350 pounds per acre), 1,3-D:chloropicrin (Telone C35 at 350 pounds per acre), and metam sodium:chloropicrin (50 gallons per acre:122 pounds per acre) — and used in combination with VIF or TIF tarps. A great deal of reliance is currently placed on chloropicrin as a component in fumigant mixtures. However, chloropicrin was listed as a toxic air contaminant by the California Department of Pesticide Regulation in 2010, which may indicate that more restrictive regulations are in store in California (CDPR 2011).

Dimethyl disulfide (DMDS). The fumigant DMDS also holds promise if odor issues can be solved. A reduced-rate treatment of DMDS and chloropicrin (80:20 at 60 gallons per acre) was successful in controlling weeds and pathogens; however, its use resulted in worker and neighbor complaints; the distinctive odor was still strong in treated plots more than a month after application (Weiland et al. 2011).

1,3-dichloropropene (1,3-D). This fumigant is used with chloropicrin in forest seedling nurseries to improve weed control. However, few published studies address its use in forest nurseries, and most research involving 1,3-D has been conducted only in the southeastern United States, where soil and environmental conditions differ greatly from those in the West (Enebak et al. 2011; Enebak et al. 2012).

Iodomethane. Relatively few studies have been conducted with iodomethane. Unlike other fumigants, iodomethane behaves in a similar manner to methyl bromide and was the most likely replacement in all performance aspects before it was withdrawn from the market. When it was available in 2011, serious issues with its price (Weiland et al. 2011) and regulation (Washington State Department of Agriculture denied registration due to environmental concerns) limited its deployment.

Iodomethane with chloropicrin has been successful in soil disease and weed control, in both spring (80:20 at 275 pounds per acre) and fall applications (50:50 at 175 to 350 pounds per acre) (unpublished industry data and Weiland et al. 2011).

Effects on seedling quality. Alternative fumigants have produced varying effects on final seedling density and quality when compared to the industry standard, methyl bromide plus chloropicrin. In seedbed trials, germinant density with alternative fumigants can equal that of methyl bromide or, as in the case of some dazomet trials, result in losses of up to one-third of the seed sown as the result of phytotoxicity from residual fumigant (Littke et al. 2002).

Stunting is also commonly observed following the use of MITC agents. Attempts to manage undersized seedlings with fertilization were not successful (industry data, unpublished), and reduced seedling colonization by mycorrhizal fungi does not appear to be a factor. Tanaka et al. (1986) showed that ectomycorrhizal colonization of Douglas-fir (*Pseudotsuga menziesii*) was not significantly different in standard- versus dazomet-fumigated and nonfumigated soils even when twice the normal rate of methyl bromide with chloropicrin was applied. For alternative fumigants to be fully implemented, research is needed to overcome these inconsistent results on seedling growth and quality.

Factors affecting fumigant efficacy. Fumigant efficacy is negatively affected by the presence of root debris in the field. Root tissues are more resistant to fumigant penetration than bulk soil, so excessive amounts of residual debris may reduce overall fumigant efficacy. In addition, soil bulk density is critical; soils with higher bulk density reduce fumigant efficacy against soilborne pests (Weiland et al. 2011). Finally, additional research is needed to determine the critical threshold (concentration × time; CT) values for various pathogens to fumigant gases. Methyl bromide toxicity values suggest that control of *Pythium* and *Phytophthora* species is easier to attain than control of other pathogens such as *Fusarium*, *Phomopsis* and *Rhizoctonia* (Munnecke et al. 1978). Similar data is lacking for the alternative fumigants.

Alternative application methods

A number of fumigation methods have been developed that reduce the amount of fumigant applied and/or increase fumigant retention time in soil. Some of these methods are not easily used in forest nurseries. The application of fumigants through buried drip lines, for example, is incompatible with several nursery cultural practices, such as cultivating for weeds, seeding or transplanting operations, and root pruning and wrenching to produce compact root systems. All could destroy buried irrigation lines. However, water treatments to seal in dazomet (James et al. 2004), low-permeability plastic films, and reduced-rate fumigants (Weiland et al. 2011) are becoming commonplace. The methods described below can be incorporated into a pest management program to provide credits to reduce buffer zone sizes.

High soil moisture. Cultural practices to prepare fields for fumigation have focused on tillage and ripping to remove soil pans that hinder fumigant diffusion. New best management practices (BMPs), as defined in the EPA reregistration eligibility decisions (REDs), require higher soil moisture content (> ~15% dry weight basis) at the time of application to retard fumigant efflux from the soil. Previously, operational soil moisture content at fumigation was kept low (2% to 10% dry weight basis) in combination with deep soil ripping to achieve maximum fumigant penetration. Gan et al. (1999) suggested that higher soil moisture differentially affects fumigant behavior, increasing the degradation of 1,3-D but not MITC. Similarly, Wang et al. (2006) concluded soil moisture plays a critical role in the conversion, distribution and efficacy of alternative fumigants (MITC agents, chloropicrin, 1,3-D). In general, higher water content increased the conversion of dazomet or metam sodium to MITC, but also limited the distribution of fumigants in soil. Future alternative fumigant treatment studies are needed under standard soil environmental conditions to evaluate the best management practices recommendations.

VIF and TIF. Placing VIF and TIF over fumigated soil reduces fumigant emissions by more than 90% compared to HDPE, which only reduces emissions by 50% (Gao et al. 2011). The advantage of these films is that fumigants are retained in the soil longer, thereby increasing the amount of time that pathogens are exposed to toxic levels of the gas, which should increase disease control efficacy. One drawback, however, is that the waiting period for film removal should be longer than 1 week to allow the retained fumigant to degrade (Gao et al. 2011); otherwise, workers may be exposed to an emission surge when the film is cut. Recent experience with VIF and TIF combined with improvements in soil incorporation and sealing techniques warrants the review and retesting of soil fumigant treatments that were previously determined to be inadequate for forest nursery production under HDPE (e.g., early studies with lower rates of dazomet and metam sodium).

Reduced fumigant rates. Because VIF and TIF retain soil fumigants for longer periods of time, fumigant rates may be reduced to achieve similar efficacy as full rates. One study from three forest nurseries in Oregon and Washington found that reduced rates of fumigants could be used under VIF for control of *Fusarium* and *Pythium* species (Weiland et al. 2011). Specifically, iodomethane:chloropicrin (50:50 at 244 pounds per acre), metam sodium:chloropicrin (50 gallons:122 pounds per acre), and DMDS:chloropicrin (80:20 at 60 gallons per acre) under VIF were as effective as methyl bromide:chloropicrin (67:33 at 350 pounds per acre) under HDPE. These results also held true for *Cylindrocarpon* species (figs. 1 and 2).

Reduced-rate treatments are a potential option for nurseries with large buffer zones. To recover planting space, the center of a nursery field could be fumigated at the full rate, and then a reduced rate could be applied under TIF to the buffer zone of the full-rate fumigant. This second application would reduce the size of the required buffer zone at the field edge. The area treated with reduced-rate fumigant could be used for transplants, which do not require as stringent of a treatment as seedbeds.

Bed fumigation. Another method that could reduce the amount of fumigant applied is using bed (or row) fumigation in place of flat (or whole-field) fumigation. It reduces the area to which fumigant is applied, but it's unknown whether the nonfumigated tire path between beds would serve as a reservoir for weeds and soilborne pathogens. If subsequent cultural operations, such as root wrenching and weeding, resulted in significant mixing of nonfumigated and fumigated soil, recontamination of the newly fumigated beds might occur more rapidly than if the entire field had been fumigated. One might suspect that the risk is relatively high; however, a previous study found that pathogen populations remained low in fumigated beds "despite the immediate proximity of unfumigated beds and the repeated movement of tractors and irrigation water across the plots" (Hansen et al. 1990).

It may be that if the nonfumigated region between beds can be maintained weed-free for several consecutive years, pathogen densities there would eventually drop, reducing the risk of recontamination over time. Also, soil preparations and nutrient additions might be made prior to fumigation to reduce postfumigation mixing of soils.

One final drawback to bed fumigation is the perception that there is a greater loss of fumigant around tarp edges. Fumigants might dissipate more rapidly through the nontarped, unfumigated regions between beds than from a flat fumigated field that is entirely covered by plastic. Furthermore, the amount of land left unfumigated in the tire tracks is also relatively small and would not contribute much to a buffer zone credit.

Although some nurseries in the Pacific Northwest use bed fumigation with dazomet, it is not widely used with other fumigants. The success of bed fumigation in other agricultural systems is promising, and this application method may yet prove amenable to tree seedling production.

Nonfumigant methods

Although some studies have demonstrated the potential for nonfumigant methods to control nursery pathogens and pests, these practices have not been studied in depth. Often, these studies report inconsistent seedling density and quality as well as a concomitant increase in the populations of potentially pathogenic microbes (e.g., *Fusarium* and *Pythium* species).

An increase in the populations of *Fusarium* or *Pythium* species does not necessarily mean that there will be an increase in disease incidence or severity. The populations can be pathogenic or nonpathogenic and may occur with other factors such as increased microbial diversity, better plant health and suppressed disease development (James and Dumroese 2007; Stewart et al. 2006). Nevertheless, methods to easily distinguish pathogenic from nonpathogenic populations are not currently available, and nursery managers must make disease management decisions without this information.

Because of these issues, the understanding and development of nonfumigant treatments lag behind those of alternative fumigant treatments and have limited the widespread adoption of nonfumigant methods by growers. To achieve adequate disease control, combinations of nonfumigant methods need to be investigated, possibly in rotation with fumigants or fungicides.

Bare fallow. Bare fallow, maintaining a vegetation-free condition for a period of time, is a nonfumigant treatment, though it is not chemical-free, because it requires the use of herbicides to keep the ground bare. Weeds, weed residues, cover crops and green manures increase the organic residue in the soil, and pathogens such as *Fusarium* and *Pythium* species can survive in soil as facultative saprobes on these simple organic substrates when plant hosts are absent.

Hansen et al. (1990) found that grass or legume cover crops increased pathogen population densities over those in bare fallow plots throughout the crop cycle in nonfumigated conifer seedling beds (in forest nurseries). Similarly, a corn green manure crop resulted in high *Fusarium* levels (> 1,000 colony-forming units per gram) that persisted through a subsequent 2-year fallow period (James 2000). *Fusarium* species readily colonized soil organic matter, particularly roots of the previous conifer seedling crop, as well as the organic corn debris (James 2000).

Bare fallow in the season before planting can be effective in reducing pathogen populations by depleting the food base for facultatively saprobic pathogens (those that can survive on dead organic matter as well as cause disease on living plants). Additionally, bare fallow during the summer months may further reduce populations of pathogens, such as *Pythium* species, which thrive in moist conditions. In some cases, this reduction is enough to produce plant densities, seedling heights and stem diameters similar to those produced in fumigated plots (Hildebrand et al. 2004). In other studies, however, the reduction in pathogen populations has not been enough to reduce damage in comparison to fumigated areas (James 2001). Furthermore, bare fallow can leave some soils susceptible to wind erosion.

Organic amendments. Organic amendments, which are used regularly in forest nurseries to improve soil physical and chemical properties, have been shown to stimulate bacteria, fungi and other soil organisms that can suppress soil pathogens. The effects vary among different amendments.

Aged sawdust (with delayed nitrogen application) benefited conifer seedlings over mature composts in USDA Forest Service nursery trials (Hildebrand et al. 2004). This was attributed to the sawdust's slow decomposition possibly favoring the growth of competitive soil saprobes to the detriment of soil pathogens that use simple organic substrates. Similarly, Barnard et al. (1997) found that materials with high carbon-to-nitrogen (C:N) ratios, such as composted pine bark, resulted in better disease suppression and seedling

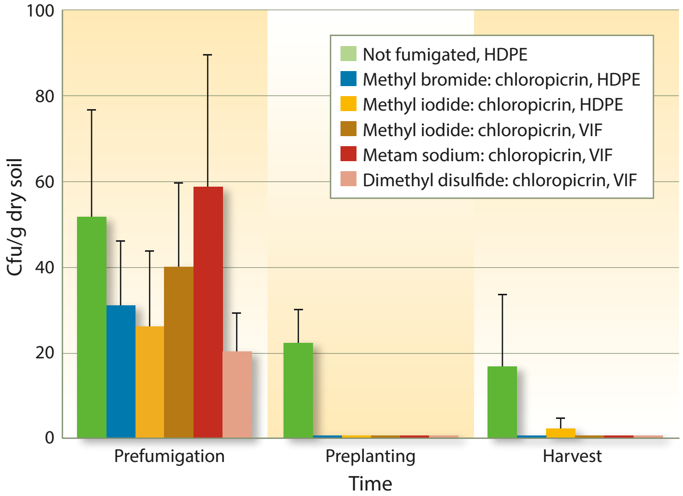

Fig. 1. Mean soil populations of *Cylindrocarpon* species (± SE) before fumigation in August 2008, 6 months after fumigation but just before planting in spring 2009, and at the end of the growing season in November 2009 in six fumigation treatments applied at three forest seedling nurseries (cfu = colony-forming units).

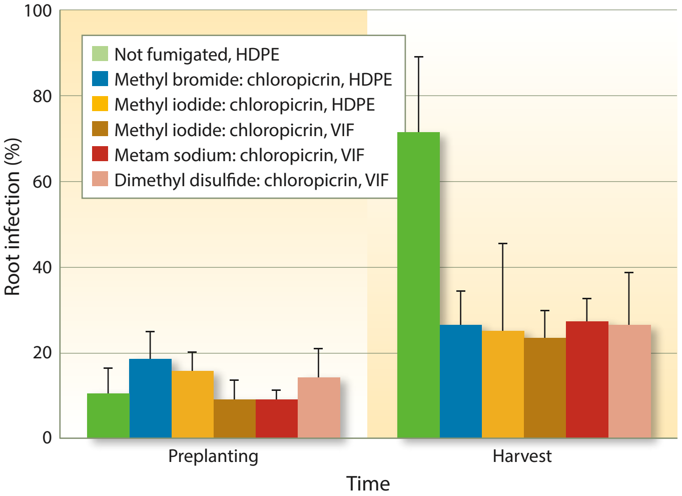

Fig. 2. Mean percentage of Douglas-fir seedling root infection (± SE) by *Cylindrocarpon* species before planting into fumigant treatments in spring 2009 and at the end of the growing season in November 2009 in six fumigation treatments applied at three forest nurseries.

quality than materials with low carbon-to-nitrogen ratios.

Regardless, organic amendments do not achieve the level of disease suppression found with chemical fumigation (James 2001). Khadduri (2010) examined Douglas-fir seedlings planted into compost-amended soil that had either been spring fumigated with a methyl bromide:chloropicrin combination or left unfumigated. Although plots with biosolid and bark-based composts had the highest average number of packable seedlings relative to other compost amendments, seedlings raised in fumigated soil had better nutrient, pathology, morphology and packout measurements than seedlings grown in nonfumigated soil, regardless of compost treatment.

Brassicaceous plants (e.g., *Brassica*, *Sinapsis* and *Limnanthes* species) as a green manure cover crop may provide some biocontrol properties when they are incorporated into the soil. Upon decomposition, glucosinolates produced in the plant tissues convert to isothiocyanates, which can be toxic to soilborne pathogens including *Pythium* and nematode species (James et al. 2004; Zasada et al. 2012). However, results have been mixed.

To achieve adequate disease control, combinations of nonfumigant methods need to be investigated, possibly in rotation with fumigants or fungicides.

In forest nursery studies, James et al. (2004) found a dramatic increase in *Fusarium* species populations and seedling mortality following incorporation of *Brassica juncea*. It appeared that insufficient toxicity levels in combination with increased organic matter resulted in an unintended favorable environment for pathogens. Glucosinolate degradation products, including isothiocyanates, can also be phytotoxic and are known to inhibit seed germination and seedling growth (Haramoto and Gallandt 2005). Given the sensitivity of conifer seedlings to MITC, the impact of brassicaceous cover crops on crop germination and stunting cannot be discounted and should be considered in future experiments involving brassicaceous species for pathogen control.

Biological control. Most of the recent studies on the use of biological control agents in forest nurseries show they had little to no success in controlling root pathogens. Linderman et al. (2008), for example, tested 10 biological control agent formulations against damping-off caused by *Fusarium oxysporum* and *Pythium irregulare* in inoculated greenhouse-grown Douglas-fir seedlings. None was effective in reducing the incidence of damping-off. Similar observations were reported from other trials including field applications of biological control agents (Hildebrand et al. 2004; James et al. 2004), though there have been a few indications of success with biological control agents and mycorrhizae (Ocamb et al. 1997). Given the difficulty in achieving success, however, it is unlikely that biological control will play much of a role in nursery pest management without additional studies.

Abiotic environment modification. Solarization and application of steam are considered impractical for forest nurseries in the West, especially those in the relatively cool climates of western Oregon and Washington. Solarization can be somewhat effective in those areas, but is limited by the number of sunny days (Hildebrand 1989). For example, Pinkerton et al. (2002) found that populations of *Pythium*, *Phytophthora*, *Rhizoctonia* and *Cylindrocarpon*, but not *Fusarium*, were reduced in solarization studies involving strawberries and red raspberries in Oregon and Washington.

Although solarization did not eliminate all pathogens and its efficacy diminished with increasing soil depth (due to a decrease in ambient soil temperature), it might prove useful prior to fumigation with reduced-rate fumigants or in combination with bare fallow. Similarly, steam injection has some promise but requires significant energy and time inputs to be effective (James et al. 2004) and, when soils are cool and moist, it can be impossible to bring soil temperatures up to target levels for an adequate duration.

The most effective abiotic treatment by far is water management. Strategic irrigation timing and frequency, along with treatments to keep the soil well drained, are critical for disease management (Dumroese and James 2005).

Containerized production. Some growers have switched from direct sowing in nursery beds to sowing in small, containerized seedling plugs (e.g., miniplugs) or other containers (e.g., Cone-tainers or Styroblocks) in a greenhouse. In certain cases, hybrid production systems are used, in which seedlings are started in containers in a greenhouse and then transplanted into outdoor nursery beds. As long as some general sanitary precautions are taken (Dumroese and James 2005), containerized seedling production reduces some of the risks associated with soilborne pathogens and inclement weather and decreases the necessity for, or frequency of, soil fumigation.

Very young, succulent seedlings are considered the most susceptible to infection by soilborne pathogens. In the field, seed beds are fumigated annually to reduce the risk of damping-off. Disease risk is further reduced by using raised beds and warm planting temperatures to promote rapid germination and seedling establishment, and by preventing excessive succulence with lower levels of nitrogen fertilization. Containerized systems reduce disease risk by starting seeds in a clean, protected environment such as a greenhouse. Growers must use sterile containers and soilless media, clean irrigation water, and disinfested seeds. Once the seedlings have reached an appropriate size, they can be sold directly as container stock or transplanted into field beds to produce larger bareroot plants, although transplant beds require periodic fumigation. In a controlled, greenhouse environment, the seeds may be sown at an earlier date than in the field. If timed correctly, this process can remove 1 year from the production cycle (Riley and Steinfeld 2005).

In the West, approximately 25% of the forest nursery seedlings are produced in containers. The infrastructure needed to produce the additional 150 million seedlings in containerized systems would require a large expenditure of capital. Annual expenditures for heating, additional labor, and supplies (containers and planting media) would also be incurred and shipping costs would rise, as containerized seedlings are more expensive to ship due to their bulk and weight. As a result of these costs, containerized seedlings are consistently more expensive than bareroot stock. The price of similarly-sized containerized seedlings can be approximately double those of bareroot seedlings, while those from hybrid production systems (e.g., plug plus 1 year in transplant bed) can be up to 20% more expensive.

Research needs

As the forest nursery industry transitions away from methyl bromide, more knowledge is needed about a number of critical issues.

Pathogen identification. For the most part, methyl bromide's success limited research about the species identity of soilborne pathogens that commonly affect tree seedling production; as long as it was applied correctly, there was little need to identify the pathogens to achieve adequate control. In contrast, effective nonfumigant practices generally rely on accurate species identification and knowledge of pathogen biology.

Although it is generally known which genera cause disease (e.g., *Cylindrocarpon*, *Fusarium* and *Pythium*), little is known about which particular strains or species are pathogenic. Accordingly, caution should be used when interpreting soil population values as a criterion that fumigation needs to occur, or as a measure of treatment efficacy. Studies have demonstrated that high populations of *Fusarium* or *Pythium* do not always correlate with seedling damage and mortality (Hansen et al. 1990; Hildebrand et al. 2004), because the populations may include nonpathogenic isolates. What is more important to know is the proportion of pathogenic to nonpathogenic isolates within the soil population. The greater the number of pathogenic isolates in proportion to the nonpathogenic isolates, the greater the risk for disease.

Progress is being made on pathogen identification. Much of the groundwork was accomplished by R. L. James and colleagues, who identified pathogenic species of *Fusarium* and *Pythium* (e.g., James 2002). More recently, a number of new *Fusarium* and *Pythium* species have been described from forest nursery soils (Weiland 2011; Weiland et al. 2011), and research has identified eight *Pythium* species that are virulent pathogens of Douglas-fir seedlings (Weiland et al. 2013).

Tools have also been developed that distinguish between pathogenic and nonpathogenic isolates. Stewart et al. (2006), for example, found genetic markers that differentiated nonpathogenic isolates of *Fusarium oxysporum* from pathogenic isolates of *F. commune*. In addition, newer technologies (e.g., multi-pathogen detection arrays) are becoming available that allow for rapid screening of soil samples for multiple plant pathogens. Future research should continue to focus on the identification and differentiation of pathogenic and nonpathogenic species as well as the development of technologies to quickly evaluate soil populations for their potential to cause disease.

As the forest nursery industry transitions away from methyl bromide, combining nonfumigant methods such as container production with fumigants will provide the best strategy for disease control. Above, container production in the Weyerhaeuser Rochester Greenhouse, Rochester, WA.

Pathogen monitoring. Pathogen populations may shift in response to new fumigant chemistries and rates, or in response to changes in disease management methods. For example, reduced-rate formulations may select for pathogens that can survive lower doses of fumigant, thus increasing the risk for developing pesticide resistance. Similarly, new pathogens, or previously minor pathogens that were controlled by methyl bromide, may become problematic if they are less sensitive to other fumigant chemistries. Many alternative disease control methods are new to the forest nursery industry and have been tested under a relatively narrow range of environmental conditions; their long-term impacts on pathogen populations remain unknown. Periodic monitoring for newly emergent pathogens should help the industry avoid unexpected losses.

There is little information about the movement of soilborne pathogens from nursery to nursery on infested planting stock. Hansen et al. (1979) found evidence that this has occurred in the Pacific Northwest forest nursery industry, but additional research is needed to fully evaluate the risks. This issue is particularly important given the experience of the ornamental nursery industry with *Phytophthora ramorum* and may become even more pressing if the movement of planting stock among forest nurseries increases in response to nursery closures. In the meantime, nurseries that receive stock should carefully inspect for evidence of disease.

Spring fumigants. Many private nurseries in the region rely on fall fumigation to ensure that enough land is available to meet spring production demands. However, customer orders continue to arrive throughout the winter months and additional land may need to be fumigated in the spring. There is little evidence about whether alternative fumigants perform as well as methyl bromide under spring environmental conditions. Phytotoxic effects may be observed if the fumigants linger in cool, moist soil for long periods of time; dazomet, for example, can damage young seedlings when applied in spring immediately before planting (James 2002).

Soil temperatures higher than 50°F (10°C) are also needed before dazomet and other MITC agents become active. These soil temperatures are often not reached until mid-April at some nurseries, and fumigation at that time would push back sowing to mid- or late May, resulting in a shorter growing season and smaller seedlings. Several of the new fumigant chemistries appear to be adequate for fall fumigation; however, research is critically needed to evaluate their appropriateness for spring fumigation.

Precision application. Additional research is warranted into precision fumigation, which involves the modification of equipment to more precisely deliver fumigants at the desired rate and injection depth to specific locations within a field (Sances et al. 2008; Upadhyaya et al. 2009).

Precision fumigation uses GPS technology, coupled to a shank-type applicator, to determine the correct location in the field to begin and end fumigation. Although these technologies are at the beginning stages of development and testing, they could eventually play an important role in reducing the amount of applied fumigant and may be particularly valuable in testing the feasibility of bed fumigation for the forest nursery industry. One estimate from an early prototype indicated that fumigation rates could be reduced by approximately 50% (Upadhyaya et al. 2009).

Integrated pest management. Perhaps the most important research need is the continued development of integrated pest management (IPM). Used alone, many alternative methods of soilborne pest control may never be as effective as methyl bromide. However, if they can be coordinated into a cohesive integrated pest management program, successful pest control might be achieved. Weiland et al. (2011), for example, found promising results in nurseries that used bare fallow in combination with reduced-rate fumigants under VIF.

To be sure, integrating multiple approaches is more complicated than traditional methyl bromide fumigation, but given the political and public emphasis on environmental health and sustainability, it is likely that government agencies will continue to strictly regulate fumigant application. Integrating nontoxic methods to limit pathogen establishment and population growth (e.g., bare fallow, proper irrigation practices and drainage, and recycled water treatment) and practices that reduce fumigant use without compromising disease control (e.g., low-permeability plastic films and reduced-rate fumigant formulations) appears to be the best strategy at this time. Furthermore, as pathogen identification technologies improve, it will become possible for nursery managers to tailor a program to target soilborne pests that predominate at their location.

Research on the risks associated with the absence of any disease control treatment over an extended period of time (i.e., > 2 years) would enhance the usefulness of information from integrated pest management studies. Data from long-term, nontreated field plots could be used to determine the pathogen-carrying capacity of nursery soils, examine the likelihood of developing disease-suppressive soils, and establish whether there are natural fluctuations in pathogen populations that can be exploited to enhance disease control.

Progress and outlook

In 1994, Linderman et al. reported research priorities for the forest and ornamental nursery industries as identified from the 1993 USDA workshop on methyl bromide alternatives. The short-term priorities were to develop 1) new chemicals (including fumigants), chemical application technologies and optimal application rates; 2) integrated pest management systems integrating existing chemical, cultural, physical and biological control practices; and 3) new crop production systems. For the most part, many nurseries are still not using alternative fumigants because of cost and the perceived inconsistencies in control. Growers are also wary about the continued availability of alternative fumigants given frequent changes in environmental regulations and fumigant application rules. Although not established yet, optimal application rates for alternative fumigant chemistries are being developed as new technologies (precision delivery, low-permeability plastic films) are combined with reduced fumigant rates in field trial evaluations. However, until all fumigant chemistries are taken off the market, there will likely be little progress in developing an integrated pest management system that does not include some component of soil fumigation for bareroot seedling production. Forest nurseries in Canada, and a few in the United States, have transitioned to containerized production successfully. Nevertheless, the current demand for seedlings in the United States cannot be met by the existing infrastructure for container seedling production.

Long-term priorities identified by Linderman et al. (1994) included pest-resistant hosts, safer chemicals that target specific pests, biological control, soil solarization, and pasteurization or other heat treatment methods. Interest was also expressed in the detection of pest populations and forecasting pest damage. Unfortunately, there has been little progress toward these goals. To our knowledge, little to no research has been conducted regarding genetic host resistance against soilborne pests; most resistance-screening programs have targeted host-specific pathogens such as the foliar and stem rusts of pine. Heat treatment and biological control methods have been tested and are considered too expensive, impractical, or of limited efficacy at this stage of development (Hildebrand 1989; James et al. 2004; Pinkerton et al. 2002). However, new pesticide chemistries are continuously being tested for their efficacy against specific pests (Zasada et al. 2012), and progress is being made in pathogen identification and detection (Weiland 2011; Weiland et al. 2013).

In many ways, the forest nursery industry is still in the same position as almost 20 years ago; many growers still rely on methyl bromide, and the fumigant is expected to be eliminated in the near future. The range of environments, crops and pest species makes it nearly impossible to develop a single, nationwide solution for forest nursery pest management that will replace methyl bromide. In the short term, many will opt to continue using methyl bromide until it is completely removed from the market. Once it has been eliminated, growers will likely switch to alternative fumigant chemistries, which offer broader pesticidal activity and better consistency in control than currently available nonchemical disease control strategies. If fumigation is ever completely eliminated as a pest control strategy, one potential solution would be container production. A second alternative would be to attempt bareroot production in the absence of fumigation by using the best integrated pest management methods available, which would likely include a concomitant increase in herbicide and fungicide use. However, it is generally assumed that this strategy would be largely ineffective and result in significantly fewer and smaller seedlings of lesser quality.

The current challenge is to integrate newer, promising pest control measures (alternative fumigant chemistries and application methods) with existing nursery practices (field preparation, soil moisture and fertility management, seedling densities) and nonfumigant disease control measures (bare fallow, fungicide application) to achieve a successful pest management program. Each of these separately can provide a certain amount of pest control. However, coming up with the optimal combination of strategies that will work under the widest range of conditions and locations will be difficult.

Continued support from the forest nursery industry, as well as state and federal agencies and research universities is critical for conducting the necessary research and will ensure that healthy seedlings will continue to be produced for restocking U.S. forest lands.

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RESEARCH ARTICLE

Monitoring soil carbon will prepare growers for a carbon trading system

by Emma C. Suddick, Moffatt K. Ngugi, Keith Paustian *and* Johan Six

California growers could reap financial benefits from the low-carbon economy and cap-and-trade system envisioned by the state's AB 32 law, which seeks to lower greenhouse gas emissions statewide. Growers could gain carbon credits by reducing greenhouse gas emissions and sequestering carbon through reduced tillage and increased biomass residue incorporation. First, however, baseline stocks of soil carbon need to be assessed for various cropping systems and management practices. We designed and set up a pilot soil carbon and land-use monitoring network at several perennial cropping systems in Northern California. We compared soil carbon content in two vineyards and two orchards (walnut and almond), looking at conventional and conservation management practices, as well as in native grassland and oak woodland. We then calculated baseline estimates of the total carbon in almond, wine grape and walnut acreages statewide. The organic walnut orchard had the highest total soil carbon, and no-till vineyards had 27% more carbon in the surface soil than tilled vineyards. We estimated wine grape vineyards are storing significantly more soil carbon per acre than almond and walnut orchards. The data can be used to provide accurate information about soil carbon stocks in perennial cropping systems for a future carbon trading system.


Robert Rousseau

In an analysis of baseline soil carbon content in conventional and organic almond, walnut and wine grape acreages, researchers found that the organic walnut orchard had the highest total soil carbon. *Above*, a conventional almond orchard at Arbuckle, Colusa County.

California is the nation's most economically important state in terms of agricultural production, which was valued at $43.5 billion in 2011 (USDA NASS 2012). Of the 43 million acres of agricultural land in California, 37% (16 million acres) is grazed. Of the remaining cropland, three-quarters (20 million acres) is intensively irrigated, producing many varieties of annual row crops as well as high-value specialty perennial crops such as almonds and grapes. However, climatic changes, including rising temperatures and changing precipitation patterns associated with rising anthropogenic greenhouse gases, could pose a serious threat to crops in California (Hayhoe et al. 2004; Lee et al. 2011), and may influence the types and management of crops that can be grown in the state in the future.

To avert the detrimental effects of climate change in California, the state passed the California Global Warming Solutions Act of 2006 (AB 32). This legislation requires greenhouse gas emissions to be reduced to 1990 levels by 2020. Participation is currently voluntary for the agricultural industry but could possibly be made mandatory if measuring and monitoring protocols for agricultural emissions become more defined in the future.

Crop growers may be able to benefit from AB 32 by receiving financial incentives to implement agricultural practices that will reduce their greenhouse gas emissions, sequester carbon and assist the state in its quest to reach the 2020 emissions targets (Suddick et al. 2010). Further financial incentives may arise from a greenhouse gas emissions cap-and-trade or carbon credit system, where the industrial sector (including electricity, manufacturing and transportation) may purchase greenhouse gas emission offsets from crop growers instead of, or in addition to, directly reducing their own emissions (UCS 2009).

Implementing a carbon credit system for agriculture would require a systematic method to accurately measure and account for agricultural greenhouse gas reductions and to quantify the amount of carbon stored in agricultural soils. However, little is known about greenhouse gas emissions from, and carbon

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sequestration potentials of, California's agricultural lands, especially for high-value specialty perennial crops such as walnuts, almonds and wine grapes (Suddick et al. 2011). Likewise, little is known about how changes in land management affect the total soil carbon content of the state's agricultural soils. Again, this is especially true for high-value specialty perennial crops (Suddick et al. 2010).

Monitoring soil carbon

Because perennial crops are drastically underrepresented in terms of carbon stock estimates and surveys, we developed and implemented a long-term soil carbon monitoring network for three high-value specialty perennial crops (walnuts, almonds and wine grapes) under various management practices and soil types in Northern California.

Long-term monitoring is needed because small changes in soil organic matter (SOM), which is the decomposed fraction of plant and animal residues that contributes to the overall productivity level of soils and its carbon content, is generally difficult to measure accurately over short periods due to the large background carbon stock already in the soil. Long-term monitoring will produce a time series of measurements that could be used in conjunction with process-based biogeochemical models (such as the CENTURY soil organic matter model; DayCent, the daily time step version of CENTURY; and the denitrification and decomposition, DNDC, model).

These models use mechanistic equations to represent plant growth, nutrient use and availability, water, soil carbon dynamics and greenhouse gas emissions, using data collected at the local farm scale or local data scaled up to a regional scale. Such models provide the predictive capabilities that are needed to evaluate and assess how soil carbon storage may be affected by any future alternative management and land-use change scenarios as well as by environmental factors. The inclusion of more field data from a long-term monitoring study (such as the one described here) will enhance the capacity of these models to predict future impacts of land use, especially for crops not measured previously, like the perennial crops in this study. Furthermore, time series provide the most rigorous validation data, leading to unbiased confidence in model outputs (Paustian et al. 2009).

Here, we outline methodology to provide verifiable estimates of current soil carbon stocks in perennial crops in Northern California. Our approach is built on methods described by Paustian et al. (2000) and Ogle et al. (2006). We also suggest how the data collected can be further used in voluntary carbon reporting using a greenhouse gas and carbon management accounting tool such as the CarbOn Management Evaluation Tool — Voluntary Reporting (COMET-VR). An online management tool, COMET-VR provides a simple, reliable method to estimate soil carbon sequestration based on estimates of annual soil carbon flux from the CENTURY model (Paustian et al. 2009). The CENTURY model is a biogeochemical model that estimates how changes in land management affect soil carbon. To help improve the accuracy of the COMET-VR accounting tool and the CENTURY model, baseline soil carbon stocks for California agricultural systems need to be assessed, especially for perennial crops, which have previously not been modeled due to lack of data required for model validation and calibration. Furthermore, the data collected during this study could ultimately be used in other databases that may be set up for a carbon credit trading system.

The main objectives of this study were to establish a pilot soil monitoring network that accounts for current and future soil carbon stocks in perennial cropping systems and allows comparison with soil carbon stocks in native ecosystems such as oak woodland and grassland in Northern California. To maintain the network, scientists will need to revisit the same sites at regular intervals, such as every 5 years. The long-term purpose of the network is to improve sequestration rate estimates by monitoring how land-use changes and land management practices affect soil carbon stocks over time, rather than providing single data points in time on soil carbon stores.

In addition, because soil carbon is linked with soil quality, understanding relationships between soil carbon and other soil quality indicators is needed to understand or accurately predict carbon

Wine grapes already store a great amount of carbon under current land use in California.


Robert Rousseau

Developing baseline soil carbon estimates is the essential first step that will allow growers to calculate their carbon sequestration rate. *Above*, M.K. Ngugi with GPS marker ball at Dixon Ridge Farms, Winters.

storage and carbon loss in agricultural land. The cycling of carbon and nitrogen in soils is intrinsically linked, and nitrogen, like carbon, is a critical component of soil organic matter. Therefore, we also gathered data on how management practices and land use affect nitrogen content, bulk density, coarse or fine texture, pH and soil moisture.

Here we present the initial baseline data collected.

Field sites

In early 2008, we established four field sites (an almond orchard, two wine grape vineyards and a walnut orchard) in four counties in Northern California (fig. 1, table 1). We chose high-value specialty perennial cropping systems because they are severely underrepresented in inventories of greenhouse gases and soil carbon stocks. We also sampled oak woodland and native grassland near one of the vineyard sites. At each site, we studied various agronomic management practices associated with the crop, such as cover cropping, no tillage, and conventional and organic farming (table 2).

Nickels almond orchard. We chose an almond orchard at Nickels Soil Laboratory, Arbuckle, Colusa County, and sampled both a conventionally managed orchard block under microsprinkler irrigation and an organically managed orchard block that was newly established (less than 3 years old).

Burke vineyard. The Burke Ranch vineyard in Amador County had two treatments: conventional tillage and no tillage.

Burke native sites. For comparison with the cultivated sites, we also sampled oak woodland and native grassland in the Burke Ranch property in Amador County. The two native sites provide a comparison between land currently under agricultural management and land undisturbed by any management. Additionally, these sites will provide a baseline for carbon and nitrogen stocks should the native sites be converted to agriculture in the future, thus providing an estimate of carbon (and nitrogen) loss following conversion to agriculture.

Dixon walnut orchard. We chose a conventionally managed walnut orchard block at Dixon Ridge Farms in Winters, Solano County, that was homogenously tilled and had not had a cover crop planted for the past 20 years. Also at Dixon Ridge Farms, we chose an organically managed walnut orchard block that was adjacent to the conventional block. The organic walnut block was subdivided into three areas, with three regimes of waste orchard biomass and compost applications: (1) 1 ton of walnut shells and orchard waste prunings added with compost, (2) 3 tons of walnut shells added with compost and (3) cover crop and compost added.

Oakville vineyard. The vineyard at the Oakville Research Station, Oakville, in Napa County, had many management treatments, including old and new cover cropping practices, dry farming and established old and new clean cultivation management.

Soil monitoring network

We created a soil network consisting of a total of 95 microplots over the three production systems. Each microplot consists of an equilateral triangle that is 6.6 feet (2 meters) on each side and from

TABLE 1. Characteristics of four perennial cropping sites, soil carbon monitoring study, 2008

Site characteristics	Nickels Soil Laboratory (almond)	Burke Ranch (vineyard)	Dixon Ridge Farms (walnut)	Oakville Research Station (vineyard)
City, county	Arbuckle, Colusa County	Plymouth, Amador County	Winters, Solano County	Oakville, Napa County
Latitude, longitude	38° 57′ 30″ N 122° 4′ 18″ W	38° 29′ 23″ N 120° 47′ 53″ W	38° 31′ 29″ N 121° 54′ 3″ W	38° 25′ 55″ N 122° 24′ 48″ W
Crop	Almonds	Wine grapes	Walnuts	Wine grapes
Mean annual temperature	16 °C	17 °C	17 °C	15 °C
Total annual precipitation	16.89 inches	22.99 inches	22.83 inches	24.69 inches
Soil type	Arbuckle sandy loam, 1–5% slope (150[*]) and Hillgate loam 1–5% slope (147[*])	Ahwahnee loam, 9–16% slope (AaC2[*])	Brentwood clay loam, 0–2% slope (BrA[*]) Yolo loam (Yo[*]) and Yolo silty clay (Ys[*])	Bale loam, 0–2% slope (103[*])
Coarse fraction (greater than 2 mm)	5.44 ± 4.08%	3.62 ± 3.49%	0.05 ± 0.01%	4.3 ± 2.3%
Taxonomic class	Fine loamy, mixed, superactive, thermic Typic Haploxeralfs and fine, smectitic, thermic Typic Palexeralfs	Coarse loamy, mixed, active, thermic Mollic Haploxeralfs and loamy, mixed, superactive, thermic Lithic Haploxerepts	Fine, smectitic, thermic Typic Haploxerepts and fine silty, mixed, superactive, nonacid, thermic Mollic Xerofluvents	Fine loamy, mixed, superactive, thermic Cumulic Ultic Haploxerolls

[*] Soil mapping unit from Natural Resources Conservation Service (NRCS) soil survey.

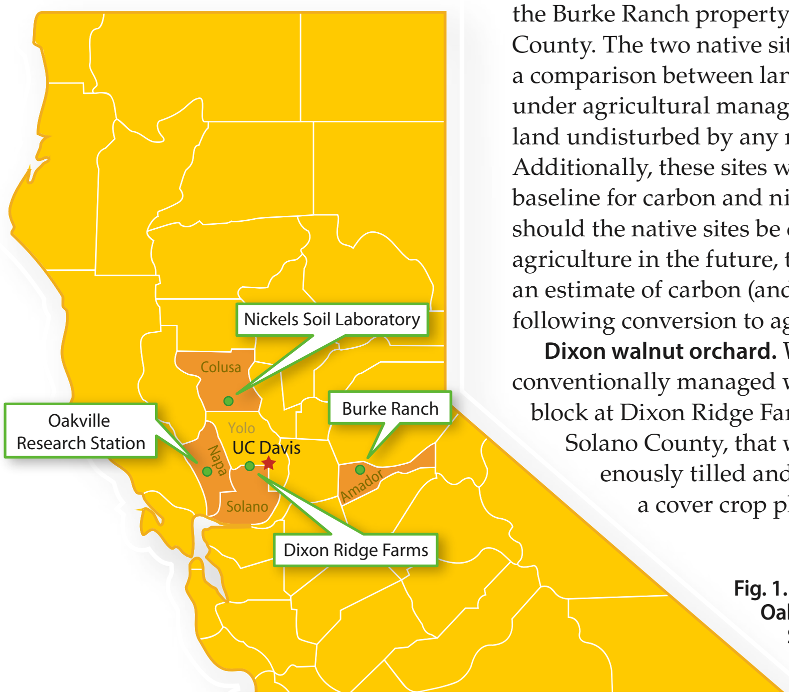

Fig. 1. Soil carbon sampling sites: vineyard at Oakville Research Station, Oakville, Napa Valley; walnut orchard at Dixon Ridge Farms, Winters, Solano County; almond orchard at Nickels Soil Laboratory, Arbuckle, Colusa County; vineyard at Burke Ranch, Plymouth, Amador County.

which three core samples are taken (fig. 2). This design is a modification of a protocol described by Ogle et al. (2006) that has been proposed as a method to be used for a nationwide soil monitoring network in the United States. A similar approach to both this study and the study by Ogle et al. (2006) was developed in western Canada for long-term monitoring of soil carbon on farms (Ellert et al. 2002). The triangular microplots are geo-referenced using a global positioning system (GPS) receiver that provides the exact spatial location and coordinates to allow precise resampling over time, thus helping to minimize the impact of spatial variability on measured soil carbon stock changes over time (Lark 2009).

Microplots. We chose to take three cores per microplot based on an analysis by Conant and Paustian (2002). The analysis showed that, when the number of cores is fixed, this triangular configuration is the most efficient way to minimize the coefficient of variation both within and between microplots. We used the triangular microplot design (fig. 2) in the walnut and almond orchards, woodland, and grassland. The apexes of all of the triangles pointed north (fig. 2), and we buried marker balls (Electronic Marker System, 3M Corp., Austin, TX) at the apex points to allow precise relocation of the microplots in the future. Each marker ball has a unique self-leveling transmitter inside it. When used with the locator (3M Dynatel Locator, 3M Corp., Austin, TX), the transmitter sends a signal between the marker ball and the locator, returning the exact location of the marker ball. The triangle design was not appropriate for vineyards because the rows were too narrow, so instead we took three replicate core samples over the length of the study rows. We buried a marker ball at the end of each vineyard row sampled and recorded how far each soil core sample was from the marker ball.

Soil samples. We took soil samples that were 1.5 inches (3.8 centimeters) in diameter and 3.28 feet (1 meter) deep from a number of microplots established for each site (table 1) with a Geoprobe (Geoprobe Systems, Salina, KS), a direct-push hydraulically powered sampler. Samples in many previous studies on soil organic matter have been derived mainly from the upper 11.8 inches (30 centimeters) of soil, where management-induced changes to soil carbon generally occur. However, over a relatively long time period, the effects of changes in land use and management may be seen only at much deeper depths.

Three cores per microplot (with the initial sampling taken at each of the triangle apices) were taken and analyzed by increments in depth: top depth, 0 to 7.9 inches (0 to 20 centimeters); middle depth, 7.9 to 19.7 inches (20 to 50 centimeters); and deepest depth, 19.7 to 39.4 inches (50 to 100 centimeters). Samples were air dried in labeled plastic zip-top bags, sieved to less than 2 millimeters, and analyzed using standard methods for pH (1:1 H_2O), total carbon and nitrogen (flash combustion and chromatographic separation, COSTECH), bulk density and soil moisture (Sparks 1996). Total soil nitrogen was measured as another indicator of soil quality.

Texture analysis was carried out by the Agriculture and Natural Resources Analytical Laboratory particle size analysis hydrometer method (Sheldrick and Wang 1993). Samples were then stored and archived for potential re-analysis at a future date. By archiving the soil samples, any new methodologies to measure soil carbon that may be devised in the future may be calibrated against soil samples already analyzed with previously established methods (Post et al. 2001).

Soil quality indicators

To characterize the current soil quality in the perennial cropping systems sampled in this study, we measured basic parameters such as soil pH, bulk density and moisture (table 3).

pH. The pH was typically between a slightly acidic 6.1 to a slightly alkaline 7.9, and tended to increase with depth. All treatments at the wine grape vineyards and almond orchards had a soil pH between 6.1 and 7.4, which generally makes soil nutrients such as nitrogen and phosphorus more readily soluble and so more available to crops. All treatments at the walnut orchard in Dixon Ridge Farms had a soil pH above pH 7.5, which is slightly higher than the optimum soil pH for walnuts of 6.5 to 7.2.

Bulk density. The bulk density was calculated based on the less-than-2-millimeter fraction of the soil collected. Coarse particles that did not pass through a

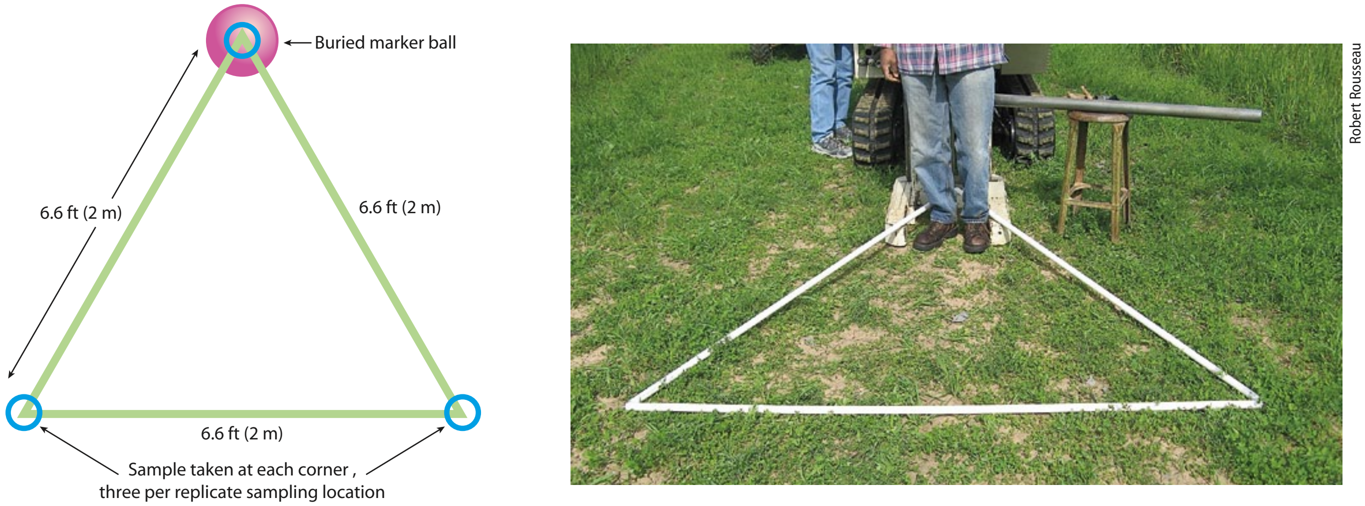

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Fig. 2. Triangle layout for sampling soil cores. One core was sampled at 3.3 feet (1 meter) depth at each corner of the triangle, and the marker ball was buried 3.3 feet deep at the north point of the triangle. GPS locations were recorded for each corner of the triangle.

2-millimeter sieve (after some crushing) were also weighed, and the percentage of coarse fraction for the bulk soil samples was calculated (table 1). Because average coarse fractions were under 5% for most sites, fine bulk density was calculated for all soil samples at each site.

Values of bulk density (table 3) are necessary in order to convert the percentage total soil carbon obtained in the laboratory into a mass per unit area value (short ton carbon acre^{-1}). Bulk density was also measured as an indicator for the level of compaction present in the soils at each sampling location; a high bulk density indicates low soil porosity and compaction of soil, which may result in soil erosion and poor plant growth and reduced yields due to shallow root growth. Bulk density is related to soil organic matter content: a soil containing high carbon and organic matter has a low bulk density.

Bulk density ranged from 1.10 to 1.79 g cm^{-3} at the top depth, was lowest in the Oakville vineyard with the cover cropped treatments (mowed only, tilled only, and mowed and tilled), and was highest in the Nickels conventional almond orchard. The bulk density generally increased with soil depth for all croplands under the various management practices. This was particularly true for the walnut orchard at the Dixon Ridge Farms site, where bulk density at the deepest depth was high, ranging from 1.52 to 1.61 g cm^{-3} in the organic blocks and 1.41 g cm^{-3} in the conventional block. The exceptions were the Nickels, Oakville and Burke sites, where bulk density was higher in the middle layer than in the top or deeper soil layers. Bulk density in the middle layer ranged from 1.23 to 1.90 g cm^{-3}; the lower values were in the cover crop mowed and tilled plot at the Oakville vineyard, and the upper values were in the conventional plot at the Nickels almond orchard.

The bulk density data suggest that there may be a plow pan layer, which is a hard layer of subsoil or clay, at the middle depth at the vineyard and almond sites. The presence of a plow pan layer would be consistent with the soil types at these sites, which have a well-developed subsoil, or Bt horizon, which indicates the accumulation of silicate clay in these soils. A plow pan layer can also be associated with tillage practices, including disking, plowing and mowing, which can cause soil compaction and damage to the soil structure as heavy machinery passes over the soil. This may explain the high bulk density values within the vineyard sites as they were all subjected to some tilling. Additionally, the organic orchard at the Nickels site was approximately 3 years old at the time of sampling, and the high bulk density observed within the middle soil layer may be a result of disking and plowing practices that occurred approximately when the organic orchard was planted, although the conventional block at Nickels also had a high bulk density, which is more typical in sandy soils like those at Nickels.

Soil moisture. Soil moisture ranged from 2.6% (Burke grassland) to 24.6% (Dixon Ridge Farms) in the top depth of the soil. The sandy soils present at both the Nickels almond orchard and the Burke Ranch site resulted in the lowest soil moisture of all of the study sites (table 3). The three organic walnut blocks at Dixon Ridge Farms, all had higher soil moisture than the conventional block. This is most likely due to the application of the walnut shells and compost, which when left on the soil surface reduces the loss of moisture through the reduction of evapotranspiration.

Baseline soil carbon and nitrogen

Here, we report baseline carbon and nitrogen values as the mass of carbon or nitrogen per unit area of soil (table 3), calculated using bulk density measurements at each of the three depth increments for all sites and all management practices (fig. 3).

Carbon stocks. At the top depth, carbon totals ranged from 10.30 to 24.58 short ton acre^{-1} (23.06 to 55.05 Mg ha^{-1}, mean 36.86 ± 8.15 Mg ha^{-1}) (mean 16.46 ± 3.40 short ton

TABLE 2. Management practices and site abbreviations, soil carbon monitoring study, 2008

Site	Crop	Management practice	Management practice description	Site abbreviation
Nickels	Almonds	Conventional	Synthetic herbicides, pesticides and nitrogen fertilizers, microsprinkler irrigation	Nic_Con
		Organic	Manures and composts as source of nitrogen	Nic_Org
Burke	Wine grapes	Tilled	Tilled, drip irrigation	Bur_T
		No-till	No tillage, drip irrigation	Bur_NT
	Grassland	None	Left to grow naturally	Bur_Gr
	Woodland	None	Left to grow naturally	Bur_Wd
Dixon Ridge Farms	Walnuts	Organic 1	Compost 36–45 kg (80–100 lb) N, 1 ton walnut shells	DRF_W
		Organic 2	Compost 36–45 kg (80–100 lb) N, 3 tons walnut shells	DRF_W3
		Organic 3	Compost 36–45 kg (80–100 lb) N, cover crop added	DRF_CC
		Conventional	Synthetic herbicides, pesticides and nitrogen fertilizers, microsprinkler irrigation	DRF_Con
Oakville	Wine grapes	Cover crop mowed only	Grown with winter cover crop, mowed in spring	OakCC_M
		Cover crop tilled only	Grown with winter cover crop, tilled in spring	OakCC_T
		Cover crop mowed and tilled	Grown with winter cover crop, mowed in spring, cover crop incorporated by tillage	OakCC_MT
		Dry farmed	Limited irrigation, light tillage to keep soil surface moist	Oak_DF
		Clean cultivated	Clean cultivation removes all ground vegetation and leaves soil bare	Oak_CCul
		New clean cultivated	Newly established clean cultivated	Oak_NCCul
		New cover crop	Newly established winter cover crop	Oak_NCC

TABLE 3. Soil parameters for the different management regimes at each of the four sites

Site and crop	Management practice	Number of microplots*	Depth	Soil moisture	pH	Bulk density	Soil N†	Soil carbon†	C:N ratio
			inches	*%*		*g cm^{-3}*	·········· *Mg ha^{-1}* ··········		
Nickels Almonds	Conventional	8	0–7.9	4.2 (2.04)‡	7.3 (0.16)	1.79 (0.09)	2.10 (0.30)	25.46 (5.52)	11.8 (1.74)
			7.9–19.7	6.3 (2.11)	7.4 (0.21)	1.90 (0.08)	1.95 (0.73)	24.26 (10.95)	12.5 (3.44)
			19.7–39.4	7.5 (2.38)	7.4 (0.15)	1.32 (0.24)	1.91 (0.52)	26.70 (10.22)	13.6 (4.33)
	Organic	4	0–7.9	8.5 (4.78)	6.8 (0.15)	1.69 (0.05)	2.01 (0.14)	23.06 (3.79)	11.5 (1.98)
			7.9–19.7	10.5 (5.21)	7.2 (0.21)	1.87 (0.14)	1.94 (0.28)	16.40 (6.52)	8.8 (5.09)
			19.7–39.4	9.0 (2.14)	7.4 (0.11)	1.60 (0.28)	2.69 (1.27)	42.68 (57.27)	11.2 (8.71)
Burke Wine grapes	Tilled	11	0–7.9	4.3 (1.25)	6.2 (0.33)	1.46 (0.21)	2.91 (1.25)	29.32 (8.51)	10.9 (1.65)
			7.9–19.7	7.1 (2.02)	6.6 (0.34)	1.60 (0.08)	2.16 (0.58)	22.95 (4.37)	11.6 (2.11)
			19.7–39.4	7.3 (1.97)	7.0 (0.33)	1.43 (0.47)	2.36 (1.69)	18.24 (7.51)	10.8 (8.50)
	No-till	14	0–7.9	2.8 (1.16)	6.4 (0.26)	1.37 (0.41)	5.07 (6.49)	36.44 (17.40)	11.0 (1.53)
			7.9–19.7	5.4 (1.49)	6.7 (0.31)	1.49 (0.19)	7.40 (12.38)	27.45 (22.52)	10.0 (2.45)
			19.7–39.4	6.3 (3.35)	6.5 (1.90)	1.02 (0.44)	5.87 (14.16)	11.04 (7.52)	10.9 (13.01)
Burke Woodland	No management	3	0–7.9	2.7 (1.26)	6.6 (0.20)	1.33 (0.12)	3.06 (0.52)	43.88 (8.91)	14.42 (0.73)
			7.9–19.7	3.8 (1.15)	6.5 (0.31)	1.64 (0.13)	6.40 (8.41)	25.07 (9.46)	12.1 (2.30)
			19.7–39.4	3.5 (1.22)	6.6 (0.28)	1.11 (0.31)	1.10 (0.38)	15.08 (2.26)	17.0 (2.65)
Burke Grassland	No management	3	0–7.9	2.6 (0.53)	6.2 (0.15)	1.42 (0.06)	3.24 (0.59)	39.82 (6.76)	12.5 (0.80)
			7.9–19.7	4.7 (0.57)	6.4 (0.24)	1.76 (0.02)	2.15 (0.70)	24.73 (4.86)	12.3 (2.52)
			19.7–39.4	6.0 (1.14)	6.6 (0.22)	1.12 (0.18)	0.64 (0.60)	6.17 (5.41)	11.9 (4.25)
Dixon Ridge Farms Walnuts	Organic 1	4	0–7.9	24.6 (2.16)	7.6 (0.06)	1.30 (0.04)	5.32 (0.40)	51.62 (4.37)	9.7 (0.41)
			7.9–19.7	22.5 (2.09)	7.7 (0.07)	1.48 (0.06)	5.03 (0.64)	41.97 (7.17)	8.3 (0.45)
			19.7–39.4	22.0 (4.77)	7.7 (0.06)	1.52 (0.07)	6.82 (0.51)	54.68 (4.46)	8.1 (0.46)
	Organic 2	4	0–7.9	19.7 (0.80)	7.6 (0.04)	1.37 (0.05)	4.36 (0.39)	41.52 (3.90)	9.5 (0.23)
			7.9–19.7	20.7 (1.19)	7.7 (0.08)	1.56 (0.04)	4.57 (0.77)	33.20 (6.70)	7.3 (0.52)
			19.7–39.4	20.1 (1.22)	7.7 (0.04)	1.61 (0.02)	6.43 (1.49)	38.67 (9.67)	6.1 (1.25)
	Organic 3	4	0–7.9	21.3 (0.48)	7.7 (0.04)	1.28 (0.03)	5.23 (0.31)	55.05 (4.74)	10.5 (0.30)
			7.9–19.7	20.9 (0.52)	7.7 (0.10)	1.50 (0.04)	5.47 (1.12)	50.06 (13.93)	9.0 (0.41)
			19.7–39.4	20.9 (0.79)	7.8 (0.06)	1.56 (0.06)	6.89 (0.96)	57.00 (12.94)	8.3 (0.91)
	Conventional	12	0–7.9	15.9 (1.75)	7.9 (0.09)	1.32 (0.06)	3.92 (0.24)	38.16 (3.49)	9.7 (0.57)
			7.9–19.7	16.9 (1.65)	7.8 (0.06)	1.38 (0.04)	3.96 (0.53)	36.77 (4.04)	9.4 (0.91)
			19.7–39.4	17.5 (1.68)	7.8 (0.04)	1.41 (0.13)	5.29 (1.07)	46.09 (9.18)	8.8 (0.70)
Oakville Wine grapes	Cover crop mowed	3	0–7.9	22.2 (0.84)	6.9 (0.15)	1.10 (0.05)	2.20 (0.11)	34.11 (3.25)	15.56 (2.17)
			7.9–19.7	24.2 (0.15)	6.9 (0.27)	1.31 (0.07)	3.93 (0.20)	51.02 (2.85)	13.00 (0.33)
			19.7–39.4	27.2 (0.97)	6.9 (0.41)	1.10 (0.10)	5.48 (0.51)	54.87 (11.39)	10.00 (1.76)
	Cover crop tilled	3	0–7.9	23.3 (0.80)	6.8 (0.25)	1.11 (0.01)	2.23 (0.02)	36.47 (2.37)	16.39 (1.08)
			7.9–19.7	24.1 (0.60)	6.8 (0.27)	1.28 (0.03)	3.85 (0.10)	49.52 (5.58)	11.56 (3.37)
			19.7–39.4	26.6 (1.83)	6.9 (0.14)	1.23 (0.07)	6.14 (0.35)	53.32 (6.36)	8.67 (0.58)
	Cover crop mowed and tilled	3	0–7.9	23.1 (0.37)	6.7 (0.18)	1.13 (0.03)	2.26 (0.06)	33.47 (1.10)	14.83 (0.60)
			7.9–19.7	24.6 (0.46)	7.0 (0.24)	1.23 (0.07)	3.70 (0.22)	49.80 (5.01)	13.44 (1.07)
			19.7–39.4	27.5 (1.51)	7.1 (0.20)	1.07 (0.08)	5.33 (0.39)	51.79 (4.06)	9.72 (0.54)
	Dry farmed	4	0–7.9	12.5 (0.54)	6.2 (0.09)	1.22 (0.04)	3.21 (0.20)	36.27 (3.97)	11.3 (0.55)
			7.9–19.7	16.6 (0.81)	6.5 (0.07)	1.30 (0.08)	3.90 (0.16)	41.68 (4.13)	10.7 (0.68)
			19.7–39.4	17.9 (0.90)	6.6 (0.07)	1.09 (0.10)	4.09 (0.58)	43.21 (5.03)	10.6 (0.19)
	Clean cultivated	8	0–7.9	14.5 (1.58)	6.3 (0.09)	1.25 (0.13)	3.08 (0.26)	33.37 (2.95)	10.8 (0.36)
			7.9–19.7	16.8 (1.97)	6.4 (0.17)	1.56 (0.11)	4.81 (0.29)	49.56 (4.57)	10.3 (0.55)
			19.7–39.4	17.3 (1.64)	6.7 (0.05)	1.57 (0.09)	5.58 (1.06)	47.41 (13.11)	8.3 (1.07)

* Number of microplots sampled.

† To convert from metric units (Mg ha^{-1}) to English units (short tons acre^{-1}), multiply the metric value by 0.4465.

‡ Standard deviations in parentheses.

Continued on next page

TABLE 3 (*continued*). Soil parameters for the different management regimes at each of the four sites

Site and crop	Management practice	Number of microplots*	Depth	Soil moisture	pH	Bulk density	Soil N†	Soil carbon†	C:N ratio
			inches	*%*		*g cm^{-3}*	·········· *Mg ha^{-1}*	··········	
Oakville Wine grapes (*continued*)	New clean cultivated	3	0–7.9	11.7 (0.08)‡	6.2 (0.14)	1.16 (0.07)	3.33 (0.28)	36.67 (3.95)	11.0 (0.30)
			7.9–19.7	14.0 (0.26)	6.5 (0.04)	1.31 (0.05)	4.62 (0.57)	48.81 (5.72)	10.5 (0.03)
			19.7–39.4	16.1 (0.44)	6.7 (0.07)	0.99 (0.13)	4.07 (0.78)	42.57 (7.26)	10.5 (0.34)
	New cover crop	4	0–7.9	13.9 (1.27)	6.5 (0.45)	1.36 (0.09)	2.96 (0.47)	31.98 (5.60)	10.8 (0.51)
			7.9–19.7	14.9 (0.65)	6.1 (0.19)	1.62 (0.07)	4.87 (0.73)	50.93 (14.11)	10.3 (1.71)
			19.7–39.4	15.5 (1.31)	6.4 (0.18)	1.73 (0.10)	4.76 (0.83)	38.94 (15.77)	7.9 (2.09)

* Number of microplots sampled.

† To convert from metric units (Mg ha^{-1}) to English units (short tons acre^{-1}), multiply the metric value by 0.4465.

‡ Standard deviations in parentheses.

acre^{-1}), were lowest in the organic almond orchard at Nickels and were highest in the organic 3 block (DRF_CC) of the Dixon Ridge Farms walnut orchard. The high carbon stocks in the top depth of all three organic blocks of the walnut orchard may be due to the large amount of waste walnut shells, orchard prunings, manures and composts that have been added to the soil over the years. Furthermore, compared to the conventional walnut orchard block, blocks 1 and 3 of the organic walnut blocks also had significantly more carbon at the top and middle depths ($P = < 0.001$) (fig. 3). Again, this is most likely due to the higher inputs of carbon added to the organic blocks than to the conventional orchard. Previous studies have reported similar increases in soil carbon related to organic management practices (Kong et al. 2005; Lal 2004).

However, the average soil carbon was not higher in organic than in conventional systems in the almond orchards at the Nickels site, which had the lowest carbon values of all of the sites. In fact, at the top depth, carbon was slightly higher in the conventional almond orchard than in the organic orchard. This is most likely due to the fact that this organic orchard was less than 3 years old, while the conventional orchard was approximately 20 years old. Due to its early stage of growth, the organic orchard probably had less belowground biomass, which would result in lower soil carbon levels. The young organic orchard at Nickels offers a unique opportunity to show the long-term trend of carbon stocks from a newly organic-converted orchard as it grows.

At Burke Ranch, carbon was highest in the no-till vineyard. Compared to the tilled vineyard at the top and middle depth, soil carbon was 27% higher in the no-till vineyard. Previous studies have also shown that soil carbon generally increases in the surface layer of soil under no-till practices (Paustian et al. 2000; Six et al. 2002), which decrease soil disturbance and therefore mineralization of carbon (Veenstra et al. 2007). However, soils appear to have a saturation point, at which their capacity to increase soil carbon reaches an equilibrium.

At the top depth, carbon levels were similar amongst the various practices at the Oakville vineyard site, but tended to be highest in the dry farmed, tilled and new clean cultivated treatments. Dry farming involves less irrigation, which encourages vine roots to grow deeper in search of moisture, increasing carbon in the middle and deepest depths (fig. 3).

Carbon and soil depth. In the Oakville vineyard, carbon stocks increased at the plow pan layer, in the middle depth, at all sites (fig. 3). This carbon increase may be due to tillage and cover crop incorporation practices, which mix the organic matter into the lower soil levels. At Burke Ranch, carbon stocks were lower beneath the plow pan layer and higher in the top soil layer at all sites, including the woodland and the grassland. Woodland and forest soils generally have more organic matter on the soil surface (leaf litter) and in the upper soil layers (Murty et al. 2002). In the Nickels almond orchard, carbon was higher in the deepest layer of the organic block than in the conventional orchard; however, this was not statistically significant. This difference is most likely due to the fact that when a new orchard is being prepared, the old orchard is deep ripped and plowed but the deeper perennial roots are left in the ground. New trees are then planted on top of the underground remnants of the old orchard, and this abundant belowground biomass sequesters carbon in the deeper soil layers.

Nitrogen. At the top depth (0 to 7.9 inches), nitrogen ranged from 0.90 to 2.37 short ton acre^{-1}, with an average of 1.48 short ton acre^{-1} (± 1.52) (2.01 to 5.32 Mg ha^{-1}, mean 3.32 ± 1.10 Mg ha^{-1}). The lowest values were in the organic and conventional almond orchards, with similar values in the cover crop series at the Oakville vineyard. The highest values were in two of the organic blocks of the walnut orchard. In general, soil nitrogen did not exhibit significant changes with increasing soil depth (fig. 3).

Land use and soil carbon. We observed that the variance in carbon and nitrogen content between the cropping systems and management practices studied is related to the different inputs and outputs under each management type. For example, soil carbon and nitrogen were higher in no-till than in conventional tillage in the Burke vineyard. Additionally, soil carbon levels were higher in the organic walnut orchard blocks (which had greater inputs of organic matter) and the Oakville plots with cover crops than in the Nickels almond orchard, which did not have cover crops. Thus, as has also been observed in previous studies (Paustian et al. 2000; Six et al. 2002), land use and management practices are important factors in determining soil carbon content (Lal 2004).

Soil carbon by crop. Using very simple calculations based on our soil carbon data set, we extrapolated estimates of the total amount of carbon in each of the three soil

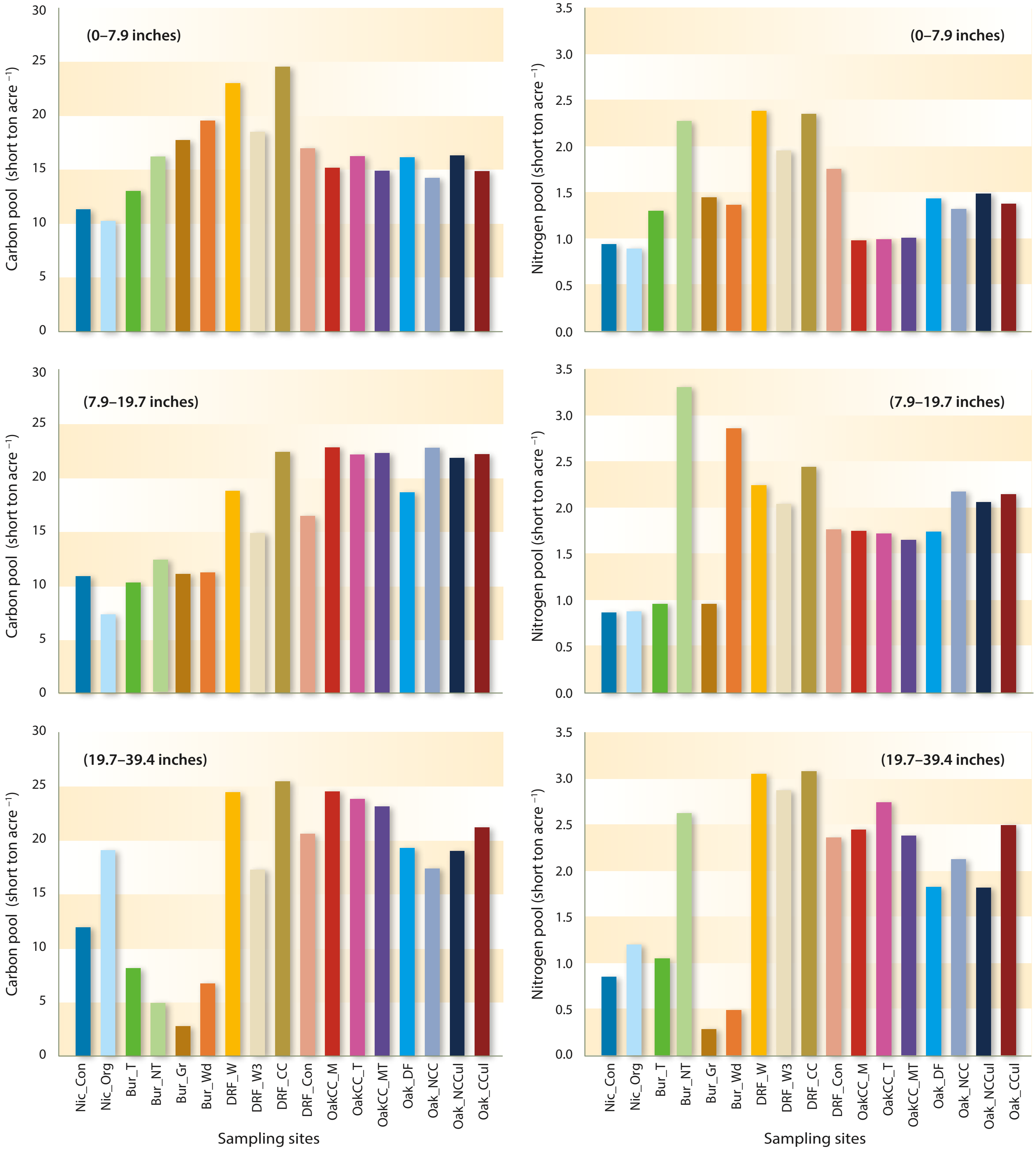

Fig. 3. Carbon and nitrogen at three depth increments for each management practice at the almond and walnut orchards and the wine grape vineyards, and native grassland and oak woodland sites. Sampling site abbreviations are explained in table 2.

depth increments as well as the cumulative total for the top 3.28 feet (1 meter) of soil for each of our study sites (table 4). Based on the total acreage of each of the sampled perennial crops within California, we also estimated the total soil carbon in each crop type statewide. We caution that our estimates are crude and a more detailed future analysis should be undertaken to include actual distribution of crops in relation to soil type and climate regime. That said, we do provide basic numbers of total carbon in perennial cropping soils.

Our estimates indicate that wine grapes already store a great amount of carbon under current land use in California (including management practices such as cover cropping, conventional tillage, no-till and dry farming). Specifically, altogether, the state's wine grape vineyards store approximately 7.23, 9.19 and 8.47 × 10^7 tons of carbon at depths of 0 to 7.9, 7.9 to 19.7 and 19.7 to 39.4 inches (0 to 20, 20 to 50, and 50 to 100 centimeters), respectively (table 4). California walnut and almond orchards currently store approximately 5.90 and 5.25 × 10^6 tons of carbon, respectively, at 3.3 feet (1 meter) depth.

TABLE 4. Estimates of soil carbon at four depths for the total acreage of walnut and almond orchards and wine grape vineyards in California

		Carbon for total crop acreage at depth			Carbon for total crop acreage
Crop	Estimated acreage	0–7.9 in.	7.9–19.7 in.	19.7–39.4 in.	at 3.3 ft (1 meter) depth
	× 10^4 *acre*	× 10^7 *tons*			× 10^6 *tons*
Walnuts	24.29	2.02	1.75	2.13	5.90
Almonds	74.13	1.62	1.36	2.28	5.25
Wine grapes	52.61	7.23	9.19	8.47	24.89
Total	151.03	10.87	12.30	12.87	36.03

How growers can use baselines

Baseline soil carbon values can be used to create carbon inventories at the farm scale, which detail the total carbon stored on site. They are a useful tool for future management and decision making that can be used to estimate and understand carbon emissions and storage and the management practices that affect soil carbon. Developing baseline soil carbon estimates is the essential first step that will allow growers to calculate their carbon sequestration rate. That rate is required if they are to calculate credits that could be traded or sold to regulated companies from industries seeking to offset their emissions.

Some examples of the offsets that growers could sell are those related to sequestering carbon in soils, including cover cropping and no-tillage operations. Additionally, growers may use the COMET-VR online management tool, which can be run by answering simple questions about their land (e.g., state, county, size, soil type, crop rotation and tillage), and in return they obtain a soil carbon sequestration amount over 10 years based on the CENTURY model output. They can also observe how much carbon they could sequester on their land if they changed to more carbon friendly management/grower practices (e.g., reduced tillage). A grower who registers these carbon values now as credits through the Voluntary Emission Reduction Registration Program may in the future be able to trade such credits. Additionally, registered credits may go toward obtaining financial incentives from other programs such as the Environmental Quality Incentive Program, which provides technical and economical assistance for enhancing conservation efforts, including those to reduce greenhouse gas emissions and increase carbon sequestration.

Long-term soil carbon monitoring

Establishing this soil monitoring network has provided essential data for further analysis of how soil types, crop type and management practices interact to affect carbon storage in perennial cropping systems, which will enable future assessments of soil carbon at the local and regional scale. Furthermore, the data from this study will contribute to the validation and verification of biogeochemical simulation models and voluntary carbon reporting such as COMET-VR for perennial orchard and vineyard systems, crops not modeled previously in Northern California (Paustian et al. 2009).

There have been many approaches to monitoring soils at a national level, but few have been successful or implemented in California. Our results suggest that continuing this soil monitoring network for the foreseeable future will allow us to detect carbon and nitrogen trends both in the soil surface layers and into the deeper subsurface layers of Northern California perennial cropping systems with changing land-use and management practices.

Our soil monitoring system is simple and, due to the high sample volume, provides precise, unbiased estimates of soil carbon stocks for the many different management practices, both organic and conventional, in different perennial cropping systems in Northern California. These estimates can be used for future carbon accounting and reporting requirements in a possible future cap-and-trade, low-carbon economy. In addition, our system provides the verifiable and comparable results needed for carbon reporting systems. Continuing this network and extending it to Southern California are

Robert Rousseau

Geoprobe sampling at Dixon Ridge Farms organic walnut orchard. *Inset*, geoprobe soil core sampling to a depth of 39.4 inches (1 meter).

Robert Rousseau

To characterize soil quality, researchers took soil samples and measured soil pH, bulk density and moisture. Above, soil core and GPS located marker ball at Dixon Ridge Farms.

essential to efficiently monitoring carbon fluxes statewide.

While our soil monitoring network is currently used to quantify carbon stocks in perennial crops of Northern California, the network system could also be applied and used to collect and estimate total carbon and nitrogen stocks in other crops statewide, as well as on a national or global scale. If others implemented the same system, it would give a greater overall picture of carbon content deep in the soil of agricultural lands. Adopting a common system would also facilitate comparing management practices and land uses with each other, as all samples would have been collected, analyzed and archived with a similar approach.

Crop growers in the state would receive the major potential benefit of implementing this soil monitoring network. Knowing how much carbon their agricultural land holds and its potential for carbon sequestration would give growers the information needed to participate in a future carbon trading system, which may be established in a low-carbon economy. Accurate information of carbon stocks provides a possible financial incentive through carbon credits that can be sold to other industries regulated by greenhouse gas emission caps.

Furthermore, even without a carbon trading system, California growers could benefit from understanding how various land management practices affect both soil carbon and soil quality. For example, soil quality is pertinent to crop production and to ensuring sustainable food security for the future. By knowing the current soil quality and how management and land-use changes could improve the soil, growers will be able to optimize their management regimes. For example, they could use reduced tillage as well as incorporate cover crops and other biomass residues into soils to enhance nutrient retention, sequester carbon and enhance water infiltration, thus improving soils for a more sustainable crop-growing future.

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RESEARCH ARTICLE

Researchers combat resurgence of bed bug in behavioral studies and monitor trials

by Vernard R. Lewis, Sara E. Moore,
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The worldwide resurgence of bed bugs has recently created urban pest challenges in California. Regardless of information source — newspaper, Internet, television, university or government — the message is the same: bed bugs are back, and with a vengeance. Until recently, the pest's longstanding rarity and a historical reliance on pesticide-based management have not encouraged research and public education to develop and make available current information on bed bug biology, detection and control. UC is currently directing comprehensive, collaborative programs of research and education to combat this emerging nuisance and public health threat. Laboratory and field tests were conducted by UC researchers on several commercial bed bug monitors and confirm that additional research is needed to improve the performance of existing monitors and to develop new ones.

Dong-Hwan Choe

Accurately detecting bed bug infestations is crucial to the development of effective control strategies. In a recent study, UC researchers tested several commercial monitors for capture performance and found that additional research is needed to improve their effectiveness.

For centuries, and perhaps for millennia, bed bugs (*Cimex lectularius* [L.] [Hemiptera, Cimicidae]) have been present in human habitations. Archeological evidence suggests these blood-sucking pests first plagued humans when they lived in caves (Usinger 1966). As people moved from caves into villages and cities, bed bugs also established themselves in the new human habitats. Throughout human history, accounts of infestations have been reported, irrespective of class or economic condition (Potter 2011). Bed bug infestations were frequently encountered in many parts of the world, including North America, for several decades into the 1900s (Cooper 2011; Potter 2011; Reinhardt and Siva-Jothy 2007).

The decline in bed bug infestations started during World War II and was due, in part, to a control campaign that included the extensive use of the insecticide DDT (Ebeling 1978). This campaign included pest eradication for U.S. troop facilities (barracks, battlefield trenches, military-issued personal equipment, transport equipment and ships) as well as other public facilities throughout the world (Potter 2011). After the war, general improvements in household and personal cleanliness, along with widespread use of synthetic insecticides (primarily organochlorines and organophosphates) resulted in a dramatic reduction of bed bug infestations; bed bugs became rare, and infestations were restricted to areas afflicted with unsanitary conditions (Ebeling 1978; Snetsinger 1997).

Why the resurgence?

During the late 1990s, the first reports of resurgent bed bug infestations started to come from several parts of the world. Almost synchronic infestations were reported in England, Australia and North America (Boase 2001; Reinhardt and Siva-Jothy 2007). Soon after these reports, documentation of the extent of the bed bug "plague" began to appear in U.S. pest control industry surveys (Potter et al. 2011). The sudden resurgence captured media attention, which highlighted the escalation of bed bug problems in university dorms, hospitals, theaters, hotels and public buildings in North America. Some reports even mentioned the closing of department stores due to bed bug infestations (Roberts and Burke 2010). The exact causes of the resurgence are not known, but important factors appear to include increased international travel among humans, pesticide resistance among bed bugs, the ease with which bed bugs can spread, and reduced indoor use of residual insecticides (Cooper 2011; Jones and Bryant 2012).

Bed bug resurgence in California has recently been reported by state and county public health officials (Lewis 2013),

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the pest control industry (Hopper 2010) and UC (Lewis 2013; Lewis et al. 2012, Sutherland et al. 2013). Media outlets in the state have featured articles and news segments on the "new" household pest (KGO-TV 2009; Los Angeles Times 2012).

Although state authorities, pest control industry representatives and UC scientists all agree that a significant increase in bed bug infestations has occurred, detailed surveys on the prevalence and intensity of infestations in hotels, apartments, college housing, public buildings and transportation facilities are still lacking. In response to the nationwide bed bug outbreak, the U.S. Environmental Protection Agency and U.S. Centers for Disease Control and Prevention issued a joint statement on the growing bed bug problem and need for control (CDC and EPA 2010).

The recent resurgence of bed bugs has public health implications, as well as economic and psychological impacts associated with infestations and bites. As a result, scientists have refocused their attention on understanding bed bug biology, ecology and management. Newly published molecular-based research has yielded clues about the origin of infestations and also about distribution patterns in the United States (Booth et al. 2012). The same paper confirmed results of a previous study showing that bed bug populations within a building are closely related, for instance within and between adjacent rooms or between apartments spanning multiple floors, and are likely dispersed inadvertently by humans (Wang et al. 2010). Additional recent studies have documented resistance to pyrethroid insecticides in several bed bug populations in the United States (Romero et al. 2009; Zhu et al. 2010) and the ineffectiveness of total-release aerosol foggers used in an attempt to eliminate bed bug infestations (Jones and Bryant 2012).

Other studies on bed bugs include the identification and description of airborne aggregation pheromones (Siljander et al. 2008), evaluation of the efficacy of canine detection (Pfiester et al. 2008) and evaluation of the performance of passive and active monitors (Wang and Cooper 2011, 2012; Wang, Gibb, Bennett, McKnight 2009; Weeks et al. 2010). Passive monitors are those that do not contain bed bug attractants (for instance carbon dioxide), while active monitors do contain such attractants.

Since the 1970s, only five new active ingredients (acetamiprid, chlorfenapyr, dinotefuran, hydroprene and imidacloprid) have been registered for and enjoyed wide use against bed bugs (Cooper 2011; Potter et al. 2011). The performance of integrated pest management (IPM) approaches and nonpesticidal methods (heat application) have also been the subject of recent reports (Naylor and Boase 2010; Pereira et al. 2009; Wang, Gibb, Bennett 2009).

During the late 1990s, the first reports of resurgent bed bug infestations started to come from several parts of the world.

Research at Berkeley and Riverside

The accurate and precise detection of bed bug infestations is a management challenge of long standing, yet it remains an essential first step in the development of any effective control strategy.

Chemical detection. At UC Berkeley, two of the authors (D.-H.C. and N.T.) tested the possibility that bed bug infestations can be detected by means of characteristic chemicals that are emitted by the pests. Bed bugs are extremely sensitive to body heat and chemical odors such as carbon dioxide and pheromones, and they rely on these cues when locating potential sources of blood meals and harborages. Many studies have described a distinctive odor that bed bugs produce, and several volatile aldehydes have been identified from the insect's scent glands (Cooper 2011). To determine whether bed bugs do in fact produce diagnostic airborne odors, the authors captured samples of airborne volatile chemicals either on solid-phase microextraction (SPME) fibers or on small charcoal-filter canisters. These samples were then extracted and analyzed using gas chromatography–mass spectrometry (GC–MS).

Under laboratory conditions, both SPME fibers and charcoal canisters were effective at capturing volatiles produced by bed bugs. No diagnostic volatile chemicals were evident when the researchers collected headspace samples from 10 adult bed bugs (in glass vials) that were not disturbed with the addition of carbon

Dong-Hwan Choe

The developmental stages for bed bugs, *Cimex lectularius*, are, from left to right, egg, nymphal instars 1 through 5, and adult. The top adult is female, and the bottom is male. Adults are approximately 4 to 5 millimeters long (the diameter of a pencil eraser) and eggs are about 1 millimeter (the size of a grain of sand). The scale at the base is in millimeters.

dioxide (fig. 1, green line). Significant amounts of 2-hexenal and 2-octenal were detected, however, when 10 adult bed bugs were disturbed with carbon dioxide (fig. 1, orange line). Subsequent quantitative analysis of the volatiles was conducted using varying numbers of bed bugs. First, carbon dioxide gas was injected into experimental shelters that contained different numbers (0, 1, 5, 10 and 20) of bed bugs (fig. 2A). Immediately after injecting the gas, the volatiles were collected from each shelter using an activated charcoal volatile trap connected to a vacuum (fig. 2B). The activated charcoal volatile traps were extracted with methylene chloride containing an internal standard (*n*-dodecane, 0.025 mg/ml) to determine the relative abundances of the collected volatiles.

This study revealed a positive relationship between the number of bed bugs and the amount of 2-hexenal and 2-octenal detected (fig. 2). Although a single bed bug in a shelter could not be detected on this basis, the presence of five or more could easily be detected (fig. 2). Also, because these signature chemicals were detected at this high quantity only when live bed bugs were present in the shelters, this research might guide the development of a novel detection method for bed bugs hidden in items or locations for which visual inspection is either impossible or impractical (e.g., electronics). The research team is currently seeking funding support and collaboration opportunities with pest control industry and engineering experts to investigate the technical and commercial feasibility of this detection method.

Dog detectors. One of the authors (D.-H.C.) has initiated two new bed bug research projects at UC Riverside since 2011. The first project focuses on training methods for bed bug detection dogs. Detection, or sniffer, dog use for bed bug inspection has become increasingly common in California and nationwide. However, the methods for training and handling the dogs vary considerably between companies and handlers, and this raises questions concerning the accuracy and reliability of the dogs' performance. The UC Riverside laboratory is currently exploring a new training method that uses only response to bed bug volatiles to measure a dog's detection performance. This new method, if successful, might eliminate the need to maintain live bed bug colonies for use in the continued training and conditioning of dogs.

Plant volatiles as fumigants. The second project addresses common concerns of the general public, including "What if I pick up bed bugs or eggs in my luggage while traveling?" and "How can I better protect myself and my home when I return, especially if I also have suspicious-looking bites?" To help address these concerns, the UC Riverside laboratory is testing several plant-derived essential oil volatiles to determine their efficacy as fumigants against bed bug adults, nymphs and eggs. Some of these materials (for example, clove and wintergreen oil volatiles) are known to have adulticidal and ovicidal effects on other ectoparasites, such as head lice. These volatiles can be less toxic to humans than synthetic fumigants such as sulfuryl fluoride and dichlorvos, so this research may lead to the development of a relatively safe and possibly effective home remedy for bed bug infestations that involve smaller personal items such as purses, carriers and luggage bags. Also, these alternative materials might be useful in combating bed bug strains that are resistant to common synthetic insecticides. Lastly, an additional bed bug laboratory project involving an investigation of the possible effect of temperature on the insecticidal activity of plant essential oil volatiles is under way.

Applying research: UC Berkeley

For decades, there were no published reports that mentioned bed bug monitors. Only in the last few years has such research begun to appear in scientific journals. However, these studies were conducted in the eastern United States

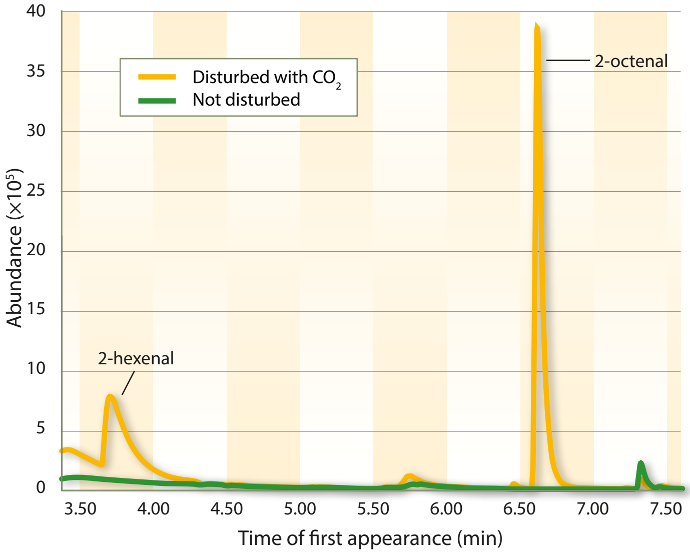
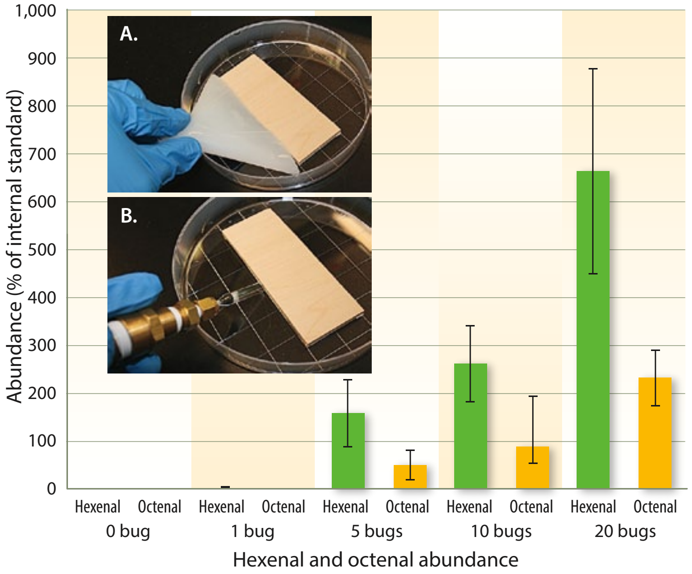


Fig. 1. Detection of bed bug–specific volatile chemicals, using SPME and GC–MS. The abundance (the sum of ion abundances, no unit) is represented on the *y*-axis and the retention time (time of first appearance of each compound) is represented on the *x*-axis.



Photos: Dong-Hwan Choe

Fig. 2. Bed bug volatiles, collected from wooden shelters using an aeration device fitted with charcoal volatile traps. The abundance (mean ± SEM) is expressed as a percentage of an internal standard (*n*-dodecane, 0.025 mg/ml). (A) Carbon dioxide gas was injected into shelters with different numbers of bed bugs. (B) The authors collected volatiles from the shelter using an activated charcoal volatile trap connected to a vacuum.


Robin L. Tabuchi

Layout of wooden testing arenas inside the Villa Termiti at UC Berkeley's Richmond Field Station used for simulated field tests of the performance of active and passive bed bug monitors.

and did not include data points in California, where climatic conditions, human habitation practices and bed bug strains may be different. (There are at least six different strains with different behaviors and susceptibilities to pesticide treatments maintained in rearing facilities at Sierra Research Laboratory, Modesto, CA.) The monitor study we describe in this paper is the first to our knowledge to test bed bug capture performance among several monitors commonly sold in California.

For three of the authors in the monitor performance study, the principal design used for these performance-monitoring trials was a wagon-wheel arrangement featuring a centrally located bed bug release point. In total, four arenas were constructed (only two are shown). A single passive or active monitor was placed at a distance of 38.1 centimeters from the center of the arena. A small piece of cardboard with live adult bed bugs covered with an inverted Petri dish was placed at the center of the arena. Passive monitors do not contain any attractants or lures, and those used in this study were Bedbug Detection System (Catchmaster, AP&G, Brooklyn, NY) and ClimpUp HD (Hotel Discreet) insect interceptor (Susan McKnight, Memphis, TN). The attractive monitor used was NightWatch (BioSensory, Putnam, CT); it contains carbon dioxide, heat and additional chemical lures. The actual placement distance for each monitor was calculated as the radial distance from the center using a string and was also randomized along compass cardinal directions for each arena. Controls, or untreated checks, are replicates that did not contain any monitors, and they were included to measure background levels of bed bug wandering and foraging in test arenas.

The test arenas also included several furniture items that served as possible harborage and forage choices for the bed bugs: a small bed, a table and a rug. Experimental factors included the type of monitor (passive or active) and the bed bug density level (10, 50 or 100 bed bugs per arena). The population for each density was made up of an equal number of starved males and starved females. Males and females were also marked with a nontoxic paint to make it easy to distinguish them visually by sex. Monitor type and density level were randomly assigned for each individual trial.

All tests were conducted under ambient conditions (temperature and relative humidity), and each continued for 24 consecutive hours, overnight, in order to allow for bed bug movement throughout the arenas. The following day, we counted how many bed bugs the monitors had captured, how many remained in the initial cardboard harborage source, in or on furniture items, and how many were scattered about the floor. To ensure that our counts were complete, all monitors, harborage sources and furniture items were disassembled and searched for concealed bed bugs. All arenas and their contents were cleaned and disinfested between trials to remove any lingering volatiles or laid eggs.

Results from the study indicate considerable movement of adult bed bugs within the test arenas and among the furniture items during the 24-hour release period (fig. 3). Most bed bugs were found near the initial cardboard harborage source that was centrally located on the floor of the test arena. A much smaller number of bed bugs were found

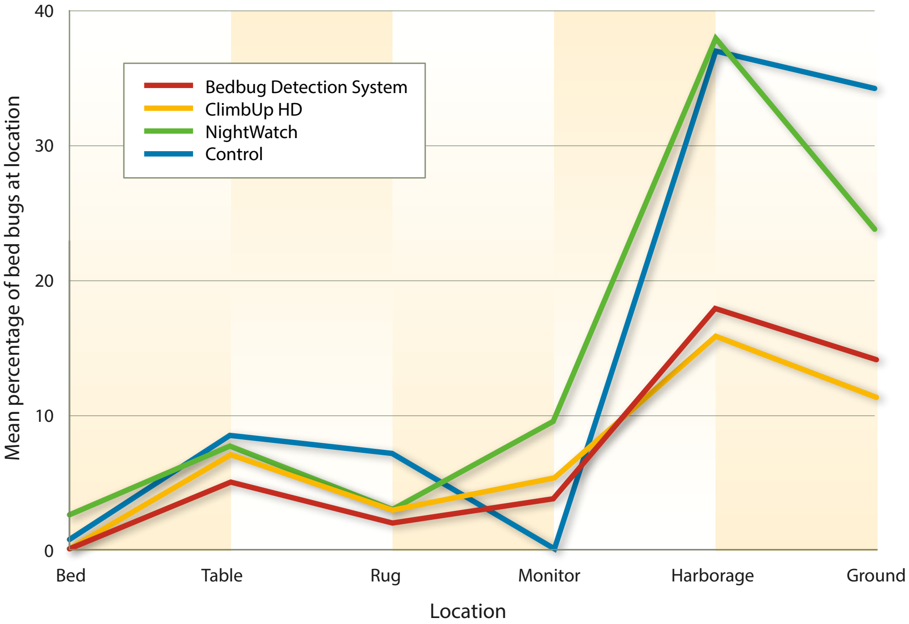


Fig. 3. The mean percentages of adult bed bugs found in the various test arena locations for each of three monitors tested. All bed bug densities (10, 50 and 100) and replicates were combined to produce the traces.

in monitors and in or on furniture items. The active monitors captured approximately twice as many bed bugs as the passive monitors (10% versus 5%, respectively), but given the experimental design this was not a statistically significant difference ($F = 0.21$; $DF = 2/13$; $P > 0.81$). Females were spread over a larger area within the test arenas and items than were males (fig. 4).

Although highly variable, our capture rates among monitors were at least 2%, and as high as 10% (active monitors), of the total number of bed bugs released in test arenas (fig. 3). However, capture performance could be enhanced if more monitors were used per unit of space, or if monitors were left out for a longer time, or if active monitors were used rather than passive monitors. Additional studies will be needed to determine differences in movement and foraging behavior among various strains of bed bugs in human habitats.

Education and outreach

One of the authors (A.M.S.) provides education and outreach for professional clientele engaged in pest management within the San Francisco Bay Area. These groups now have a special interest in bed bugs and their management since San Francisco has recently been identified as a hotspot of bed bug activity (Sutherland 2013). With this in mind, the author has begun collaborative research and outreach projects with local government agencies and professional pest control companies. Their collective goals are to demonstrate the effectiveness of education- and communication-based IPM programs for bed bug management, compare such IPM approaches to conventional bed bug management programs and provide effective management tools for difficult environments such as low-income and multiple-occupancy apartments. This author has also conducted training workshops for UC Cooperative Extension in the seven-county Greater Bay Area to increase their knowledge and confidence for dissemination of IPM-based information to the general public, recognizing bed bugs as a key pest in urban ecosystems.

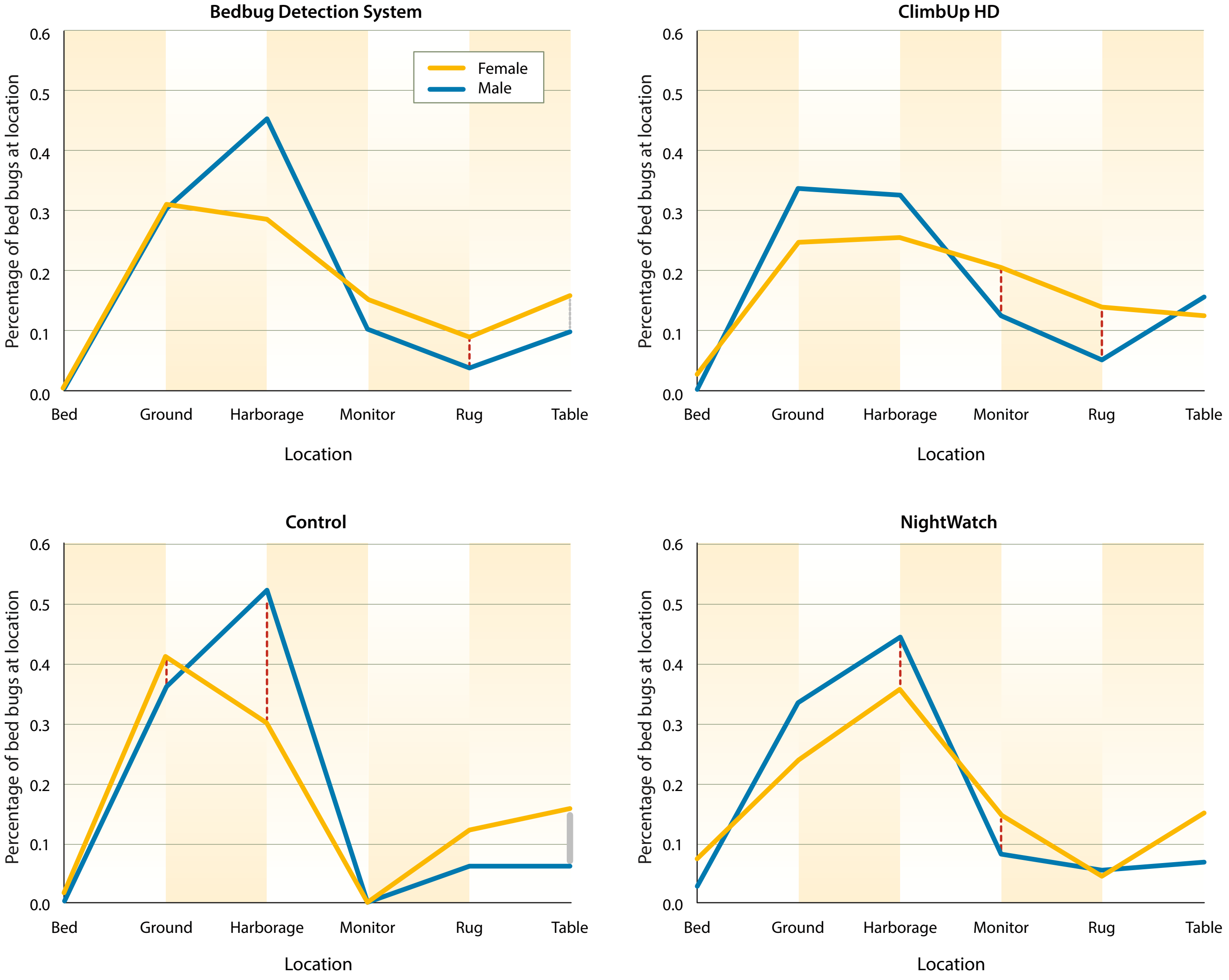


Fig. 4. Percentages of female and male adult bed bugs found in the various test arena locations in a study of three commercially available monitors plus a control. The vertical red dotted lines represent significant differences between male and female numbers (individual *t*-tests > 3 and significance level < 5%).

Challenges and opportunities this decade

The global movement of people and goods continues to increase at a rapid pace. This globalization allows the worldwide dissemination of pests, an effect that is particularly significant along the Pacific Rim, which includes California. Unfortunately, many pests — and bed bugs in particular — are opportunists that are very adept at hiding among human clutter and within human habitations, especially those with a high turnover rate (hotels and short-term apartments, for instance); therefore, our urban centers are vulnerable to bed bug infestation. Meanwhile, the state of California has raised its pest control standards to embrace IPM approaches that provide effective pest management while at the same time safeguarding the environment by minimizing the use of pesticides and reducing the harmful effect of residual runoff into urban waterways.

Most experts agree that there is a bed bug problem in California, but additional research is needed to document the extent of the problem. Field surveys will be a daunting task, and will test the limits of any detection method. All currently available monitors will need additional testing, especially under field conditions. Two of the most important issues pertaining to bed bugs are verifying bites, instead of relying on complaints alone, and improving disclosure by reducing the stigma associated with admitting to, or being accused of, having them. However, existing science can't differentiate live bed bugs after

Closer look: What if I suspect a bed bug infestation?

While scientists agree there is a bed bug resurgence — as do Californians with first-hand experience — the extent of the problem is not fully known. Accurate monitors are still under development, especially where multi-unit dwellings are involved.

For several decades, UC entomologists and others did not need to manage bed bug populations. After World War II, during which DDT, organophosphate (OP) and organochlorine (OC) pesticides were developed, chemical treatments became standard and were widely effective across the country. Resistance by bed bugs to DDT first occurred in the 1950s. By the 1980s, U.S. manufacturers had ceased production of DDT and organochlorines. The replacement organophosphates were removed from public use in the 2000s, and the class of pesticides called pyrethroids are currently being phased out for public use.

As generations of pesticides were developed and used, resistant strains of bed bugs emerged and spread. Molecular studies indicate they have spread from Europe to the East Coast of the United States, and now from the East Coast to the West.

Once they are in a multiple-unit dwelling, bed bugs spread through inadvertent human carriers. Within a building, scientists have found bed bug populations are highly inbred. Bed bugs do not fly, but the immature stages are light enough and could be carried on a strong breeze. Humans can inadvertently carry them from room to room and floor to floor.


Dong-Hwan Choe

Bed bug nymphs and adults.

Eggs can cling to the bottom of a shoe and be carried to a new room, especially in carpeted areas. They can be moved on laundry carts or bed linens. While the adult bed bugs can be seen (they are a red color and the size of a small apple seed), the larvae upon hatching are 1 millimeter (the size of a grain of sand and a creamy whitish yellow color that is difficult to see).


Dong-Hwan Choe

Bed bug eggs.

Adult bed bugs can survive for up to 1 year without a blood meal, but once they sense carbon dioxide (which mammals emit as a result of respiration), they begin moving around, then homing in on the heat source and mammalian odors nearby, finding the human or animal present. They become more active at night, and the bites are not felt at first. Welts may develop the following day and generally redden; however, there is considerable variance in the response of humans to bites, so when in doubt about a skin irritation, it's best to consult your physician.

Home infestation. If you think you have a suspicious welt, you should consult your health care professional to confirm the causative agent. For additional information on bed bug biology and control, see Pest Notes: Bed Bugs, available at www.ipm.ucdavis.edu/PMG/PESTNOTES/pn7454.html).

For severe infestations you should contact a professional pest management company local to your area. When cleaning bed linens and clothing items that may be infested, you will need to hot wash and then in a drying cycle at 140°F for at least 15 minutes.

Multi-unit dwelling infestation. If you find yourself in an apartment or dorm with bed bug problems, you will probably be asked to prepare your room for treatment by bagging and sealing your personal items in protective bags, moving large furniture items away from walls, and leaving your apartment or dorm room for treatment (up to several hours, depending on treatment).

If you are a manager or owner of such a dwelling, you will want to verify complaints by using monitors, and you will want to monitor not only the unit involved but the units next door and upstairs and downstairs. This is best done with active monitors that have documented success (for additional details, see Pest Notes: Bed Bugs, available at www.ipm.ucdavis.edu/PMG/PESTNOTES/pn7454.html).

– Janet White, based on research from Vernard Lewis

a treatment from those that were recently brought in from an outside source. More accurate and discerning methods of bed bug detection and monitoring, proven in field tests, will better enable professionals and the public to make informed decisions regarding remedial treatment and prevention.

V.R. Lewis is UC Cooperative Extension Specialist, Department of Environmental Sciences, Policy and Management, UC Berkeley; S.E. Moore is Lab Technician and R.L. Tabuchi is Lab Manager for V.R. Lewis at UC Richmond Field Station; A.M. Sutherland is San Francisco Bay Area IPM Advisor with UCCE and UC IPM, Alameda County; D.-H. Choe is Assistant Professor and Assistant UCCE Specialist, Department of Entomology, UC Riverside; and N.D. Tsutsui is Professor and Agricultural Experiment Station Scientist, Department of Environmental Sciences, Policy and Management, and Faculty Curator, Essig Museum of Entomology, UC Berkeley.

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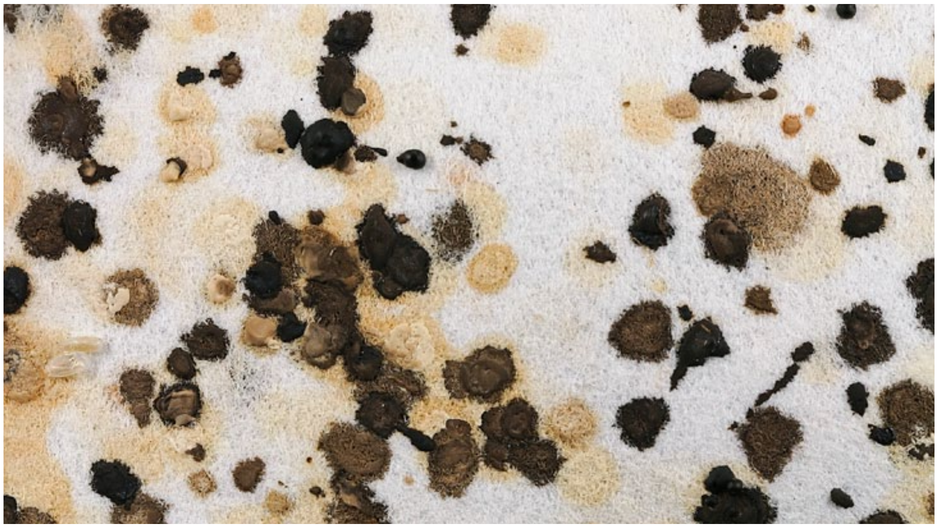

Dong-Hwan Choe

Bedbug fecal spots on a piece of white filter paper. Size of spot and color vary with bed bug size, meal and digestion time.

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RESEARCH ARTICLE ABSTRACT

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

by Bradley D. Hanson, Suduan Gao, James Gerik, Ruijun Qin, J. Alfonso Cabrera, Amit J. Jhala, M. Joy M. Abit, David Cox, Brian Correiar, Dong Wang *and* Gregory T. Browne

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.


Brad Hanson

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.

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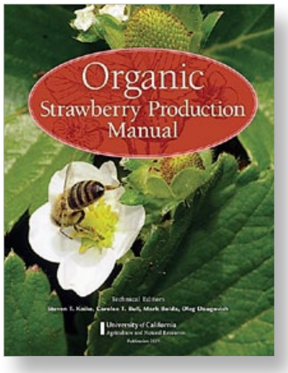

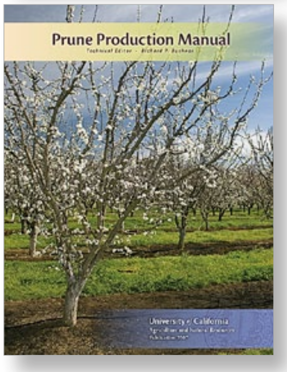

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COMING UP *in California Agriculture*

Joseph H. Connell

UC researchers have developed a way to verify that fertilizers labeled "organic" actually contain ingredients like compost instead of cheaper synthetic compounds.

Developing testing protocols to assure the quality of fertilizer materials for organic agriculture

California leads the nation in organic farms and sales, but confidence in the state's organic produce was shaken in 2008, when major suppliers of organic fertilizer were caught using cheaper inorganic compounds. This prompted the passage of AB 856, which gave regulators more authority over organic fertilizers. However, there was still no good way to test whether fertilizers were actually organic.

Now, based partly on an analysis of 180 commercially available fertilizers and their raw components, UC researchers have developed a relatively simple, inexpensive method for distinguishing organic from synthetic fertilizers. This method assesses N-15, an isotope of nitrogen that is relatively high in organic sources; ammonium, which is relatively low in most organic sources; and the ratio of carbon to nitrogen, which has a characteristic value for a given organic source.

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

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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.

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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.

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).

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.

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 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 64ºF 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 80ºF 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

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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.

least significant difference (LSD) procedure with $\alpha = 0.05$.

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 ($\mu g\ m^{-2}\ s^{-1}$), 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).

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.

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

Treatment	Rose nursery				Tree nursery			
	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.

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

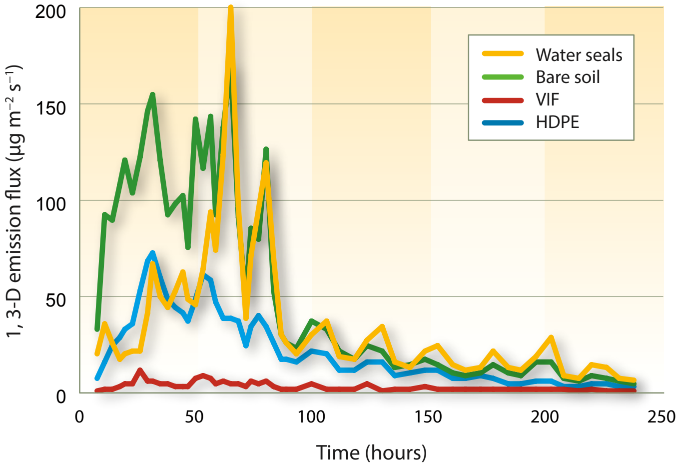

Fig. 1. Emission flux of 1,3-dichloropropene (1,3-D) with different surface treatments in a 2007 Kearney Agricultural Center field trial, near Parlier. Data were collected from three replicate plots and averaged over two application shank types (*n* = 6).

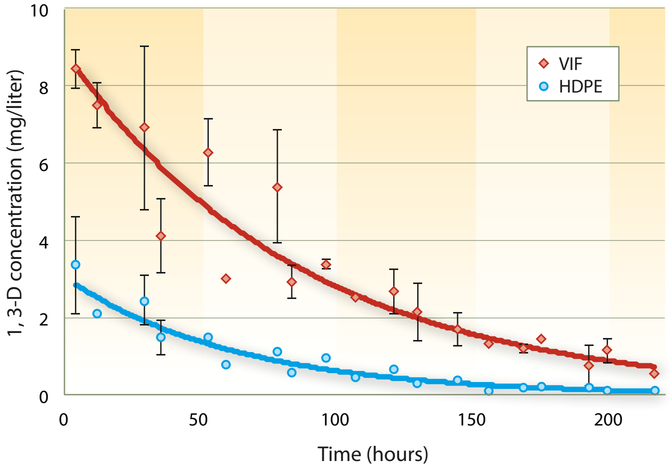

Fig. 2. Air concentration of 1,3-D between the soil surface and plastic film following application of 332 pounds per acre Telone II sealed with VIF or HDPE film (*n* = 3) in a 2007 Kearney Agricultural Center field study, near Parlier.

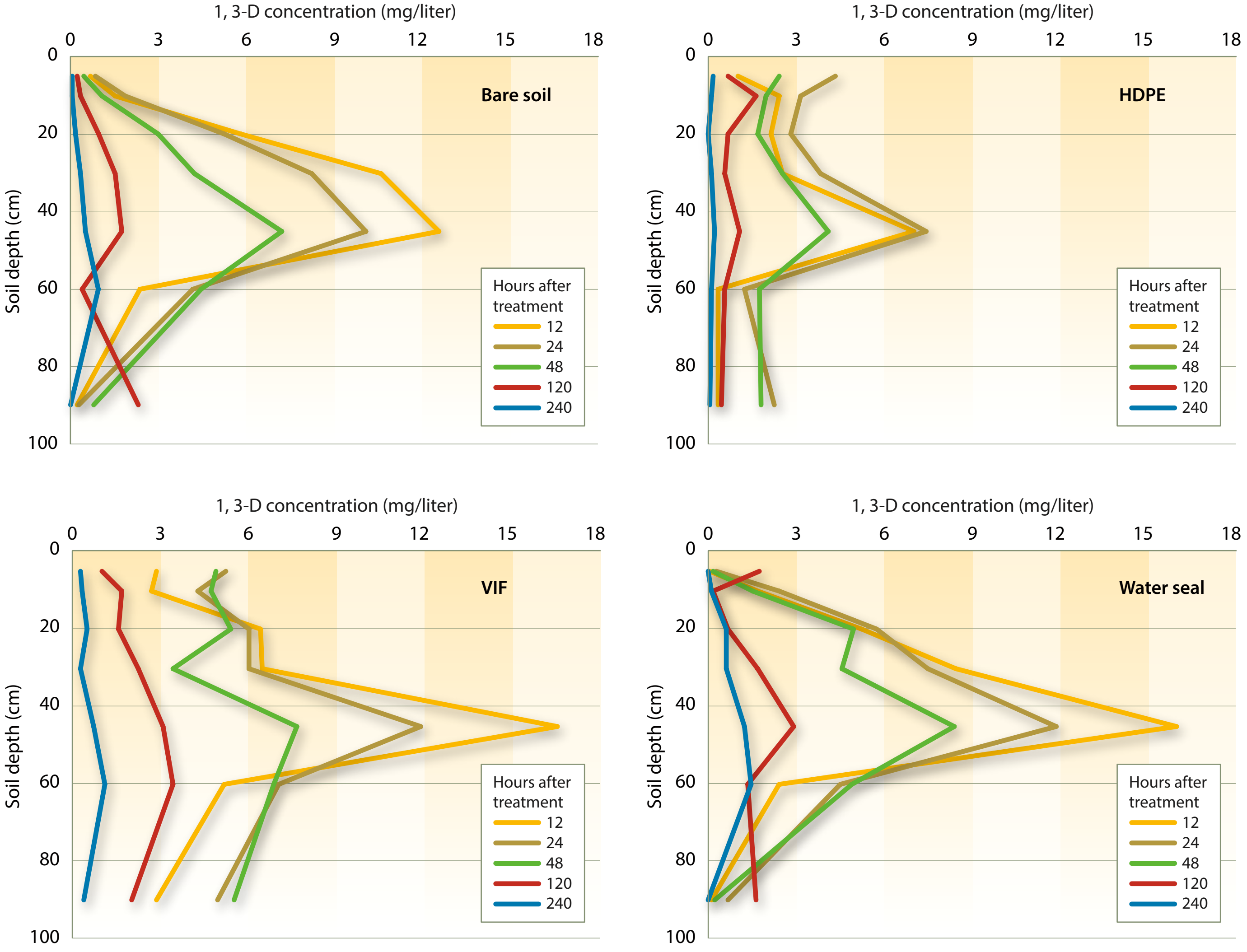

Fig. 3. Distribution of gas 1,3-D in the soil profile after shank injection in a 2007 Kearney Agricultural Center field study, near Parlier. Data were collected 12, 24, 48, 120 and 240 hours after treatment from three replicate plots and are averaged over two application shank types (*n* = 6).

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.

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.

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 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.

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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