California Agriculture

The evolving berry industry

Also:
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Methyl iodide revisited
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The evolving berry industry

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Introduction

A crossroads for strawberries

Seven articles in this issue speak to a longstanding question: What will the California strawberry industry look like without methyl bromide?

2016 marks the last year in which California growers will use methyl bromide, a highly effective soil fumigant that kills a wide range of pests, from fungi to insects to weeds. First identified as an ozone-depleting compound in 1991, methyl bromide was scheduled for phaseout in the United States by 2005 under the Montreal Protocol, an international agreement to protect the stratospheric ozone layer. While methyl bromide was used on many crops, it was perhaps most irreplaceable for California strawberries, which helped the industry win exemptions that have allowed a significant, though declining, quantity of the chemical to be used through 2016. Despite years of research into alternatives, no equally effective replacement has emerged.

Strawberries are California’s third-largest crop, behind only almonds and grapes, with annual farmgate sales of $2.5 billion (2014). In our first research article (page 107), Laura Tourte et al. review economic data on the berry sector — blackberries and raspberries as well as strawberries — in Santa Cruz and Monterey counties, and look ahead to factors, including the phaseout of methyl bromide, that are likely to shape future growth.

In a paper chronicling events leading up to the 2012 withdrawal of methyl iodide, once promoted as a viable methyl bromide substitute, Julie Guthman (page 124) reports survey findings that point to a variety of reasons why strawberry growers did not move quickly to adopt the chemical after it was approved by state regulators. Concerns about public opposition topped the list, followed by a variety of other factors, including concern about methyl iodide’s toxicity, and a lack of strong incentive to switch to the new chemical because of the availability of other fumigants, including methyl bromide.

Three articles look at new approaches to managing soilborne pests without methyl bromide. In this issue’s Outlook (page 101), Margaret Lloyd and Tom Gordon make the case for using a suite of strategies to manage soilborne pathogens — including collective action among growers to help limit the spread of pathogens between fields. A news item (page 104) on research at the UC ANR Hansen Agricultural Research and Extension Center covers ongoing research on anaerobic soil disinfestation, a chemical-free technique that is being used in a growing number of commercial fields. And a paper by Amanda Hodson and Edwin Lewis (page 137) reviews a variety of approaches to managing for soil health — in strawberries and other crops — as a pest suppression strategy.

Fumigants other than methyl bromide, such as chloropicrin, remain widely used in California strawberry production. Rachael Goodhue et al. (page 116) examine how increasingly stringent buffer zone requirements for chloropicrin application impact growers differently depending on their proximity to developed land. Shachaf Triky-Dotan et al. (page 130) report on the effectiveness of several fumigants at dosages lower than the maximum label rate.

The issue also includes two research papers not focused on strawberries. Patrick Baur et al. (page 142) report results from a survey of produce growers regarding on-farm food safety practices. They found that practices that may negatively impact wildlife, such as exclusion fencing and vegetation clearing, remain widespread, despite a lack of clear evidence that they have a food safety benefit. Finally, Daniel Geisseler and Gene Miyao (page 152) review the use of soil testing to guide the management of soil phosphorus and potassium in California cropping systems.

Note: The research papers on strawberries in this issue were assembled through the journal’s normal submission and peer-review process. That is, by coincidence, the journal accepted a number of strawberry-related papers at roughly the same time; there was no special solicitation of papers about strawberries.

-Jim Downing, Executive Editor
Growing for the future: Collective action, land stewardship and soilborne pathogens in California strawberry production

Margaret Lloyd, UC Cooperative Extension Farm Advisor, Yolo, Solano and Sacramento counties
Tom Gordon, Professor, Department of Plant Pathology, UC Davis

California accounts for more than 80% of U.S. strawberry production, a harvest worth $2.5 billion in 2014. Fertile soils and the prevailing climate on the Central Coast support per acre yields twice that of Florida, the second largest producer, and 10 times more than most other states.

Yet California strawberry growers face significant challenges. Among the most important is the declining availability of suitable land. The potential for a given field to produce an acceptable yield depends not only on physical and chemical characteristics of the soil but also, critically, on the presence or absence of soil dwelling pathogens that can infect strawberry roots and cause diseases that limit fruit production. As described below, effective control of soilborne pathogens of strawberries was once readily achieved by means that are no longer available to strawberry growers.

It now seems likely that no single measure will suffice to meet the challenge of soilborne pathogens. Rather, a multi-faceted approach will be required, one that integrates advances in disease resistance through breeding with closer attention to the factors that influence the survival, activity and spread of pathogen populations in soil. Many of the latter, such as rotating crops and cleaning equipment, frequently involve multiple operators. As a result, there is a need to recognize that pathogen-free soil is effectively a common-pool resource and that protecting it will require collective action.

The end of methyl bromide

Since the early 1950s, diseases caused by soilborne pathogens have been managed primarily through the use of preplant soil fumigation. Before that time, Verticillium wilt, caused by *Verticillium dahliae*, imposed a major limitation on strawberry production. Recognition of the fungicidal properties of chloropicrin and the enhanced efficacy achieved by addition of methyl bromide lifted this...
limitation and allowed for a dramatic expansion in the production of fresh strawberries in California. However, because methyl bromide was identified as a contributor to ozone depletion, the United States and most other nations agreed to phase out its use as a soil fumigant, in line with the Montreal Protocol approved by the United Nations in 1987. This phaseout was to be completed by 2005 in developed countries and 2015 in developing countries, though critical use permits have extended use in California strawberry production, with incremental allocation reductions each year. Today, phaseout is nearly complete.

Consequently, chloropicrin is now typically the sole fungicidal fumigant in mixtures applied to soil prior to planting strawberries. Whereas control of Verticillium wilt was routinely achieved with a 2:1 blend of methyl bromide and chloropicrin applied at 350 pounds per acre, chloropicrin alone is not fully effective even at 400 pounds per acre, which is well above usual application rates. The efficacy of soil fumigation has been further constrained by the shift, for economic reasons, to drip application of fumigants to beds, rather than flat fumigation of an entire field. Bed fumigation fails to fully treat the soil, which allows for a progressive increase in soil inoculum levels over time.

Emerging problems

The adoption of altered fumigation practices has been closely associated with the emergence of diseases not previously known to affect strawberries in California. These diseases include Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *fragariae*, and dieback caused by *Macrophomina phaseolina*. A similar pattern has been observed elsewhere in the United States and in other countries where methyl bromide is no longer used, such as Spain, Israel and South Korea, strengthening the causal relationship between diminished efficacy of fumigation and increased prevalence of disease caused by soilborne pathogens.

Because decades of study have failed to identify an environmentally acceptable and cost-effective substitute for methyl bromide, it seems unlikely that preplant fumigation will ever again provide complete control of soilborne diseases.

Multiple strategies

Sustaining high yields will require an integrated approach that employs more disease-resistant cultivars and cultural practices that can suppress pathogen activity in soil.

Higher levels of genetic resistance to disease in strawberry cultivars can be achieved through breeding. However, this disease resistance will never be complete and it will always be subject to compromise as resident pathogen populations evolve and new strains are introduced.

Accordingly, while genetic resistance will be a central strategy in disease management, it must be coupled with measures that minimize inoculum levels of strawberry pathogens in soil.

Such measures can include rotation of strawberries with non-susceptible crops, which provides an interval during which pathogen populations can decline by attrition. The rate of attrition is quite variable and dependent on many factors, but in general, a pathogen population may be expected to decline by approximately 50% each year when no host plant is available. Growers who do not rely on soil fumigation aim for a 3- to 4-year rotation to maintain economically viable production levels.

Soil amendments such as compost can also be beneficial by encouraging the growth of microbes (bacteria and fungi) that will inhibit plant pathogens and limit their ability to initiate infections.

It will also be important to limit opportunities for introduction of inoculum with soil or transplants. In the past, with fully effective fumigation practices, any pathogens that may have been present by the end of one season would likely be eliminated before the next crop was planted. Now, however, growers need to be mindful of the risks that attend movement of soil into their fields, as can occur with farming equipment and hand-held implements. Once a pathogen is established in a field, soil from that field can serve as a source of inoculum for other fields when equipment moves between them. It should be noted that because a pathogen population must increase to a certain threshold before it causes disease, the absence of symptoms offers no assurance that a field is free...
Collective action

The withdrawal of methyl bromide increases the mutual dependence of growers: to the extent that individual growers do not take steps to manage the spread of soil pathogens, the entire community will suffer. Although land suitable for strawberry production is privately held, it may be seen as a common-pool resource. And to avoid a tragedy of the commons, it must be managed with a degree of collective action.

There are a number of obstacles to collective action. Using soil amendments, rotating crops and thoroughly cleaning equipment between fields all add costs. But the associated benefits are not fully realized immediately — rather, these actions must be justified as longer-term investments in the productivity of the broader land resource. In addition, while growers working their own land stand to eventually realize a direct return from such investments, growers on leased land may not. Furthermore, implementing these practices often involves other operators — such as vegetable growers, specialty equipment operators and harvesting crews — who may have little stake in helping to control the pathogens that affect strawberries.

Incentivizing collective action requires a means of incorporating the production risk posed by soil-borne pathogens into the valuation of land, providing a financial basis for engaging growers and landowners in protecting fields against infestation. Making this type of valuation work demands more efficient — faster and less costly — quantitative measures of pathogen populations in soil. In addition, to properly gauge the risk posed by a given inoculum level, it will be necessary to better understand how physical, chemical and biological soil characteristics influence the activity of plant pathogens. This knowledge could then be used to establish metrics that characterize the inherent capacity of soil to suppress pathogen activity. These are areas of active research that involve collaboration among the University of California, the U.S. Department of Agriculture and the strawberry industry. Much progress has been made but many challenges remain.

Along with development of more effective soil-borne pathogen assessment tools, it will be necessary to demonstrate to landowners and growers that measures of disease risk influence the value of the land in a manner that can be reliably quantified. If these efforts are successful, it should be possible to justify investments that reduce risk.

For such investments to become an industry standard will require a degree of communication and collaboration on a regional scale that has not been common in California agriculture. However, history shows that such collaboration is possible and can be highly effective. In the 1960s, lettuce growers in Monterey County agreed to adopt a “lettuce free” period from December 7–21 each year when no lettuce can be grown, to help manage the disease known as lettuce mosaic. This agreement, which remains in force today, has been an essential element in the effective management of a devastating disease. While this example offers a hopeful indication of what can be achieved, the challenge facing strawberry growers is more complex and the cooperation needed will be more extensive. Work toward this goal benefits from a strong social network, and a research and extension system in California, which lay a good foundation for developing local and public cooperative governing mechanisms for soil to sustain a productive strawberry industry into the future. At a pivotal time when land is still productive but pathogens are becoming more widespread, a regional plan for maintaining uninfested, pathogen-free soil has an opportunity to emerge as the foundation for a sustainable industry in the absence of fumigation.
At Hansen Agricultural REC, better blackberries and a soil disinfestation alternative

Hazel White

At 27 acres, Hansen Agricultural Research and Extension Center (HAREC), in Ventura County, is small. It is exposed to the Santa Ana winds and has heavy clay loam soil infested with one of the highest levels of Verticillium wilt fungus recorded anywhere in the state. And yet it’s proving a major resource for Central Coast growers interested in producing a very profitable blackberry crop or in managing soil pests in strawberries without fumigation.

HAREC has developed a growing program for a firm, sweet, large blackberry to produce a good yield during a high-prices sales window in late summer and fall. UC Cooperative Extension (UCCE) Farm Advisor Oleg Daugovish, in charge of berry research, is also contributing to the international knowledge bank on anaerobic soil disinfestation (ASD), an alternative to chemical fumigation that uses waste carbon products, such as rice bran. Growers of high-value organic strawberries in the Central Coast region have taken up ASD enthusiastically.

Prime-Ark 45 blackberry

In fall 2011, a new, publicly available primocane blackberry variety, Prime-Ark 45, from the University of Arkansas fruit breeding program was planted at HAREC. “It looked good, tasted good, and yielded well,” Daugovish recalls. Since then he has established how to manipulate the timing of the harvest, working with UCCE researchers with blackberry trials under way in other parts of the coast: Mark Bolda, UCCE Director and Farm Advisor in Santa Cruz County, and Mark Gaskell, UC Small Farms Program Advisor in San Luis Obispo and Santa Barbara counties (Gaskell and Daugovish 2016). “Our results are consistent and add up to the same story,” says Daugovish. “This is a high-quality crop, easy to manage, and fruiting can be optimized for the lucrative window in late summer.”
The timing of the harvest is key, because until August, and after October or November, imports from Mexico are heavy and keep blackberry prices lower. Production of blackberries in Mexico expanded from 5,431 acres in 2004 to 27,195 acres in 2011 and is still expanding. Demand for blackberries in the United States has also increased significantly, especially on the West Coast and among younger people (21 to 39) and people with high incomes (GAIN 2013).

HAREC trials have established that a late mow-down of the canes, in January or February rather than December, and tipping canes in late April or early May to 45 centimeters (18 inches) result in the largest crop from August to October.

Fertilization also increases yields substantially. In 2014, the plots were not fertilized, which resulted in poor growth and yields as low as 1.2 kilograms (2.6 pounds) per plant. Last year, 7 to 9 pounds of nitrogen per acre per week was applied using fertigation until 2 to 3 weeks before harvest, and the per-plant yields were about 2 kilograms (4.5 pounds), the heaviest crop seen since 2013.

In all seasons the marketable yields could have been almost double if not for the crop loss due to spotted wing drosophila. No pesticides were used during the growing season, and up to 60% of the fruit have been unmarketable during the warmest harvesting weeks. This year, Daugovish is using insect netting on tunnels with double-door entrances to test the effects of insect entry prevention on crop yield and returns. The light net cover will likely reduce sunburn and wind damage, which have been contributing to fruit losses at HAREC.

“There will be saturation in the blackberry market at some point,” says Daugovish, “but at present there’s still room for expansion.” Growers might consider planting Prime-Ark Freedom, a newer variety from University of Arkansas, which is thornless. Daugovish hopes to plant it at HAREC and test other publicly available caneberry varieties.

**Anaerobic soil disinfestation (ASD)**

ASD research is particularly interesting because no one yet fully understands the complex interactions of ASD, only that it works. And it seems to work better the more years it is practiced, as if the suppression of pathogens is incremental or their effect becomes less aggressive as soil properties change and microbial populations shift over time.

Slightly more than 1,000 acres of commercial strawberries in the coastal counties were grown on land treated with ASD last year after 8 years of trials at HAREC, where the research began as a collaborative effort with UC Santa Cruz scientists. Daugovish is now running ASD optimization trials at HAREC and in grower fields, to make it easier and cheaper for growers to use.

The standard ASD treatment involves mixing 9 tons per acre of rice bran into the top 24 inches of soil just before strawberry beds are listed, in summer, covering the beds in plastic mulch (black or clear), applying irrigation until the soil is saturated (and anaerobic conditions are set) and waiting 3 to 5 weeks. Then the planting holes are cut through the plastic, and soil conditions become aerobic again.

The bran is a waste product from processing plants in the Central Valley; it is inexpensive but transportation costs are significant. Mixed into soil, it is a carbon source for soil microbes, which decompose it.
anaerobically. The goal is to suppress soilborne pathogens such as *Verticillium dahliae*, *Fusarium oxysporum* and *Macrophomina phaseolina* and to modify the soil environment to benefit plant growth. Daugovish estimates the ASD cost per acre with 9 tons of rice bran is about $3,000, but the bran also serves as preplant fertilizer (providing nitrogen and phosphorus), usually a $400 to $600 expense in organic systems.

Growers using ASD, mostly organic growers, have seen greatly increased yields. At HAREC, 1.2 pounds per plant were harvested from ASD-treated plots last year, a 52% improvement over yields from untreated checks. Organic growers using ASD have increased their yields 35% to 50% above the average non-ASD yield of 0.6 to 1 pound per plant in the Ventura area.

Joji Muramoto and Carol Shannon, at UC Santa Cruz, working with UCCE farm advisors Mark Bolda (Santa Cruz County) and Surendra Dara (San Luis Obispo and Santa Barbara counties), have similar trials under way. In replicated field trials in coastal counties in 2014, strawberry fruit yields after ASD treatments were almost identical to those obtained from standard chemically fumigated soils (Muramoto et al. 2014).

Last year, Daugovish established in one trial that irrigation could be delayed for 1 week, to give growers the necessary time for connecting and testing the irrigation lines. Even better, the trials suggested that irrigation might be unnecessary; the process worked in the heavy HAREC soils with the existing moisture in the soils after bed shaping. Optimizing or eliminating the irrigation step is significant: it would reduce growers’ water costs and the risk of nutrient leaching. This year, Daugovish has trials under way in growers’ fields on sandy soil, with no irrigation during ASD, and the results look promising.

Using drip-applied liquid glycerin, a byproduct of biodiesel processing in Kern County, as the carbon source last year didn’t work as well as using rice bran; nor did spreading ground dry grape pomace, a byproduct from coastal wineries. Both resulted in significantly lower yields than were recorded in the rice bran plots. This year, Daugovish is trialing three more carbon sources, all free waste products from local industries: coffee grounds, brewery waste, and grass clippings from sod suppliers.

His goal is not only to find more carbon sources as effective as rice bran, but also to develop a bank of knowledge using various products. He is in touch with researchers in Japan and Spain, where strawberry growers have similar soil pest challenges, and ASD is known as pasteurization or biosolarization.

“It’s the beginning of a new era,” says Daugovish, now that researchers have molecular tools to measure levels of some soil pathogens very rapidly and are developing tools for measuring levels of others. In place of a single successful blanket chemical treatment that killed everything (methyl bromide), a new soil science is developing that will measure real-time pathogen and microbial populations and perhaps require multiple layers of management — different varieties with different levels of disease resistance/tolerance, different soil treatments — in a single field. “Growing berries is going to be a different game in the years to come,” he says.

Local UC Master Gardener volunteers, who help harvest the berry crops at HAREC, understand the situation as much as anyone. During fruit harvests, Daugovish explains what’s happening in his research trials and trials elsewhere. The Master Gardeners play an important role at HAREC, and Daugovish likes to hear their thoughts on how the work there translates into their own gardening practices, so they are all, together, part of something important, local and global.

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**References**


The fresh market berry industry in Santa Cruz and Monterey counties

by Laura Tourte, Mark Bolda and Karen Klonsky

The fresh market berry industry in Santa Cruz and Monterey counties has contributed significantly to the agricultural vibrancy of the two counties and the state of California. Dramatic growth in strawberry, raspberry and blackberry production has been documented over the last 50 years, and most notably since the 1980s. Factors influencing this growth include innovations in agricultural practices and heightened consumer demand. Here, we review the historical context for the berry industry in Santa Cruz and Monterey counties. Organic production, production economics and challenges for the future are also discussed.

During the 1960s and 1970s, the number of acres planted to berries, tons produced and value of production fluctuated. The fluctuations can be partly explained by farm management: in the past growers often rotated berry and vegetable crops to assist with soil and pest management, thereby influencing these statistics. However, annual crop reports from the county agricultural commissioners show that since the 1980s, berries have become increasingly important to each county’s overall value of production, and by 2014 accounted for 64% and 17% of the total value of all agricultural products in Santa Cruz and Monterey counties, respectively (table 1). The industry’s growth can be explained by a shift of some acreage out of tree fruits (e.g., apples, pears and apricots) and field crops (e.g., grains, dry beans and sugar beets), among others, into berries, and by additional acreage put into agricultural production.

Berry industry growth

During the 1960s and 1970s, the number of acres planted to berries, tons produced and value of production fluctuated. The fluctuations can be partly explained by farm management: in the past growers often rotated berry and vegetable crops to assist with soil and pest management, thereby influencing these statistics. However, annual crop reports from the county agricultural commissioners show that since the 1980s, berries have become increasingly important to each county’s overall value of production, and by 2014 accounted for 64% and 17% of the total value of all agricultural products in Santa Cruz and Monterey counties, respectively (table 1). The industry’s growth can be explained by a shift of some acreage out of tree fruits (e.g., apples, pears and apricots) and field crops (e.g., grains, dry beans and sugar beets), among others, into berries, and by additional acreage put into agricultural production.
Strawberries are the undisputed leader in the berry sector and in 2014 represented 58% and 94% of the value of all berry production in Santa Cruz and Monterey counties, respectively (table 1), and 50% and 93% of all berry acreage (data not shown). Table 2 documents the remarkable expansion of the strawberry industry over time in both counties with respect to acreage, tons produced and value of production. Between 1960 and 2014, acreage more than tripled and production increased tenfold. The value of production, in real (inflation-adjusted) dollars, increased by 424% in Monterey County and by 593% in Santa Cruz County, reaching an astonishing value of nearly $1 billion in 2010 and 2014. Gains in both strawberry acreage and value of production grew steadily and most strikingly in Santa Cruz County (tables 1 and 3), where production conditions for caneberries (raspberries and blackberries) are optimal. For example, caneberry fields in Santa Cruz County are situated in areas that have well-drained soils and are protected from damaging winds. Also, fields are planted to take advantage of the growth and yield gains associated with southern exposures. Moreover, field-to-cooler travel distances are shorter in Santa Cruz County, which is critical for safeguarding the quality and marketability of these highly perishable crops. By 2014, raspberries represented 33% of the county’s value of production for all berries. In contrast, Monterey County raspberry production accounted for only 6% of the county’s total berry value.

Blackberries have not been consistently reported as a separate category in archived statistical analyses, but instead were often included under the terms “bush- or miscellaneous berries”. Therefore, similar data for blackberry acreage and value of production cannot

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**TABLE 1. Value of all products and berry production in Santa Cruz and Monterey counties, 1960 to 2014**

<table>
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<th>All berries†</th>
<th>Strawberries‡</th>
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<td>352.0</td>
<td>180.8 (51)</td>
<td>126.5 (70)</td>
<td>44.4 (25)</td>
<td>2,923.3</td>
<td>231.2 (08)</td>
<td>228.0 (99)</td>
<td>2.1 (1)</td>
</tr>
<tr>
<td>2010</td>
<td>532.5</td>
<td>324.6 (61)</td>
<td>197.2 (61)</td>
<td>91.7 (28)</td>
<td>4,006.2</td>
<td>793.6 (20)</td>
<td>751.1 (95)</td>
<td>42.5 (5)</td>
</tr>
<tr>
<td>2014</td>
<td>616.5</td>
<td>395.8 (64)</td>
<td>228.1 (58)</td>
<td>131.3 (33)</td>
<td>4,493.4</td>
<td>754.3 (17)</td>
<td>709.3 (94)</td>
<td>45.0 (6)</td>
</tr>
</tbody>
</table>

Source: Santa Cruz and Monterey county agricultural commissioners’ crop reports (MCAC 2014; SCCAC 2014); berries includes strawberries, raspberries, blackberries and miscellaneous berries. Value figures are not adjusted for inflation.

* Number in parentheses is the percent berries of total value of all products.
† Number in parentheses is the percent strawberries of total value of all berries.
‡ Number in parentheses is the percent raspberries of total value of all berries.
§ Statistic not available.

**TABLE 2. Strawberry acreage, production and value in Santa Cruz and Monterey counties, 1960 to 2014**

<table>
<thead>
<tr>
<th>Year</th>
<th>Acreage</th>
<th>Tons produced</th>
<th>Tons per acre</th>
<th>Value of production</th>
<th>Value per acre*</th>
<th>Acreage</th>
<th>Tons produced</th>
<th>Tons per acre</th>
<th>Value of production</th>
<th>Value per acre*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$ million</td>
<td>$ million</td>
<td></td>
<td></td>
<td></td>
<td>$ million</td>
<td>$ million</td>
</tr>
<tr>
<td>1960</td>
<td>1,070</td>
<td>10,060</td>
<td>9</td>
<td>4,118,000</td>
<td>3,849</td>
<td>3,510</td>
<td>40,742</td>
<td>12</td>
<td>16,934,000</td>
<td>4,825</td>
</tr>
<tr>
<td>1970</td>
<td>730</td>
<td>14,965</td>
<td>21</td>
<td>6,281,000</td>
<td>8,604</td>
<td>2,600</td>
<td>36,010</td>
<td>14</td>
<td>14,152,000</td>
<td>5,443</td>
</tr>
<tr>
<td>1980</td>
<td>1,355</td>
<td>32,800</td>
<td>24</td>
<td>21,154,000</td>
<td>15,612</td>
<td>2,785</td>
<td>59,185</td>
<td>21</td>
<td>45,279,000</td>
<td>16,258</td>
</tr>
<tr>
<td>1990</td>
<td>2,771</td>
<td>57,276</td>
<td>21</td>
<td>63,486,000</td>
<td>22,911</td>
<td>5,830</td>
<td>183,000</td>
<td>31</td>
<td>181,459,000</td>
<td>31,125</td>
</tr>
<tr>
<td>2000</td>
<td>4,580</td>
<td>138,728</td>
<td>30</td>
<td>126,520,000</td>
<td>27,624</td>
<td>6,990</td>
<td>225,966</td>
<td>32</td>
<td>227,984,000</td>
<td>32,616</td>
</tr>
<tr>
<td>2010</td>
<td>3,317</td>
<td>129,330</td>
<td>39</td>
<td>197,228,000</td>
<td>59,460</td>
<td>10,664</td>
<td>425,000</td>
<td>40</td>
<td>751,114,000</td>
<td>70,435</td>
</tr>
<tr>
<td>2014</td>
<td>3,298</td>
<td>100,061</td>
<td>30</td>
<td>228,140,000</td>
<td>69,175</td>
<td>11,054</td>
<td>413,000</td>
<td>37</td>
<td>709,296,000</td>
<td>64,166</td>
</tr>
</tbody>
</table>

Source: Santa Cruz and Monterey county agricultural commissioners’ crop reports (MCAC 2014; SCCAC 2014); berries includes strawberries, raspberries, blackberries and miscellaneous berries. Value figures are not adjusted for inflation.

* Before production costs and taxes.
be reported here. However, between 1990 and 2010, Santa Cruz County agricultural commissioner crop reports reported an upward trend for the broad category with respect to acreage planted (up by 242%) and value of production (up by 596% in real dollars). In 2010, blackberries were promoted to a position of prominence in the report and shown as a separate statistic; at the same time, the miscellaneous berry category was shown to be very small indeed. Between 2010 and 2014, however, blackberry acreage and value of production leveled off and have shown only modest gains (data not shown). This may be because there has been less emphasis on production and market research and promotion for blackberries than for strawberries or raspberries. No comparable data are available for Monterey County.

The two counties have contributed significantly to California’s total berry sector; in 2014, area strawberry acreage represented 35% of the statewide total, 37% of the total tons produced and 38% of the total value of production (CDFA 2015; USDA-NASS 2015). Area raspberry acreage represented 43% of the statewide total, 42% of the total tons produced and 39% of the total value of production. Comparable statewide statistics are not available for blackberries.

County agricultural commissioners’ reports show that the majority of all berries produced in the two counties — up to 98% — are sold as fresh market fruit (MCAC 2014; SCCAC 2014). In years with adverse production conditions or low prices, a higher percentage of the crop may be diverted to the freezer or processed products market. Fresh market fruit is handled and sold primarily through local grower-shippers; a much smaller share is sold directly to consumers through farmers markets, community supported agriculture operations, farmstands and other direct and intermediated market channels such as restaurants, independent grocers and schools.

**Agricultural practices**

**Strawberries**

Arguably the most momentous shift in cultural practices for strawberries was the introduction of preplant soil fumigants, beginning with chloropicrin (CP) in the 1950s and methyl bromide (MB) in the 1960s. Fumigation is a soil disinfection practice that improves plant productivity and helps with the management of arthropods, nematodes, weeds, soilborne fungi and other plant pathogens. Some of the most difficult to control pathogens include *Verticillium dahliae*, *Fusarium* spp. and *Macrophomina phaeolina*. Without soil fumigation, these pathogens have the potential to completely destroy strawberry plantings. Early on, when CP and MB were mixed and applied together, the synergistic effects allowed strawberries to be produced as an annual rather than a biennial crop, and to be grown continuously on the same land without rotation to another crop, resulting in an increase in annual strawberry acreage. The use of fumigants also led to higher and more predictable yields and fruit quality, and further enabled the development of more stable markets for strawberries (Wilhelm and Westerlund 1994). Yields for strawberries statewide increased from a range of 2 to 4 tons per acre prior to the introduction of soil fumigants to 16 tons per acre by 1969 (Geisseler and Horrowth 2014).

Additional cultural improvements included the development of both UC (public) and proprietary strawberry varieties uniquely adapted to coastal production conditions. Varieties were bred, for example, for disease resistance, yield and market potential. Notable UC-bred strawberry varieties include Tufts (1970s), Pajaro, Douglas, Chandler, and Selva (1980s), Camarosa and Seascape (1990s), and Aromas, Albion and Monterey (2000s). Irrigation practices also evolved, shifting from furrow irrigation in the 1960s to drip irrigation in the 1980s, which led to further improvements in plant disease management and greater water use efficiency. These and other enhancements meant that by 2012, yields could exceed 35 tons per acre (Geisseler and Horrowth 2014). More recently, the strawberry industry has focused on “fine-tuning” fertility and water management for more efficient resource use, along with additional yield and fruit quality improvements (Bottoms, Bolda, et al. 2013; Bottoms, Hartz, et al. 2013).

The Santa Cruz–Monterey area is also recognized for its early experience with conversion of conventional strawberry production to organic management (Gliessman et al. 1996). Organic strawberry production was shown to result in lower yields, which, when offset by

### TABLE 3. Raspberry acreage, production and value in Santa Cruz and Monterey counties, 1960 to 2014

<table>
<thead>
<tr>
<th>Year</th>
<th>Santa Cruz County</th>
<th>Monterey County</th>
<th>Value of production</th>
<th>Value per acre</th>
<th>Value of production</th>
<th>Value per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acreage</td>
<td>Tons produced</td>
<td>Tons per acre</td>
<td>Value of production</td>
<td>Value per acre</td>
<td>Acreage</td>
</tr>
<tr>
<td>1960</td>
<td>75</td>
<td>264</td>
<td>4</td>
<td>179,000</td>
<td>2,387</td>
<td>na</td>
</tr>
<tr>
<td>1970</td>
<td>75</td>
<td>300</td>
<td>4</td>
<td>687,000</td>
<td>9,160</td>
<td>na</td>
</tr>
<tr>
<td>1980</td>
<td>95</td>
<td>422</td>
<td>4</td>
<td>1,580,000</td>
<td>16,632</td>
<td>na</td>
</tr>
<tr>
<td>1990</td>
<td>894</td>
<td>5,294</td>
<td>6</td>
<td>13,619,000</td>
<td>15,234</td>
<td>723</td>
</tr>
<tr>
<td>2000</td>
<td>1,711</td>
<td>14,372</td>
<td>8</td>
<td>44,424,000</td>
<td>25,964</td>
<td>172</td>
</tr>
<tr>
<td>2010</td>
<td>2,033</td>
<td>17,341</td>
<td>9</td>
<td>91,684,000</td>
<td>45,098</td>
<td>688</td>
</tr>
<tr>
<td>2014</td>
<td>2,418</td>
<td>24,083</td>
<td>10</td>
<td>131,326,000</td>
<td>54,312</td>
<td>782</td>
</tr>
</tbody>
</table>

Source: Santa Cruz and Monterey county agricultural commissioners’ crop reports (MCAC 2014; SCCAC 2014); berries includes strawberries, raspberries, blackberries and miscellaneous berries. Value figures are not adjusted for inflation.

* Before production costs and taxes.
† Statistic not available.
premium prices could potentially offer higher net returns (revenue) to growers. The importance of crop rotation for disease management was not addressed in the initial study by Gliessman et al. (1996) but has since been the focus of additional research, as have more complete analyses of the economics of organic strawberry production (Bolda et al. 2006, 2014). Growers and area researchers continue to collaborate and advance organic strawberry production techniques. Most notably, a long-term research commitment has been made to determine organically acceptable disease management practices such as anaerobic soil disinfestation (Shennan et al. 2009), the use of commercially available soil-applied biological organisms and the incorporation of soil amendments such as mustard seed and its derivatives. The area is now seen as a global leader in organic strawberry research, and in 2012 the first organic strawberry production manual was published by UC Agriculture and Natural Resources (Koike et al. 2012).

Statistics documenting expansion of the organic strawberry industry over time are not available on a county-by-county basis, but statistics for California show prodigious growth in acreage (up by over 400%) and value of production: from $9.7 million in 2000 to $93.6 million in 2012, a 621% increase in real dollars (table 4).

**Caneberries**

Like strawberries, raspberries and blackberries have benefitted from enhancements in cultural practices. When well-managed, both types of caneberries can produce crops for up to 20 years. However, to maintain acceptable quality and yield Central Coast growers typically manage raspberries and blackberries so that they produce two and five crops, respectively, prior to removal and replanting.

In Santa Cruz County, raspberry production was relatively flat in the 1960s and 1970s, but began to increase substantially in the 1980s (table 3). This can be explained by a shift from floricanes, or spring-bearing varieties, to the then newly developed proprietary primocane, or fall-bearing varieties, that do not carry the productivity constraints associated with the inadequate chill (plant cold conditioning) requirements along the Central Coast. Primocane-bearing varieties allow growers to successfully produce a high quality raspberry crop in low- or no-chill coastal locations, and further manipulate time to harvest and yield with pruning and other management practices (Finn and Clark 2011). Between 1990 and 2014, the number of acres planted to Santa Cruz and Monterey area raspberries almost tripled, tons produced increased by about 350% and the value of production was up by over 400% in real dollars (table 3).

Santa Cruz County raspberry growers began to experiment with and adopt field-scale semi-permanent protective structures or tunnels in the 1990s and 2000s (Gaskell 2004). Initially developed in Europe, field-scale tunnels allow growers to extend their production seasons, enhance yield and fruit quality, and capture high off-season prices for fresh market fruit (Gaskell 2004). The controlled environment, and resulting security of production, also allows for greater market stability. Tunnel culture is now a common practice in raspberry production. This shift away from open-field production to protected cropping, along with breeding improvements, has had lasting impacts on the raspberry industry and its expansion.

Cultural improvements geared towards fresh market blackberry production are more recent and include advances in breeding for thornless varieties and quality attributes (color, flavor and firmness [Finn and Clark 2011]). In 2011, a public primocane-bearing blackberry variety (Prime-Ark 45) became commercially available for the first time and is now being planted in the area. Since that time, additional public and proprietary primocane-bearing varieties have been in development; some have already become available. Open-field production was the norm until recently, but to ensure marketable fruit of high quality, and as growers have shifted additional acreage to primocane-bearing varieties, tunnel culture has been more widely adopted and, based on discussions with growers, is now estimated at roughly 80% of the acreage.

Like organic strawberries, remarkable growth in the statewide production of organic raspberries and blackberries was documented between 2000 and 2012 (table 4). Acreage climbed by over 500% in both organic berry categories. Value of production was up over 3,000% in real dollars for organic raspberries and up by almost the same percentage for organic blackberries. It is important to note that although the organic raspberry and blackberry categories have demonstrated extraordinary growth, they still represent a relatively small percentage of all berry production in the area.

### TABLE 4. Organic berry production in California, 2000 to 2012

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acreage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strawberries</td>
<td>509</td>
<td>1,406</td>
<td>2,009</td>
<td>2,681</td>
<td>427</td>
</tr>
<tr>
<td>Raspberries</td>
<td>157</td>
<td>332</td>
<td>919</td>
<td>1,007</td>
<td>541</td>
</tr>
<tr>
<td>Blackberries</td>
<td>45</td>
<td>114</td>
<td>363</td>
<td>312</td>
<td>593</td>
</tr>
<tr>
<td>Total</td>
<td>711</td>
<td>1,852</td>
<td>3,291</td>
<td>4,000</td>
<td>463</td>
</tr>
<tr>
<td><strong>Value ($1,000)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Percent change in real dollars (adjusted for inflation), 2000–2012</td>
</tr>
<tr>
<td>Strawberries</td>
<td>9,741</td>
<td>25,141</td>
<td>65,521</td>
<td>93,595</td>
<td>621</td>
</tr>
<tr>
<td>Raspberries</td>
<td>1,142</td>
<td>9,718</td>
<td>24,453</td>
<td>50,659</td>
<td>3,227</td>
</tr>
<tr>
<td>Blackberries</td>
<td>284</td>
<td>1,420</td>
<td>8,312</td>
<td>11,391</td>
<td>2,908</td>
</tr>
<tr>
<td>Total</td>
<td>11,167</td>
<td>36,279</td>
<td>98,286</td>
<td>155,645</td>
<td>945</td>
</tr>
</tbody>
</table>

Source: Klonsky and Richter 2010; Klonsky and Healy 2013.  
* Dollar value figures are not adjusted for inflation; however, the percent change column shows the increase in value in real dollars (adjusted for inflation).
Production economics

Specialists and farm advisors with UC Cooperative Extension (UCCE) have performed economic analyses for Santa Cruz and Monterey county fresh market berry crops for decades (UCCE 1969–2014). The studies estimate production costs for a representative enterprise based on characteristics common to the area’s farms. Data are collected from established growers, input suppliers and other industry experts so that a diversity of operations and practices are taken into account. Since 1990, UCCE researchers have used a farm budget software program to analyze the data and present results in several formats detailing costs for cultural and harvest practices, monthly cash costs and business and investment overhead costs. The studies also include an analysis estimating net returns to growers for several yield and price scenarios. Representative costs for food safety and environmental quality programs have been incorporated into more recent studies as they have evolved to become standard business practices. The resulting production and economic information is specifically designed to assist growers, bankers, researchers and government agencies with business and policy decisions.

Strawberries

The first economic analysis of fresh market strawberry production for Santa Cruz and Monterey counties was performed in 1969; at least one subsequent analysis has been conducted every decade since then. Though the level of detail and data included in each study has changed over time, some interesting trends can be noted. Annual land rent climbed from $150 per acre in 1969 to $2,700 in 2014, representing 2.5% and 5.5% of total production costs, respectively. The cost of soil fumigation for conventional strawberry production (a contracted service) increased from $350 per acre in 1969 to $3,302 in 2010, representing 5.5% and 6.9% of total production costs, respectively. Production year water use gradually decreased from 80 acre-inches per acre in 1969 to 36 acre-inches by 1996 as drip irrigation became the standard. The amount of water used to bring a crop to harvest has remained roughly the same since that time; however, growers and researchers continue to investigate methods to increase water use efficiency even further. In some areas, soil types and fields, growers have been able to reduce per acre water use by several acre-inches more (Bolda et al. 2011, 2014). When the above costs and water usage are assessed on a per ton rather than a per acre basis, production practice cost increases are less notable, and water savings even greater. Labor-intensive practices such as hand weeding and harvest are consistently shown as costly line items relative to other operations.

Representative yields for conventionally produced fresh market strawberries rose from 20 tons per acre in the 1969 study to 30 tons in 2010, an increase of 50%. Even higher yields are discussed for some varieties and production conditions; county production statistics confirm that higher yields are indeed possible (table 2). Representative yields for organic strawberries, studied over a much shorter time period, rose from 15 tons per acre in 2006 to 17 tons in 2014, an increase of 13%. As more research is directed towards organic agriculture in general and strawberries in particular, yields will likely increase even more with time. Recent efforts include improvements in cultivar breeding, cultural practices and disease management, especially soil pathogen management.

The most recent economic analyses for conventional, second year conventional and organic strawberry production were performed in 2010, 2011 and 2014, respectively. Second year conventional strawberries, or those producing a crop for a second year after having produced the first without replanting, represent about 15% of the total strawberry acreage in the area. Similarities and differences in total, cultural and pest management costs for the three management approaches are shown in figures 1 to 3.

Total costs for conventional strawberries were $47,882 per acre and include expenses for all practices from land preparation to harvest (fig. 1). For the second year conventional strawberry crop, total costs were lower at $32,798 per acre, reflecting a reduction in expenditures for land preparation and reduced harvest costs because of lower yield. For organic strawberries, total costs were $49,044 per acre, slightly higher than for conventional production, mostly due to higher soil fertility input costs.

Harvest, a labor-intensive practice, clearly represents the lion’s share of total costs, at 58% in organic production, 60% in conventional production and 67% in second year conventional berries. Cultural costs represent 26% of total costs in the conventional and organic systems, but only 15% for second year strawberries.
because there were no associated planting costs, and because pest management costs were lower (fig. 2).

Looking more closely at pest management, soil fumigation is the highest cost category for conventional production at $3,302 per acre, with weed control, another labor-intensive practice, the highest cost in second year and organic strawberries at $1,212 and $2,506 per acre, respectively (fig. 3). However, for organic strawberries the cost to control insects ran a close second at $2,488 per acre, which was dominated by control for lygus bug (*Lygus hesperus*) with a bug vacuum, and two-spotted spider mite (*Tetranychus urticae*) with the release of predatory mites. By comparison, estimated costs for insect control in conventional strawberries were lower at $702 per acre and still lower at $579 in second year conventional berries.

**Caneberries**

Raspberry and blackberry production were not routinely studied in years prior to 2003. Since then, several primocane-bearing raspberry and floricane-bearing blackberry cost and return analyses have been performed, with the most recent studies conducted in 2012 and 2013, respectively. Both studies detail establishment and first year production and harvest costs for not-yet-fully-mature crops. For raspberries, first year of production includes a $12,460 per acre construction, management and investment cost for protective tunnels. Costs for a mature raspberry crop are analyzed in the second production year and total $48,210 per acre (fig. 4). For blackberries, costs for a mature crop are shown for the second through fifth production years, and total $43,406 per acre per year.

Harvest costs again represent the vast majority of total costs, at 81% and 71% of total costs for raspberries and blackberries, respectively. For raspberries, cultural costs represented a much smaller share of total costs at $4,656 per acre, roughly half of which ($2,038) was for trellis and tunnel management. Blackberry cultural costs totaled $5,709 per acre, of which over half ($3,060) was for pruning and training canes.

**Net returns and other costs**

Each study also includes an analysis of potential net returns to growers above operating, cash and total costs for a range of yields and prices. When evaluating net returns above total costs, gains are shown for higher yield and price points; losses are also documented at many lower yields and prices (tables 5 and 6). Farms with productive soils, experienced managers, optimal production conditions and robust market plans generally

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**Source** (figs. 1 to 3): 2010 Sample Costs to Produce Strawberries – Central Coast Region; 2011 Sample Costs to Produce Second Year Strawberries – Central Coast Region; 2014 Sample Costs to Produce Organic Strawberries – Central Coast. [http://coststudies.ucdavis.edu](http://coststudies.ucdavis.edu).
realize higher net returns. In contrast, farms with less-than-optimal production conditions, reduced yields, poor fruit quality or inexperienced managers may contribute to lower net returns. Results from the strawberry analyses show that on a per acre basis, organic strawberries tend to be more profitable than conventional berries, even with lower yields. Organic price premiums explain the result; in this example price per tray for organic strawberries ranged from $12 to $18, while price per tray for conventional berries ranged from $7.30 to $11.30. Prices for second year conventional strawberries were slightly lower still to account for a portion of the crop that was diverted to the freezer market. Net returns for both caneberryes were mostly positive.

Other noteworthy entries in all recent berry studies include per acre costs for pest control advisers (PCAs), management of invasive pests and food safety and regulatory programs for water and air quality. Though each alone represents a relatively small portion of total costs, they provide readers with insights into the changing nature of berry production activities and costs over time.

### Challenges remain

Cultural practices in the berry industry have evolved to address changes in soil, water and pest management needs. New varieties have been developed to enhance yield and quality attributes. Based on historical trends, and to meet both industry needs and consumer demands, we expect to see new varieties continually developed over time. Businesses have responded to consumer and market demands for fresh, safe and organic products by implementing food safety programs and/or transitioning more lands to organic production. Water and air quality programs have been developed to comply with state regulatory requirements. In the past, growers customarily hired those with expertise in financial and market management; they now also enlist the support of experts in food safety, organic agriculture and environmental quality to assist with farm management.

But challenges remain, and management of key agricultural risks — including those for production, finances, marketing, legal and human resources — have become increasingly important. Invasive pests pose significant management and regulatory constraints and increase production, financial and market risks. Two recent examples are light brown apple moth (LBAM [*Epiphyas postvittana]*) and spotted wing drosophila (*Drosophila suzukii*). LBAM infestations can lead to loss of part or all of the crop because of field closure from regulatory actions, increasing production and financial risk. SWD presents substantial market risk to growers in that its larvae can infest fruit and render the crop unsaleable. Growers minimize the risk...
of loss from these two organisms with the routine use of PCAs. PCAs moni-
tor fields more frequently than growers alone would be able to do, identify pests
and recommend actions, for example, the use of pheromone mating disruption for
LBAM and field sanitation for SWD.

Adoption of integrated approaches, including alternatives to
fumigants, to manage diseases, weeds and other pests will be key to sustaining berry production over the longer term.

Since their introduction, the soil fumi-
gants CP and MB have unquestionably
contributed to the expansion of the berry
industry. However, the full phaseout of
MB as a pest management tool — it will
no longer be available for use in berry
production after 2016 — presents both
production and financial risks. While a
substantial research commitment has
been made to finding alternatives to MB,
nothing has yet come close to offering
the same level of protection from the
large-scale loss to soil pathogens or the
gains in productivity associated with the
application of CP and MB as synergistic
preplant fumigants. We anticipate that
the berry industry will adapt to the MB
phaseout by using alternative fumigants
and preplant soil treatments, but these
are likely to carry a higher level of risk for
berry production in the short term and
may lead to a decrease in planted acre-
age and production. However, this may
also stimulate an even more robust re-
search agenda directed towards soilborne
diseases and plant health to minimize
disruption to the industry. Reliance on
fumigants as the primary strategy for pest
management is almost certainly a thing of
the past. Instead, adoption of integrated
approaches, including alternatives to
fumigants, to manage diseases, weeds
and other pests will be key to sustaining
berry production over the longer term
(Carpenter et al. 2000; CDPR 2013).

Labor is also a current and significant
challenge for growers of berry crops.
Social and demographic changes in
Mexico — the source of a majority of the
area’s agricultural labor — have resulted
in markedly lower immigration rates into
the United States, a shrinking labor pool
and upward competition and wage pres-
sures for the agricultural workers who
remain (Taylor et al. 2012). In recent years,
growers have reported difficulty in secur-
ing and retaining sufficient numbers of

Between 1960 and 2014, strawberry acreage in the Santa Cruz and Monterey
area more than tripled and production increased tenfold. In 2014, the area
represented 35% of the state’s strawberry acreage.
workers to ensure timely and effective farm operations. The lower production figures seen in strawberries in 2014 may in part have been the result of an insufficient labor pool from which to draw (table 2). However, no known regional employment or wage data are available to specifically document this. Some growers minimize labor risk by paying higher wages and providing year-round employment when possible. However, these strategies can be difficult for some businesses to justify economically.

Arguably, the area’s berry industry, and agriculture more generally, increasingly faces political risk. Immigration legislation that may assist with the current labor challenge languishes at the federal level, with major policy changes unlikely before 2017 (Martin 2015). Farming practices are under even more scrutiny by consumers, local municipalities and state and federal agencies. Soil fumigants and pesticide use have been the focus of many intense debates and discussions, especially in Santa Cruz and Monterey counties. At the time of this writing, several new regulations related to pesticide application notifications, pesticide and fumigant application buffer zones and worker safety have been proposed by the California Department of Pesticide Regulation or the U.S. Environmental Protection Agency but have not yet been finalized. It is anticipated that implementation will begin in 2017, with full compliance required in 2018.

And, as California struggles through a fifth year of drought, water use, quality and cost has become a more robust part of the local, state and federal discourse, with directives issued and new legislation proposed. Compliance with each new directive or regulation presents production and logistical challenges for growers and can be costly to manage. Although it is unlikely that regulatory pressures will lessen in the future, there is every expectation that growers will continue to adjust business practices to meet or exceed any new requirements or standards. The economic sustainability of individual farming operations and the area’s berry industry in total will ultimately be impacted by and continue to evolve with the ever changing business environment, and by an array of risks and challenges.

References


Bottoms T, Hartz T, Cahn M, Farrara B. 2013. Crop and soil management advisors’ use of soil testing data in Santa Cruz and Monterey counties; K. Klonsky is UCCE Specialist, Extension Management Advisor in Santa Cruz, Monterey and San Benito counties; M. Bolda is UCCE Strawberry and Caneberry Farm Advisor in Santa Cruz, Monterey and San Benito counties; K. Klonsky is UCCE Specialist, Emerita, in the Department of Agricultural and Resource Economics at UC Davis.


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Buffer zone requirements are by nature spatial and their effects are site-specific, with some fields — because of their location — more impacted than others. Using a set of strawberry fields in Ventura County that were preplant soil fumigated in 2013 as a baseline, we examined how much acreage eligible for chloropicrin fumigation would have been lost if either of two buffer zone distance regulations had been in effect: any one of the four sets of alternative distances proposed in May 2013 by the California Department of Pesticide Regulation (DPR) or the buffer zone distances DPR released in January 2015. Buffer zone distances are based on several factors including the anticipated protection of human health, referred to as the percentile of protection. We find that the effects are highly dependent on the percentile of protection. From 4% to 29% of the fumigated blocks analyzed would have had an increase in buffer zone acreage depending on the percentile of protection. In those blocks, the share of total acreage that would no longer have been eligible for fumigation with chloropicrin varied from 3% to 45%. We also identify strategies that growers employed to reduce required buffer zone distances under use requirements in effect in 2013. The most frequently used strategies were using a tarp type with the lowest buffer zone requirements (“60% tarp”), extending a buffer onto a neighboring property, road and/or farm path, and reducing application rates. The results have an important policy implication: spatially defined use regulations have very different effects for different fields; aggregated industry-level analyses will miss the range of impacts on growers.

Pesticide regulations and label requirements are increasingly defined in terms of spatial parameters. Rather than specifying uniform use regulations for all applications or banning a product, regulators restrict use according to the location of identified negative environmental or human health effects. For example, to manage humans’ chronic exposure to an active ingredient, regulators may limit total use at the township level. In addition, many label restrictions specify a buffer zone distance regarding how close pesticides can be applied to bodies of surface water. Buffer zone distance requirements sometimes result in buffer zones that reduce the treatable acreage in a field. The buffer zone is the area established around the perimeter of each application block by extending the buffer zone distance from the perimeter in all directions.

While buffer zone distances intended to protect surface water quality are dependent on the physical landscape, buffer zone distances intended to address human health effects are dependent on the location of nearby residents, workers and possible bystanders relative to the field being treated.

To comply with buffer zone regulations, a grower can sometimes set up a buffer zone outside the field, for example, if a field that needs treatment is surrounded by agricultural land that doesn’t...
need treatment (fig. 1). But in other cases, such as when the field borders a subdivision, or a farm road or storage building, for example, the required buffer zone distance must extend inside the field, effectively reducing the treatable area of the field (fig. 2).

Such differences mean that the effects of a buffer zone distance requirement are heterogeneous across fields. Our objective was to evaluate how much the effects vary, and the extent to which growers are able to mitigate the loss of treatable acreage using various management strategies. We addressed these questions using a set of strawberry fields in Ventura County that had been treated with chloropicrin preplant soil fumigation in 2013. We considered the losses of treatable acreage that would have occurred if different buffer zone distances had been necessary: the four sets of buffer zone distances proposed in May 2013 by the California Department of Pesticide Regulation (DPR) and the buffer zone distances DPR released in January 2015. We also identified strategies that growers were employing in 2013 to reduce the effects of required buffer zone distances and the frequency with which they were used.

Preplant treatments of chloropicrin are widely used to control nematodes, soil pathogens and some weeds. Chloropicrin may be applied as a sole active ingredient or in a product that also contains methyl bromide or 1,3-D. Products containing both chloropicrin and methyl bromide are also subject to regulations governing the use of methyl bromide, including minimum buffer zone distance requirements (DPR 2016a).

Strawberries account for roughly 70% of the chloropicrin applied annually in California, primarily on the Central Coast between Ventura and Santa Cruz counties (DPR 2016b). Treated soil is covered with plastic tarps during the fumigation application. Potential risks are eye, nose, throat and upper respiratory irritation for people working or living near fields as a result of volatilization of chloropicrin (DPR 2010). Safety measures to reduce exposure are in place at the county, state and federal levels.

Baseline regulations

The strawberry fields in Ventura County that served as the baseline for our study were treated in compliance with two sets of regulations in place in 2013: the Phase 2 U.S. Environmental Protection Agency’s (EPA’s) label requirements for chloropicrin and DPR’s 2013 recommended permit conditions as implemented by the county. State regulations must conform to U.S. EPA’s requirements; for a state regulation to have an effect it must be stricter than federal requirements.

The regulatory provisions relevant for our analysis were buffer zone distance, buffer zone distance credits (e.g., allowing smaller buffer zone distances if high-barrier tarp is used), minimum buffer zone distance, maximum application block size and requirements for applications with overlapping buffer zones. We omit discussion of other regulatory provisions that are not relevant for strawberry production in Ventura County, e.g., regulations related to tree hole fumigation.

Phase 2 EPA requirements

The key features of the Phase 2 EPA requirements are as follows: Buffer zone distances are based on application block size, fumigant application method and rate, and tarp type, and are implemented on product labels. Buffer zone distance credits are given for the use of specific high-barrier tarps that reduce fumigant emission rates and associated human health effects, as well as for other practices not relevant for this study such as untarped applications. The minimum buffer zone distance for all fumigations is 25 feet. Maximum application block size for a 24-hour period is between 120 and 160 acres depending on the material and rate applied. Applications with overlapping buffer zones must be made at least 12 hours apart and the required buffer zone distances are dependent on the tarp types used on the individual application blocks.

2013 DPR recommended permit conditions

Recommended permit conditions were issued by DPR as guidance for counties issuing restricted material permits; although they are not mandatory, they were adopted by all permitting counties in 2013. Among tarp types, only 60% tarp (eligible for a 60% buffer credit from EPA due to its lower permeability) qualified for a buffer zone distance credit; tarps with 20% or 40% credit from EPA were not given credit in the permit conditions. Minimum buffer zone distances increased for non-60% tarps (other tarps). The minimum buffer zone distances are 25 feet for 60% tarp (EPA is 25 feet.
minimum for any tarp). For other tarps, the minimum is 60 feet for treatment blocks less than or equal to 6 acres and 100 feet for blocks greater than 6 acres and up to 40 acres. Otherwise, buffer zone distances are the same as in the EPA regulations.

The maximum application block size is 40 acres within a 24-hour period. Applications with overlapping buffer zones are subject to additional requirements: within a 36-hour period after the completion of the first application, only a combined maximum of 40 acres can be treated, and buffer zone distances depend on tarps and acreage for all applications. If both blocks use 60% tarp, the buffer distances are calculated per individual block acreage. However, if at least one block is other tarp, then the buffer distances are calculated with the combined acreage and the resulting buffer distance is applied to all of the combined blocks.

**Recent DPR regulatory initiatives**

The fumigation decisions reported for the strawberry fields in Ventura in 2013 were made under the 2013 DPR recommended permit conditions and the Phase 2 EPA regulations, described above. Our study examines what the consequences would be in terms of buffer zone acreage if the 2013 mitigation proposal or 2015 mitigation measures had been in effect at that time.

**2013 DPR mitigation proposal**

In May 2013, DPR issued the chloropicrin mitigation proposal (referred to below as the proposal) regarding potential future use requirements for fumigant products that contain chloropicrin as an active ingredient, either alone or with 1,3-D or methyl bromide in California (DPR 2013a). The objective of the proposal was to offer means of mitigating short-term adverse health effects for nearby residents and bystanders in addition to the measures in the Phase 2 EPA requirements. The proposal contains five types of mitigation measures: buffer distances, acreage limits for applications, waiting periods between applications in instances where buffer zones overlap, emergency preparedness and response requirements, and notice of intent (NOI) requirements.

The proposal details buffer zone distances based on four possible percentiles of protection for human health (80th, 85th, 90th and 95th). For each percentile of protection under consideration, buffer distances are presented for three categories of tarp (60%, other, and no tarp). The percentile of protection is the probability of not exceeding the 73 parts per billion target concentration outside the buffer zone. DPR estimates the buffer zone distance required to achieve each percentile of protection using available scientific information such as air monitoring, computer modeling and the results of toxicology studies. The four percentiles of protection were proposed as four alternative human health standards with associated buffer zone distances to be considered for future implementation. The intent of the proposal process was for DPR to ultimately select one percentile of protection for the final mitigation measures following public comment and further analyses of the proposal.

The buffer zone distance requirement for applications using 60% tarp is the same in the proposal as in the Phase 2 requirements. For other tarps, the buffer zone distances in the proposal vary with the application method, application rate, acreage treated and the percentile of protection. For some fumigation block sizes and application rates, buffer zone distances are larger than the EPA ones for applications using other tarps. The maximum application block size and requirements for applications with overlapping buffer zones were the same as those in the 2013 recommended permit conditions.

**2015 DPR mitigation measures**

In January 2015, DPR announced its decisions and intent with regard to required mitigation measures involving applications of chloropicrin (DPR 2015). The document includes an explanation of the decision process and the scope of the mitigation strategy. A few months later, DPR released the exact requirements added to the pesticide enforcement program standards (DPR 2016a). These mitigation measures include modifications to many

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Strawberries account for roughly 70% of the chloropicrin applied annually in California, primarily on the Central Coast between Ventura and Santa Cruz counties.
of the measures in the proposal and effectively replace the 2013 recommended permit conditions. The 2015 mitigation measures used for this analysis were modified in February 2016. DPR is currently working with registrants (manufacturers and distributors) to develop California-only labels for chloropicrin products consistent with the mitigation measures. Amendments to the product labels must be approved by EPA before those labels can be approved for use in California. In other words, the mitigation measures are final, although the way in which they are implemented will change from DPR interim recommended permit conditions to EPA approved product labels.

The 2015 control measures are based on the 95th percentile of protection of human health standard (DPR 2015); however, due to the inclusion of additional weather data (that allowed refinement of buffer zone distances by region), refining of buffer zone distances based on application method, and corrections of errors, the buffer zone distances in the 2015 mitigation measures are smaller than the 95th percentile buffer zone distances in the 2013 proposal except for the lowest application rate for small treatment blocks.

There are two additional changes in buffer zone distance requirements relative to the 2013 proposal. First, when applications with overlapping buffers use 60% tarp, then the buffer zone distance remains at 25 feet but the applications must treat no more than 60 acres in total. Second, when one or more applications using 60% tarp have overlapping buffers with one or more applications using other tarp, the acres treated under 60% tarp do not need to be included when calculating the required buffer zone distances for the applications using other tarp.

Field fumigation data collection

We examined a subset of restricted material permits for preplant soil fumigation of Ventura County strawberry fields in 2013. At that time, the county permit conditions were equivalent to DPR’s 2013 recommended permit conditions plus an added requirement that areas treated within a 12-hour period that have overlapping buffers are treated as a single field for the purpose of calculating buffer zone distances.

The notice of intent (NOI) data we examined report growers’ actual 2013 preplant soil fumigation decisions. An NOI is part of a restricted materials permit. Each NOI describes the fumigation of a designated field. Each field may be subdivided into any number of blocks, with each block treated as a unique fumigation event (“a fumigation”).

Each NOI contains a map (or maps) of the site, the fumigation method, the fumigant, broadcast rate in pounds of product and the tarp used. All applications we examined used some type of tarp, as is standard in California strawberry production. The NOI also may include information about the individual blocks within the site to be fumigated each day, such as the block size, the date of each fumigation and the buffer zone distance for each fumigation block. In addition, the maps show the shapes of the blocks and location of the buffers. Most importantly, they depict the physical relationships among the fumigation blocks and between the fumigation blocks and adjacent land, including the property operator of adjacent farmland, urban areas, and occupied structures. In most cases, the maps are the only way to identify overlapping buffer zones because the available GIS data do not provide information on fumigation blocks and buffers, only on fields.

The Ventura County agricultural commissioner’s office provided the NOIs in response to our request for public records. To get a diverse sample, we requested NOIs associated with permits for fields adjacent to urban areas, adjacent to strawberry fields owned by other growers, and adjacent to agricultural land in crops other than strawberries. The data include preplant fumigations using chloropicrin with and without 1,3-D, and chloropicrin without methyl bromide. The data cover 17 permits containing 80 NOIs, accounting for a total of 271 fumigations, which represent about two-fifths of Ventura County’s 2013 fumigations using chloropicrin that did not include methyl bromide. As explained earlier, each permit corresponds to one grower, each NOI to one field. Each field can be divided into fumigated blocks that each have a related buffer distance and buffer zone meeting all requirements. Therefore, the number of blocks equals the number of fumigations and, for the permits we examined, is larger than the number of fields.

For each fumigation, we entered the date, block size and buffer zone distance and indicated whether the grower extended the buffer zone distance onto his or her own property outside the fumigated block. For other tarp fumigations only, we noted the percentage of the perimeter for which there was an opportunity to extend the buffer farther outward. In addition, we entered information from the corresponding NOI, including permit number, site ID, planted and treated acres, total product and broadcast rate (pounds), and method (including use of 60% tarp).

We also entered the use of three buffer zone–reducing practices: increasing the number of hours between adjacent applications to 36 hours or more, extending buffers onto adjacent fields, farm paths or roads, and reducing block size to 6 acres or less when using other tarp.

Growers’ response to 2013 regs

As noted earlier, buffer zone distances are determined by fumigation block size, application method, tarp type and fumigant. First, we summarized the number of blocks by size. Almost a quarter of blocks (25%) were 6 or fewer acres. Another 19% were between 6 and 10 acres. Overall, 230 fumigations (85%) were 20 or fewer acres.

Next, we summarized the number of fumigations and treated acreage by method (drip/chemigation, or broadcast) and tarp type (60% or other). Table 1 reports the share of applications and acreage using each of the two application methods and each of the two tarp types.

<table>
<thead>
<tr>
<th>Applications and treated acres by fumigation method and tarp type, subset of Ventura County fumigation blocks, 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applications</strong></td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>Applications</th>
<th>%</th>
<th>Acres</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drip</td>
<td>221</td>
<td>82%</td>
<td>3,094</td>
<td>84%</td>
</tr>
<tr>
<td>Broadcast</td>
<td>50</td>
<td>18%</td>
<td>584</td>
<td>16%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tarp</th>
<th>Applications</th>
<th>%</th>
<th>Acres</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>185</td>
<td>68%</td>
<td>2,345</td>
<td>64%</td>
</tr>
<tr>
<td>Other</td>
<td>86</td>
<td>32%</td>
<td>1,333</td>
<td>36%</td>
</tr>
</tbody>
</table>
The majority of applications (64%) used 60% tarp — for 60% tarp, buffer zone distances did not change under the 2013 proposal or 2015 mitigation measures. Drip was used over 80% of the time.

Table 2 reports the share of fumigations by tarp type for each method. Although the largest number of fumigations used drip and 60% tarp, almost all broadcast applications used 60% tarp compared to 62% of drip applications. This may be because the average application rate is higher for broadcast than for drip, and buffer zone distances increase with the application rate. Thus, growers using broadcast have more of an incentive to use a tarp that provides a 60% buffer reduction credit. It is important to note that there are two important non-regulatory factors that may have driven the difference in the use of 60% tarp by application method: using 60% tarp represents a $320 per acre increase above the cost of using other tarp, and 60% tarp was physically flexible enough to cover mounded strawberry beds for bed fumigations have only recently become available.

There are a number of strategies growers can use to reduce the buffer zone for a fumigation block. First, it can be reduced by altering the governing factors: tarp type, product application rate, block size, and overlapping buffers across blocks using other tarp or across neighboring blocks fumigated at least 12 hours apart. Growers have additional options in some cases. They can locate the buffer on a road, on other property they own or operate, or on property owned by another entity.

We report in table 3 the number of fumigations and acres where such strategies were used. These numbers do not reflect entirely the importance of these strategies because it is not always feasible for a grower to choose a specific strategy. For example, growers can only choose to extend a buffer zone on other acreage they own or operate if they own or operate adjacent land. Percentages are reported as a share of the total number of NOIs where each measure was feasible, not as a percentage of all fumigations.

Table 3 shows that using a 60% tarp, putting a buffer on a neighboring property, road or farm path, and using lower application rates were the most common strategies to reduce buffer zone acreage. Virtually all fumigations extended buffer zones onto farm paths. Most fumigations used application rates substantially lower than the maximum application rate allowed on the EPA label: 83% of fumigations and 91% of treated acreage used application rates less than 66% of the permitted maximum. (The base for this percentage excludes applications of products also containing 1,3-D because 1,3-D is subject to township caps — limits on the total amount of the material that can be applied in each 36-square mile township — which could also drive a reduction in the application rate.)

Of course, growers may have used these measures for reasons other than buffer zone reduction. For example, a grower may have needed to wait 2 or more days between fumigations due to the unavailability of irrigation equipment or fumigation rigs. Growers may have used a lower product application rate to save money or because of a history of low disease pressure in the block. However, regardless of the reasons for their use, the factors reported in table 3 did determine buffer zone distance.

### Valuation of buffer zone sizes

We estimated buffer zone distances for each fumigation block under the baseline 2013 conditions (Phase 2 EPA regulations and 2013 recommended permit conditions), the 2013 DPR proposal, and the 2015 DPR mitigation measures. The distances were based on the tarp type, block size and application rate.

The 2013 baseline buffer zone distances were computed using the EPA’s online calculator (US EPA 2015) and checked against permit requirements for each NOI; we excluded two fumigations from the analysis because the EPA buffer for both fumigations was much smaller than the buffer on the NOI and we could not determine the reasons for these differences.

We estimated what the buffer zone distances would have been if the 2013 DPR proposal requirements had been in effect by using the tables for the four percentiles of protection in the proposal (DPR 2013a). Similarly, we used the tables in DPR’s 2015 mitigation measures to estimate what the

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**Table 2. Applications and treated acres by combinations of fumigation methods and tarp types in 271 Ventura County fumigation blocks, 2013**

<table>
<thead>
<tr>
<th>Method</th>
<th>Tarp</th>
<th>Applications</th>
<th>%</th>
<th>Acres</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast</td>
<td>60%</td>
<td>49</td>
<td>98%</td>
<td>580</td>
<td>99%</td>
</tr>
<tr>
<td>Broadcast</td>
<td>Other</td>
<td>1</td>
<td>2%</td>
<td>4</td>
<td>1%</td>
</tr>
<tr>
<td>Broadcast</td>
<td>All</td>
<td>50</td>
<td>100%</td>
<td>584</td>
<td>100%</td>
</tr>
<tr>
<td>Drip</td>
<td>60%</td>
<td>136</td>
<td>62%</td>
<td>1,764</td>
<td>57%</td>
</tr>
<tr>
<td>Drip</td>
<td>Other</td>
<td>85</td>
<td>38%</td>
<td>1,330</td>
<td>43%</td>
</tr>
<tr>
<td>Drip</td>
<td>All</td>
<td>221</td>
<td>100%</td>
<td>3,094</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Table 3. Use of strategies that reduce buffer distances reported in Ventura County NOIs, 2013**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Applications</th>
<th>Fumigated acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>60% tarp</td>
<td>185</td>
<td>2,344</td>
</tr>
<tr>
<td>2 or more days between adjacent blocks*</td>
<td>104</td>
<td>1,796</td>
</tr>
<tr>
<td>2 or more days between adjacent blocks, other tarp, adjacent blocks sum to ≤ 40 acres*</td>
<td>52</td>
<td>630</td>
</tr>
<tr>
<td>Buffer on other property†</td>
<td>123</td>
<td>2,065</td>
</tr>
<tr>
<td>Buffer on farm path between properties‡</td>
<td>258</td>
<td>3,559</td>
</tr>
<tr>
<td>(All) blocks ≤ 6 acres, all tarp types§</td>
<td>65</td>
<td>NA</td>
</tr>
<tr>
<td>(All) blocks ≤ 6 acres, other tarp¶</td>
<td>19</td>
<td>21%</td>
</tr>
<tr>
<td>Application rate &lt; 66% of max rate#</td>
<td>203</td>
<td>2,919</td>
</tr>
</tbody>
</table>

* Of 247 fumigations and 3,280 acres with adjacent fumigated blocks.
† Of 207 fumigations in which the owner/operator of blocks adjacent to fumigated block were indicated.
‡ Of 262 fumigations and 3,559 acres where a farm path was labeled clearly.
§ Six acres is DPR’s cutoff for a 60-foot minimum buffer for fumigations using other tarps; larger blocks have a 100-foot minimum buffer.
¶ Of 90 fumigations using other tarp.
# Of 244 fumigations that did not use products containing 1,3-D.
buffer zone distances would have been if that regulation were in effect (DPR 2016a). It should be noted that we used the tables in effect in 2015 and not the 2016 revisions to those tables. We did not consider any changes in growers’ choices regarding block size, application method, rate or tarp; many factors affect treatment decisions including pest and disease pressure, terrain, irrigation system design and cost.

After determining the applicable CDPR 2013 proposal buffer zone distance for each percentile of protection for each fumigation block, we calculated the total estimated acres in the buffer zone. If the fumigation buffer zone distance and buffer zone acreage were based on combined acreage with other blocks due to the overlapping buffer rule, we used the combined acreage to calculate them.

The buffer acreage calculations required the simplifying assumption that fumigation blocks were square due to limitations of the NOI map data, and that the buffer extended outside the fumigation block for the percentage of the perimeter that the information in the map indicated. This approach results in an approximation of the buffer zone acreage because the fumigation blocks in reality have a broad range of shapes and proportions. However, we could not discern the lengths of all block sides from the maps, and GIS data of the quality necessary to address buffer requirements were not available. Because the approach is consistent across buffer requirements, the approximation does not introduce distortions in the comparison of different requirements.

To evaluate the incremental effect of the 2013 DPR recommended permit conditions increased buffer zone distances for 28% of blocks, with variation in the extent of this increase and the associated effects on the number of treated acres. Note that these acreage effects regard total buffer zone acreage, not the planted acreage lost to incremental increases in buffer zone distances. Technically, growers are not restricted from planting in untreated areas. We used the same approach to compare the buffer zone distances and resulting buffer zone acreage that would have been required in the 2013 DPR proposal and 2015 DPR mitigation measures to the buffer distances and buffer zone acreage in the NOIs.

Calculating the treated strawberry acreage that would have been lost to buffer zones as a consequence of the 2013 proposal or 2015 mitigation measures was more complex than calculating the actual 2013 buffer zone acreages. This calculation was only necessary for fumigations using other tarps, as these tarps are the only ones where buffer zone distances increased. We assumed that growers using other tarps would be able to expand buffer zones onto their own fields, and would be able to expand onto other growers’ fields if the 2013 buffer zones already did so. Only 30 fumigations would not have been able to extend the buffer zone distance outward, in full or in part, due to being adjacent to a residential area, industrial property or permanent walking path.

**Buffer zone acreage effects**

In the case of applications using 60% tarp, there was no difference in buffer zone acreage between that reported in the NOI and the acreage that would have been necessary under the 2013 proposal or 2015 mitigation measures (the EPA buffer zone distance for 60% tarp was larger than that in the state regulations, and therefore the EPA distance takes precedence in all cases). Disaggregating applications using other tarp by application method, all fumigations with increases in buffer zone distances are drip applications with the exception of a single block with a broadcast application at the proposal’s 95th percentile of protection.

Our analysis of the acreage effects of the 2013 proposal and 2015 mitigation measures has three components. The first estimates the total increase in buffer zone acreage due to increases in buffer zone distances (table 4). The second estimates the reduction in acreage that can be fumigated due to increases in buffer zone distances (table 5). The reduction in acreage that can be fumigated is smaller than the increase in buffer zone acreage if growers can extend buffer zone distances farther outside the field. The third focuses on the subset of 30 blocks for which the recent buffer zone rules result in a reduction in the acreage that can be fumigated (table 6).

Figure 3 summarizes the number of fumigations for which the buffer zone distance would increase under the 2013 proposal and 2015 mitigation measures compared to the distances reported in the NOIs. The number increases as the percentile of protection increases in the DPR 2013 proposed regulations. The number drops under the 2015 mitigation measures, affecting only 30 fumigations (11% of the total number of fumigations). For each fumigated block, we calculated the increase in buffer zone acreage by comparing the actual buffer zone acreage derived from the 2013 NOIs to the buffer zone acreage that would have resulted under the proposed and

<table>
<thead>
<tr>
<th>2013 NOI buffer acres</th>
<th>Percentile of protection</th>
<th>2013 proposal</th>
<th>2015 mitigation measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80th</td>
<td>85th</td>
<td>90th</td>
</tr>
<tr>
<td>60% tarp</td>
<td>853</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Other tarp</td>
<td>781</td>
<td>33 (4%)</td>
<td>336 (43%)</td>
</tr>
<tr>
<td>Broadcast</td>
<td>358</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Drip</td>
<td>1,276</td>
<td>33 (3%)</td>
<td>336 (26%)</td>
</tr>
<tr>
<td>Total</td>
<td>1,654</td>
<td>33 (2%)</td>
<td>336 (21%)</td>
</tr>
</tbody>
</table>

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implemented mitigation control measures. Table 4 summarizes the results. There were 1,634 acres in buffer zones in the applications reported in the 2013 NOIs. Some applications using other tarp would have sustained increases in buffer zone acreage. The estimated additional 33 total acres that would have been required at the 80th percentile of the 2013 DPR proposal represents a 2% increase in total buffer zone acreage. The impact rises steeply across percentiles of protection. The additional 5,214 acres that would have been needed for buffers at the 95th percentile is a 319% increase over the actual 2013 buffer zone acreage. The DPR 2015 mitigation measures results in a considerably smaller increase in acres in buffers: 21%. Critically, not all of the additional buffer zone acreage will displace acres treated with preplant soil fumigation for strawberry production because of the ability to extend the buffer zone further outside the fumigation block in most cases.

Treated acreage effects

To estimate the effect of increases in buffer zone distances on treated strawberry acres, we examined the maps for the 30 fumigations that would have faced some limitations to expanding the buffer outside the field. In each case, using the percentage of the perimeter that could not expand, we estimated the loss in treated acres due to the buffer zone distance extending into the field.

In terms of the loss in treated acres across all the fumigations, not just the 30 most impacted ones, under the DPR 2013 proposal, the incremental loss was negligible at the 80th percentile (see table 5), under 0.05% of total acreage (1.43 acres out of 3,645.5 treated acres). It was substantial at the 95th percentile, almost 5% (181 acres). Under the DPR 2015 mitigation measures, the loss was only 0.6% of treated acreage.

For the 30 impacted blocks, however, the average percentage of treated acres lost was obviously significantly higher. Under the proposed mitigation measures at the 80th and 85th percentiles, it was 3% and 5%, respectively. The impacts were much more pronounced at the higher percentiles, with an average of 21.3% of treated acres at the 90th percentile becoming part of the buffer, and 45.2% at the 95th percentile (table 6). Under the DPR 2015 mitigation measures, the affected blocks lost an average of only 10.7% of treated acreage.

Implications, lessons

Recent DPR buffer zone distance requirements for chloropicrin applications would have impacted a few of the strawberry growers in our study much more than the majority of growers, primarily due to the location of their fields and nearby land uses. The heterogeneity of the buffer zone distance requirements across tarp types also would have impacted growers.
buffer zone distances for 60% tarp are determined by EPA label restrictions and are not affected by the recent DPR requirements; for other tarp, the percentile of protection in the DPR requirements does influence the buffer zone distances, which affect buffer acreage and can affect treated acreage.

An important caution is necessary. Extrapolating values from the results of this case study to infer potential effects for the rest of the strawberry industry, or for other commodities, could be misleading for a number of reasons. First, the NOIs examined here were a subset of NOIs in Ventura County for 2013 resulting from a request for a set of NOIs with applications for which buffer zone distance regulations are likely to have an effect. Fields surrounded completely by other agricultural fields, in contrast, could have no effects of the regulation on fumigation blocks. At the regional level, other strawberry-producing regions differ from Ventura County in several ways, including but not limited to total strawberry acreage, the timing of fumigation, the size distribution of strawberry fields, neighboring land uses, yields and local use permit requirements. Further, our analysis did not consider how the 2013 proposal or 2015 mitigation measures may interact with other regulatory requirements, including DPR’s requirements regarding VOC emissions and 1,3-D township caps. Any of these factors could alter acreage effects. Nonetheless, some general lessons can be derived from this case study.

First, when growers have flexibility in terms of altering practices to reduce the impact of buffer zone requirements, they will utilize them based on their field-specific circumstances; hence, mitigation measures should provide opportunities to growers to reduce the impact of those measures. As a result, the mitigation measures will encourage growers to select practices that mitigate health hazards of offsite movement of pesticides without mandating the use of specific practices. For example, the 2013 recommended permit conditions corresponded to extensive use of 60% tarp.

Second, the buffer zone distance is a key driver of the resulting acreage in buffers, dramatically changing affected acreage according to the percentile of protection in the 2013 proposal. Therefore, the science underlying the determination of a buffer zone distance should be carefully evaluated. Importantly, new scientific data resulted in substantial adjustments to buffer zone distances for the 2015 mitigation measures compared to the 2013 proposal at the 95th percentile. Investing in the science underlying regulations should be a priority for policymakers.

Finally, when a buffer zone distance requirement depends on site-specific characteristics, the impacts will be distributed unequally, because some growers can accommodate the buffer zone requirement outside the treated blocks while others cannot. As the buffer zone distance increases, this inequality is magnified.

By definition, site-characteristic based buffer zone regulations will have dramatically different effects across locations due primarily to differences in neighboring land use.

Investing in the information necessary to study the impacts of spatially defined regulations, such as detailed GIS data, should be a priority for policymakers and regulators engaged in developing these regulations.

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References


USDA
Methyl iodide, once promoted as a suitable alternative to methyl bromide for soil fumigation in strawberry systems, was withdrawn from the market in 2012 after a contentious regulatory battle that revolved around its high toxicity. At the time of its withdrawal, Arysta LifeScience, the maker of the chemical, claimed that it was no longer economically viable. In this study, I investigated what made the chemical nonviable, with a specific focus on growers' nonadoption of it. Interviews with strawberry growers in the four top California strawberry-growing counties revealed that growers' decisions not to use it were primarily related to public disapproval, although the continued availability of methyl bromide and other fumigants played a contributing role by making adoption less urgent. The study results suggest that policies in place during the methyl bromide phaseout did not strongly encourage the development and extension of less toxic alternatives, which undermined the strawberry industry's position.

In March 2012, after a decade seeking regulatory approval for the soil fumigant methyl iodide, Arysta LifeScience withdrew it from the United States and other markets. Methyl iodide, registered by Arysta under the brand name Midas, was designed to replace methyl bromide, a favored soil fumigant among strawberry growers in California, which was destined for phaseout in compliance with the international Montreal Protocol on Substances that Deplete the Ozone Layer.

Methyl iodide had been promoted as a suitable alternative to methyl bromide because it shares its soil disinfestation qualities but does not present as much harm to the upper atmosphere (Ohr et al. 1996). Many argued, however, that it was more acutely toxic to humans and environmentally degrading than methyl bromide. Pesticide Action Network of North America, for example, reported it to be a known neurotoxin and carcinogen, associated with suppression of thyroid hormone synthesis, respiratory illness and lung tumors, and a probable cause of miscarriages and birth defects (PANNA 2011).

As a preplant fumigant, methyl iodide, like methyl bromide, posed a health risk to those in the immediate vicinity of an application: farmworkers, neighbors and fumigation workers themselves. Methyl iodide poses no known risk to consumers.

During and immediately after regulatory review for approved use in California, methyl iodide met considerable opposition from public health, environmental and farmworker advocacy groups, which organized several protests,
public hearings and over 53,000 written comments opposing its registration. Registration is the process by which government agencies license pesticides for use. To register a pesticide in California, the responsible party must first obtain approval from the U.S. Environmental Protection Agency (EPA). Then the chemical must undergo a thorough scientific evaluation by California’s Department of Pesticide Regulation (DPR) to ensure it is effective and will not harm the environment or human health when used according to directions (DPR 2011, 19).

When DPR registered methyl iodide against the advice of its own agency scientists and external review committee as well as the opposition of the advocacy organizations, many of the organizations filed a lawsuit against both DPR and Arysta for failing to abide by California environmental law. Just in advance of a court ruling on the lawsuit that hinted to be unfavorable to Arysta, the company voluntarily revoked its request for registration and announced its plans to suspend operations in the U.S. market, publicly stating that the chemical was no longer economically viable.

An understanding of what led to the withdrawal of methyl iodide holds many lessons for stakeholders and the general public. A convergence of factors caused its demise, including DPR’s mishandling of the registration process, which activists were able to exploit both in the court of public opinion and in the lawsuit (Froines et al. 2013). Yet, Arysta would likely not have withdrawn from the lawsuit had widespread grower adoption of methyl iodide demonstrated the chemical’s economic viability.

This study investigated what made the withdrawal of methyl iodide possible, with a specific focus on the lack of grower adoption. It was part of a large social science study that is investigating how tighter regulations on soil fumigants are affecting grower practices and the strawberry industry. My project team conducted 74 semistructured interviews with growers in four major strawberry-growing counties (see sidebar). We thematically coded these interviews using the qualitative data software NVivo10. In addition, we spoke with 40 people closely tied to the strawberry industry about their perspectives on methyl iodide, including shippers, pest control advisers (PCAs), research and extension agents, independent researchers and people in grower organizations. For the purposes of this article, I also drew on documents from the lawsuit since they provide important data about the assumptions and perspectives of Arysta LifeScience.

Methyl bromide phaseout

Methyl bromide has been widely used since the 1970s as a broad-spectrum soil sterilizer in seed production and in several important California cash crops. The strawberry industry has been its largest beneficiary and has seen enormous increases in productivity owing to its use (Goodhue et al. 2005). Methyl bromide reliably eradicates several soil pathogens that attack the root system of strawberry plants and is also very effective in controlling weeds and nematodes. Annual applications of methyl bromide have allowed strawberry growers to plant on the same block year after year; bi-annual applications have allowed them to rotate with vegetable growers every other year in regions with a long strawberry season (notably Monterey and Santa Cruz counties). Soil disinfestation alternatives that compromise yields or increase costs are thus necessarily noncompetitive.

Based on methyl bromide’s contribution to ozone depletion, in 1991 the Montreal Protocol mandated the phaseout of methyl bromide, and as a signatory to the convention, the United States agreed to stop producing and importing it by 2005. As the phaseout drew near, however, the United States began requesting that the parties to the Montreal Protocol grant critical use exemptions (CUEs) for agricultural operations in which (a) not using methyl bromide would result in a significant market disruption and (b) there were no technically and economically feasible, available alternatives or substitutes that were acceptable from the standpoint of the environment and public health (US EPA n.d.).

A series of economic studies bolstered the case for CUEs by predicting yield losses and an industry shakeout without the use of methyl bromide and by stating that a viable alternative to methyl bromide did not exist (Carter et al. 2005; Goodhue et al. 2005). After intense lobbying by the United States delegation, largely speaking on behalf of the California strawberry industry, the CUE

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Interview methods

Grower interviews were conducted with standard social science methods for qualitative research. The project team obtained grower names and contact information through county agricultural commissioners’ offices, which collect data on all pesticide use applications and make that publicly available by state law. However, not all contact information was correct and one county (Santa Barbara) did not provide contact information in its report. Owing to these difficulties, as well as the difficulty in reaching many growers, growers were selected for participation by convenience sample, meaning that those who were willing and available to participate were selected. The sample skewed somewhat to large, more established growers but was otherwise stratified along a number of dimensions.

The sample included growers in the four major strawberry-growing counties, Monterey (n = 22), Santa Barbara (n = 9), Santa Cruz (n = 19) and Ventura (n = 24). Six growers interviewed had under 20 acres in production, eight had 21 to 50 acres in production, nine had 51 to 100 acres, 46 had over 100 acres in production and five did not report. Five growers had all organic operations, 31 had mixed conventional and organic operations, and the remaining were all conventional.

Interviews were semistructured and ranged in time from 5 minutes on the phone to 2 hours in an office. The vast majority were full interviews in which all questions were answered. Questions addressed a range of issues and practices around strawberry production, including fumigation, varietal choice, rotations, labor and marketing. In regard to methyl iodide, we asked growers whether they had ever considered using it, and why they had or had not. In accordance with a human subjects protocol approved by UC Santa Cruz’s Institutional Review Board, growers were free to refuse to answer questions and were promised nondisclosure of personally identifying information.
was incorporated into the Protocol and approved by signatories (Gareau and DuPuis 2009). Thereafter, approved CUE stocks could be allocated to fumigation companies, which would provide methyl bromide to growers who were certified as approved users, based on particular field conditions or township caps on alternatives (US EPA 2004). During negotiations, the United States agreed to stop producing and importing methyl bromide by 2015. Owing to the CUEs, use of methyl bromide on strawberries declined only marginally during the early periods of the phaseout, while it declined precipitously and even to negligible amounts for other crops (Goodhue et al. 2005).

As the 2015 phaseout drew near, methyl bromide became increasingly difficult and costly to access. Many began to rely more heavily on other, still allowable fumigants: they increased the percentage of chloropicrin they used in combination with methyl bromide, or they switched to chloropicrin alone or in combination with 1,3-D (Telone).

Meanwhile, the industry was slow to develop and test nonchemical alternatives, and, as of this writing, none has proven to be as reliable and cost effective as methyl bromide on a commercial scale. According to some of our interviewees, the procrastination in developing alternatives was in part a consequence of the CUE process, which created doubt among at least some in the industry that methyl bromide would ever be phased out.

### Methyl iodide regulatory troubles

Methyl iodide was developed by researchers at UC Riverside as a potential replacement for methyl bromide, and licensed by Arysta LifeScience under the brand name Midas. In 2002, Arysta moved to get methyl iodide approved for commercial use, first seeking registration with the EPA and then DPR. Due to emerging controversy surrounding the chemical — for example, in September 2007 more than 50 scientists, several of them Nobel laureates in chemistry, delivered a letter to EPA asking the agency to deny registration of its use as a soil fumigant — in April 2006 the EPA denied registration. A month later, it reversed course, granting a 1-year registration that, in 2008, was extended without time limitations.

In California, there are state environmental laws that go above and beyond federal standards, and a stronger pesticide surveillance system administered by DPR. By virtue of the California Environmental Quality Act (CEQA), all pesticide registrations are subject to thorough reviews and analyses of risks, and responsible agencies must prepare risk characterization documents.

Because potentially hazardous chemicals require federal approval first, DPR’s staff did not begin the risk analysis process for methyl iodide until early 2005. It completed an initial first draft in 2009, and then distributed it to the Office of Environmental Health Hazard Assessment (OEHHA) and an independent review panel of eight, convened by DPR.

OEHHA and the DPR panel provided extensive comments on the draft document by the end of 2009. Both expressed skepticism about the chemical’s safety and in their risk assessment reports concluded that the application of methyl iodide in field fumigation could result in significant health risks for workers and the general population (DPR 2010c; Lim and Nu-May 2010). Nevertheless, in April

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**More than 50 scientists, several of them Nobel laureates in chemistry, delivered a letter to EPA asking the agency to deny registration of methyl iodide’s use as a soil fumigant.**

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Methyl bromide has been used by growers since the 1970s to control soil pathogens, weeds and nematodes. Above, weeds and pathogen wilt in a Santa Cruz County field that was not treated with methyl bromide.
2010 Mary-Ann Warmerdam, DPR director at the time, announced her intent to register the chemical.

Warmerdam’s announcement was a necessary step to kick off a CEQA-required public comment period. It was during this period that activist organizations, including environmental, public health and farmworker groups, mounted an internet campaign to encourage members of the general public to comment on methyl iodide registration. DPR received 53,000 comments, all but a handful objecting to the chemical’s registration.

Despite this surge of opposition, and neglecting the recommendations of DPR’s own staff and external review panels, Warmerdam approved methyl iodide for use as an emergency registration in December 2010, albeit with stricter mitigation measures than those required by the EPA label (DPR 2010a). In her statements, she acknowledged the volume of comments received but noted that she discounted them because “most of the comments received were similar and generated through social media campaigns” and “provided no evidence that DPR’s stringent use restrictions [would] not keep exposures to methyl iodide within safe levels” (DPR 2010b).

Following approval, pressure mounted to reverse the decision. Owing to this pressure, the California Assembly’s Environmental Safety and Toxic Materials and Health committees held several hearings in February 2011. In response to a petition filed a year prior by nearly a dozen advocacy organizations, a request by California Senator Diane Feinstein and a letter signed by thirty-seven California legislators, EPA agreed to open a 2-month public comment period in March 2011.

In late 2011, boards of supervisors in two major strawberry-producing counties, Monterey and Santa Cruz, passed resolutions requesting that the state of California withdraw approval of methyl iodide until additional research was completed, peer-reviewed and published. During 2011, activists organized many direct actions. Most visibly, they held mock fumigations on the steps of the state capitol and Arysta’s offices (Greenaway 2011) and picketed some strawberry fields.

Meanwhile, activists had pursued legal action, filing a lawsuit on December 30, 2010, immediately following methyl iodide’s registration.

The lawsuit was filed by Earthjustice, a nonprofit law firm, and California Rural Legal Assistance against DPR and director Warmerdam, and Arysta LifeScience, as the real party in interest (Pesticide Action Network of North America v. California Department of Pesticide Regulation (2010), Superior Court for the State of California, Alameda County). Most of the counts were about DPR’s failure to abide by California environmental laws for transparency in decision making and its failure to make a robust assessment of potential health and environmental effects. The merits of the case were thus based on whether the agency had done due diligence in reviewing and evaluating all relevant material and whether it had made those reviews public. Helping the plaintiffs’ case, the judge admitted a wide range of documents into evidence, including internal documents from DPR staff that controverted some of its public claims (interview with Greg Loarie, Earthjustice attorney, July 7, 2014).

The two issues that received the most attention during briefing and oral proceedings concerned adequate attention to the alternatives and the methodology for determining target concentration of the chemical. The plaintiffs contended that the DPR director had chosen to omit a range of scenarios in the final report. In addition, the final registration decision for methyl iodide sanctioned target concentrations of the chemical orders of magnitude higher than DPR staff scientists had recommended in their report. An internal memo DPR received from Arysta dated Feb. 16, 2010, revealed that Arysta had put pressure on DPR to come up with assumptions more favorable to Arysta. As narrated in oral arguments on Jan. 12, 2012, the memo stated:

“There is still a gap between the current DPR view and the scenarios that would lead to acceptable labels. It is also clear that this gap cannot be closed by label mitigation measures. It is essential to re-visit the toxicology assessments to come up with less conservative assumptions.”

Finally, the plaintiffs referred to a memo written by one of DPR’s toxicologists to the director in which he questioned how the director had used a “mix and match” method to come up with a desired “acceptable” level of exposure.

The main hearing on the merits of the case, held on Jan. 12, 2012, showed that the court had grave concerns. The judge became impatient about the defendants’ claim that they had explored alternatives, noting that the record did not include an environmental evaluation of the “no register alternative,” required by the guidelines for registering a chemical. “I looked in vain in the record to try to find anything that actually was an analysis of the no project,” the judge stated. When defendant’s attorneys were unable to provide an adequate response, he said, “I have to tell you, [since] you had not done that [provided the evaluation of the no register alternative], this is a granted petition [plaintiffs win]. I just don’t see how [given that] you didn’t do that, you can say that you are CEQA compliant.”

On Mar. 20, 2012, before the judge had ruled, Arysta requested that all parties appear in court the next day. At the beginning of that court session, before giving defendants a chance to speak, the judge informed the courtroom that he was preparing to rule against the defendants for violation of CEQA on the grounds that they had not adequately studied the alternatives. In addition he was intending to grant the plaintiff’s petition for DPR to set aside its approval of methyl iodide because of lack of evidence that the director used a methodology that had scientific validity. Attorneys for Arysta then announced that Arysta was withdrawing its methyl iodide products from the U.S. market and had cancelled its registration with DPR that afternoon. The company had in fact issued a press release the previous day stating it was withdrawing Mida owing to methyl iodide’s economic nonviability. The case was eventually declared moot, with the judge stating that the plaintiffs had received all the relief they could get.

Economic troubles

Arysta might have continued to pursue legal action had methyl iodide sales been robust. But, in fact, grower adoption of the chemical was minimal. As of December 2011, a year after registration, there had been only six permits issued in California, and, aside from field trials, the chemical had been applied to less than 20 acres, and Arysta had allegedly paid for those applications. All applications were less
than 5 acres, and only one was on straw-berries (Wozniacka 2012). According to one of the lawsuit documents, in the first quarter of 2012 there were no sales at all.

Table 1 summarizes growers’ reasons for not using methyl iodide, based on coding of our interview data. (Due to time constraints and the open-ended nature of interviews, not all 74 growers interviewed responded to this question.) Of those who knew about the chemical (n = 46), a plurality did not adopt it out of concern for the bad publicity they would face from protesters and the public. “From what I understood, if you were gonna apply it, you would have protestors around your field,” mentioned one grower. Many more simply noted that the public was against it.

Contributing to their concerns, several berry shippers did not want to be associated with a controversial chemical, having received word from retailers to whom they sold that they would not take the strawberries. These shippers had advised their growers not to use it. After relating that supermarket chains told one such shipper they would not carry berries from fields fumigated with methyl iodide, another interviewed grower said, “We couldn’t adopt it because who would buy the berries if we used it?” The California Strawberry Commission, a grower marketing order, did not appear to support it either.

Some of the growers interviewed were disappointed in the methyl iodide outcome and angered by the protests, feeling that the activists had intentionally misinformed the public about its risk. “People thought we were spraying [it] and there were residues on the crop,” reported one grower. These growers were responding to the many public comments and news articles that falsely suggested that methyl iodide was a risk to consumers (as a pre-plant fumigant, the chemical’s toxicity is generally limited to those who are in the vicinity of a fumigation). However, a surprising percentage of growers declined to adopt the chemical because they concurred with the activists that the chemical was excessively harmful, a sentiment that was shared by a couple of shippers. As put by one grower, methyl iodide was “pretty scary.”

Another major reason growers did not adopt methyl iodide was that they did not have the opportunity to do so. Nineteen percent mentioned they would have tried it (or had conducted trials) but that either county restrictions or the uncertainty surrounding the chemical kept them from using it. “I didn’t get a chance to really see a lot of it, because it seemed to be taken away so quickly,” reported one grower. The window for trying the chemical was small; it was available for only 15 months, between when it was first registered on Dec. 29, 2010, and when it was taken off the market in March 2012, and there was a lawsuit pending the entire time.

Growers did not adopt the chemical also because they had not wanted or needed to. CUEs allowed methyl bromide to stay in the market, albeit in substantially lower amounts, and chloropicrin had proved reasonably efficacious, at least in the short term, so 13% of growers interviewed never seriously considered methyl iodide. “It is not worth it. I’ve got an alternative, which is chloropicrin . . . it’s not as good as methyl iodide, but I can’t risk putting the reputation of our label in such an unfavorable light,” said one grower. Another 13% were not sure of the chemical’s efficacy.

Prior to registration, there had been very few field trials to demonstrate its efficacy, particularly at a commercial scale where buffer zones would come into play. While some growers had heard of good results, others were not swayed. As one said:

The trials that I saw with that [methyl iodide] didn’t impress me . . . It’s not so much what the environmentalists said. I went strictly on the research that was done and the comparison to the tools that we have now . . . If it was something that, say, that worked better than methyl bromide, well, then it’s a different story, but it wasn’t working as effective (sic).

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<table>
<thead>
<tr>
<th>Reason for nonadoption</th>
<th>Number of responses</th>
<th>Percent of responses*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concern with protestors, public backlash</td>
<td>13</td>
<td>24%</td>
</tr>
<tr>
<td>Concern with toxicity of the chemical for themselves and workers</td>
<td>9</td>
<td>17%</td>
</tr>
<tr>
<td>No opportunity to adopt</td>
<td>10</td>
<td>19%</td>
</tr>
<tr>
<td>Not proven effective</td>
<td>7</td>
<td>13%</td>
</tr>
<tr>
<td>Not interested, did not consider</td>
<td>7</td>
<td>13%</td>
</tr>
<tr>
<td>No knowledge, or misunderstanding about chemical and controversy</td>
<td>8</td>
<td>15%</td>
</tr>
<tr>
<td>Total</td>
<td>54</td>
<td>100%</td>
</tr>
</tbody>
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* Figures in this column do not sum to 100% due to rounding.
With high land values, growers were understandably reluctant to take a risk on an unproven chemical. A final reason for nonadoption was that growers had never heard of the chemical.

These last three reasons — growers being uninterested in, unimpressed by or not knowledgeable about methyl iodide — representing 41% of those responding, suggest that extension for the chemical was unenthusiastic, if it existed. Most of the extension agents and PCAs with whom we spoke did not encourage its use, also in expectation of public pushback. It would have been rare, in any case, to have broad levels of adoption of a chemical that had barely been tested in its first year of release.

In the Blaser Declaration opposing the plaintiff’s efforts to recoup attorney’s fees (Blaser was the chief financial officer of Arysta), Arysta, in an effort to avoid paying those fees, revealed it had made many assumptions that proved unrealistic. The company did not expect the registration process to take a decade, and once the chemical was approved, the assumption was that it would immediately and fully replace methyl bromide. Arysta was not expecting DPR to impose buffer zones twice that of the EPA requirements, which significantly reduced the acreage to which a grower could apply it, while methyl bromide was not subject to such strict use restrictions. From Arysta’s perspective, methyl bromide was competing with its replacement; “demand [for methyl iodide] had failed to materialize at all.” In addition, too many unexpected costs were associated with methyl iodide, including the increased costs of regulations, and company operating costs of millions of dollars in the short term, with no prospects for significant change in the long term. Arysta tried to sell the methyl iodide license to three other businesses, but all backed out for the same reason of economic unsustainability that led Arysta to cancel the registration.

Lessons learned

Activism contributed to the failure of methyl iodide; it scared many shippers and growers into nonadoption and made extension agents and PCAs skeptical of introducing it. Regardless of whether the public understood that a preplant fumigant did not put consumers at risk, the activism was effective. Yet, it was not activism alone that made it economically nonviable. Arysta was too optimistic about the speed of the regulatory process and adoption. And yet, Arysta’s assumptions might have been more reasonable had the strawberry industry not continued to obtain CUEs for methyl bromide long past the initial deadline for phaseout.

CUEs induced complacency in the industry, giving growers hope that the exemptions would persist and slowing down the development and testing of other alternatives, including less toxic alternatives. Not only did this complacency undermine the viability of methyl iodide, it put the industry in a weak position, with no scalable solutions for soil pathogens on the immediate horizon.

Given that obtaining CUEs effectively slowed the development of these very alternatives, the immediate lesson for growers and the strawberry industry is that technology-forcing regulation ought to be heeded rather than contested, especially given the time it takes to bring a new material to commercial viability. Moving forward, regulators and policymakers should consider policies that will jumpstart the development of alternatives and extend them widely. This is more urgent than ever. Since the methyl iodide campaign, other fumigants are facing more scrutiny and potential public pressure, and DPR has signaled its intent to phase out chemical fumigants altogether. For the industry, a favorable regulatory climate can no longer be assumed, and it needs to redouble its investment and experimentation in less toxic chemical or nonchemical alternatives.


References


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The activity of commercial soil fumigants on some key soilborne pathogens was assessed in sandy loam soil under controlled conditions. Seven soil fumigants that are registered in California or are being or have been considered for registration were used in this study: dimethyl disulfide (DMDS) mixed with chloropicrin (Pic) (79% DMDS and 21% Pic), Tri-Con (50% methyl bromide and 50% Pic), Midas Gold (33% methyl iodide [MI] and 67% Pic), Midas Bronze (50% MI and 50% Pic), Midas (MI, active ingredient [a.i.] 97.8%), Pic (a.i. 99% trichloronitromethane) and Pic-Clor 60 (57% Pic and 37% 1,3-dichloropropene [1-3,D]). Dose-response models were calculated for pathogen mortality after 24 hours of exposure to fumigants. Overall, the tested fumigants achieved good efficacy with dosages below the maximum label rate against the tested pathogens. In this study, Pythium ultimum and citrus nematode were sensitive to all the fumigants and Verticillium dahliae was resistant. For most fumigants, California regulations restrict application rates to less than the maximum (federal) label rate, meaning that it is possible that the fumigants may not control major plant pathogens. This research provides information on the effectiveness of these alternatives at these lower application rates. The results from this study will help growers optimize application rates for registered fumigants (such as Pic and 1,3-D) and will help accelerate the adoption of new fumigants (such as DMDS) if they are registered in California.
formulations of fumigants (e.g., Pic-Clor 60, a mixture of 57% chloropicrin and 37% 1,3-D), there is a need to conduct similar dose-response evaluations of pathogen sensitivity to them.

In the past decade, research on alternative fumigants has focused on finding effective application rates for the various application methods, such as drip fumigation and fumigant applications under low permeability films. More recently, due to federal and state regulations (CDPR 2009; USEPA 2015), research has increasingly focused on methods to reduce fumigant atmospheric emissions. These new federal and state regulations limit application rates of fumigants in order to reduce exposure risk to farmworkers and bystanders and to limit air pollution from release of volatile organic compounds (VOC) that form ground-level ozone (smog).

The new fumigant application rates are considerably lower than the previously allowed rates and may not adequately control soilborne pathogens and weeds. Currently, soil fumigants are usually applied under standard polyethylene tarp, which is highly permeable and allows large amounts of fumigants to escape into the atmosphere (Gao et al. 2013). Recent research has evaluated the potential for impermeable films to reduce fumigant emissions and to enhance the efficacy of low application rates. Tarping fields with low permeability film, such as virtually impermeable film (VIF) or totally impermeable film (TIF), has been effective in retaining fumigants in soil (Gao et al. 2013). These films can improve the efficacy of reduced fumigant application rates because they retain higher fumigant concentration and extend the exposure time (concentration × time) under the film compared to standard polyethylene film (Fennimore and Ajwa 2011; Qin et al. 2011).

A new MBF alternative, dimethyl disulfide (DMDS), recently received a federal registration and is being considered for registration in California. Previous studies assessed the technical formulations (98% to 99%) of DMDS and showed that it is biologically effective against citrus nematode (Tylenchulus semipenetrans; Cabrera et al. 2010) and several soilborne pathogens: Sclerotinia sclerotiorum, Sclerotium rolfsii, Rhizoctonia solani and Phytophthora cactorum (Fritsch et al. 2002). Limited dose-response data are available on DMDS, however, and no information is available on the proposed commercial formulation with chloropicrin (Pic), DMDS:Pic (79:21).

One additional MBF alternative assessed in the current study is methyl iodide (MI), which received a federal registration in 2007 and a California registration in December 2010. Laboratory dose-response studies — which determine the relationship between the amount of fumigant and its effect on an organism — have indicated that MI is as effective as or more effective than MBF to control soilborne pathogens and weeds (Becker et al. 1998; Hutchinson et al. 1999; Hutchinson et al. 2000; Luo et al. 2010; Ohr et al. 1996). MI has a synergistic relationship with chloropicrin under controlled conditions, similar to the relationship between MBF and chloropicrin (Hutchinson et al. 2000). However, in March 2012, all MI registrations were withdrawn by the manufacturer. Nevertheless, it may be reintroduced in the future, and the MI data presented here is helpful for understanding the role of fumigant chemistry in the mobility and efficacy of fumigants.

When registering a new fumigant, dose-response studies are not required and efficacy studies usually are conducted for only the pure product. Commercial fumigant formulations may contain several active ingredients; however, the efficacy rate is typically determined for a single active ingredient for a specific target pathogen (i.e., control of certain fungal pathogens, nematodes and weeds) and specific crops. However, the synergistic relationship caused by mixing two fumigants can enhance efficacy compared with fumigants applied alone (Hutchinson et al. 2000).

Our earlier research developed dose-response data for InLine (61% 1,3-D and 33% chloropicrin) (Klose et al. 2007). The use of 1,3-D has been capped at 90,250 pounds per year per township (36-square-mile area). With this restriction on the amount of 1,3-D that can be used in California, a new commercial formulation, Pic-Clor 60, was recently introduced into the market and is being used as a replacement for InLine. The dose-response data developed for InLine, however, may not be valid for Pic-Clor 60.

The objective of this study was to develop a dose-response model for tested soil fumigants controlling soilborne pathogens in a sandy loam soil; this soil type was selected because it represents over 80% of soils that are used for strawberry production in California. Dose-response models help determine the optimum fumigant and fumigation rate to control soilborne pathogens.

**Soil and chemicals**

Soil samples were collected from the upper soil layer (5 to 20 centimeters depth) from a commercial field in Salinas, California (Chualar loam series, fine-loamy, mixed, thermic, Typic Argixerolls), that had not been fumigated in the last 5 years. Soil characteristics were 10% of clay, 15% of silt and 75% of sand; organic matter, 0.9 g kg⁻¹; moisture content, 10%; and pH, 7.
The table 1. Probability levels of multivariate ANOVA for the effects of soil fumigants, application concentrations and the interactions between main factors on mortality of soilborne pathogens

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Fusarium oxysporum</th>
<th>Pythium ultimum</th>
<th>Rhizoctonia solani</th>
<th>Tylencyclus semipenetrans</th>
<th>Verticillium dahliae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fumigant</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Concentration</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
</tr>
<tr>
<td>Fumigant × concentration</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Soil fumigants: DMDS plus Pic (79% DMDS:21% Pic), Tri-Con (50% MBr:50% Pic), Midas Gold (53% Ml:67% Pic), Midas Bronze (50% MI:50% Pic), Arysta LifeScience, Cary, North Carolina) and Midas Gold (33% MI:67% Pic, Arysta LifeScience, Cary, North Carolina).

**Experimental setup**

Inoculum bags of soilborne pathogens *Fusarium oxysporum*, *Pythium ultimum*, *R. solani*, *Verticillium dahliae* and *T. semipenetrans* were prepared as described by Klose et al. (2007, 2008). These pathogens were selected because they affect a wide variety of high-valued crops in California, such as strawberry (*V. dahliae* can cause a complete strawberry crop failure or severe economic loss), cut flower, vegetables and several perennial crops (Ajwa et al. 2003; Klose et al. 2007).

Inoculum bags were buried in 500-gram samples of field-collected nonsterile sandy loam soil placed in 1-liter glass laboratory containers. Tap water (55 milliliters) was added drop-wise via pipette to cover the whole soil surface 48 hours before fumigation to activate the tested pathogens. The various fumigant solutions and an additional 20 milliliters of water were incorporated into the soil to bring final soil water content to 80% of field capacity.

Six fractional concentrations (100%, 75%, 50%, 37.5%, 25% and 12.5%) of the maximum label rate of each fumigant were assessed. For example, Tri-Con (50% MBr:50% Pic) was applied to the soil to achieve final concentrations in the soil of 100%, 75%, 50%, 37.5%, 25% and 12.5% of the label rate, which is equal to 2,448.8, 1,836.6, 1,224.4, 9,06.0, 612.2 and 306.1 µmol kg⁻¹ (dry wt). The maximum rate is equivalent to a field application of 336 kilograms per hectare (kg ha⁻¹) or 300 pounds per acre (lb ac⁻¹). The maximum soil concentration for each fumigant was 5,494.9 µmol kg⁻¹ for DMDS:Pic (79:21), 2,448.8 µmol kg⁻¹ for Pic-Clor 60 (57:37). Soil samples without fumigants were assessed. For example, Tri-Con (50% MBr:50% Pic) was applied to the soil to achieve final concentrations in the soil of 100%, 75%, 50%, 37.5%, 25% and 12.5% of the label rate, which is equal to 2,448.8, 1,836.6, 1,224.4, 9,06.0, 612.2 and 306.1 µmol kg⁻¹ (dry wt). The maximum rate is equivalent to a field application of 336 kilograms per hectare (kg ha⁻¹) or 300 pounds per acre (lb ac⁻¹). The maximum soil concentration for each fumigant was 5,494.9 µmol kg⁻¹ for DMDS:Pic (79:21), 2,448.8 µmol kg⁻¹ for Pic-Clor 60 (57:37). Each fumigant was applied to the soil to achieve final concentrations in the soil of 100%, 75%, 50%, 37.5%, 25% and 12.5% of the label rate.

Pathogen mortality was assessed by counting the number of viable nematodes or fungal colony forming units relative to untreated controls as previously described by Klose et al. (2007, 2008).

The field application rate (kg ha⁻¹) was converted to mg kg⁻¹ by assuming soil water were incorporated into the soil to bring final soil water content to 80% of field capacity.

### Results

A multivariate analysis of variance (ANOVA) was run to determine the effects of soil fumigants, application rates and the interactions between these two factors on the mortality of soilborne pathogens (table 1). This table indicates that regardless of the fumigant, application rate significantly affects mortality of all pathogens tested. In addition, table 1 presents a probability level of multivariate ANOVA for the effects of soil fumigants, application concentrations and the interactions between main factors on mortality of soilborne pathogens.
indicates that the type of fumigant and fumigant/concentration combination significantly affects mortality of *F. oxysporum*, *P. ultimum* and *R. solani*. However, for *T. semipenetrans* and *V. dahliae*, the type of fumigant and fumigant/concentration combination did not significantly impact mortality. To further investigate these results, dose-response curves were fit to each pathogen and fumigant combination for each concentration. An example of the dose-response curves representing the mortality rates for MBr:Pic and each pathogen is in figure 1.

As part of the dose-response analysis, slope and lethal concentration (LC₅₀) values were calculated from the dose-response curves (tables 2 and 3). In table 2, the calculated values of the slope (b), which indicates the susceptibility of the pathogens to the fumigant, were not significant (P > 0.18–0.99) for *P. ultimum* and *T. semipenetrans* because 100% mortality was achieved at the lowest dosages. By contrast, *V. dahliae* did not achieve a 100% mortality rate at any dosage, so the calculated slope was not significant. The mortality results in tables 2 and 3 reveal that *P. ultimum* and *T. semipenetrans* were sensitive to the fumigants and *V. dahliae* was more resistant.

**The mortality results . . . reveal that *P. ultimum* and *T. semipenetrans* were sensitive to the fumigants and *V. dahliae* was more resistant.**

**DMDS:Pic**

The DMDS:Pic fumigant controlled *P. ultimum* and *T. semipenetrans* even at low dosages (tables 2 and 3). The lethal concentration required to control 50% (LC₅₀) of *P. ultimum* and *T. semipenetrans* were 507.0 and 588.5 µmol kg⁻¹, respectively (table 3). Also, low values of the MIC₈₀ for *P. ultimum* and *T. semipenetrans* were 1,460.3 and 730.6 µmol kg⁻¹, respectively (table 4). The LC₅₀ values for *F. oxysporum* and *R. solani* following DMDS:Pic application were about one-fifth of the full concentration (table 3). The full concentration of DMDS:Pic resulted in only 60% mortality of *V. dahliae* (data not shown). The MIC₈₀ value for *V. dahliae* was 3,750.8 µmol kg⁻¹ as calculated by the linear relationship between fumigant concentration and mortality (table 4).

**MBr:Pic**

MBr:Pic controlled *P. ultimum* and *T. semipenetrans* and the sigmoid dose-response curves showed a significant relationship between fumigant concentration and pathogen mortality (R² > 0.83) (fig. 1). Low LC₅₀ values were found for *P. ultimum* and *T. semipenetrans* (201.4 and 240.1 µmol kg⁻¹, respectively; table 3), and MIC₈₀ values were 650.7 and 325.4 µmol kg⁻¹, respectively, which was less than 25% of the full concentration (table 4). A sigmoid curve and low LC₅₀ value for *F. oxysporum* mortality (395.1 µmol kg⁻¹) shows the effectiveness of MBr:Pic with increasing concentration (fig. 1 and table 3). *R. solani* and *V. dahliae* were controlled only at higher concentrations (fig. 1) as reflected in the mortality results. For each pathogen, R² values were: 0.93, 0.99, 0.99, 1.00 and 0.83, respectively. Error bars represent the standard error, n = 8.
by high values of MIC$_{80}$ (2,602.9 and 2,386.0 µmol kg$^{-1}$, respectively; table 4).

**MI:Pic**

All MI:Pic mixtures controlled *P. ultimum* and *T. semipenetrans* as reflected by low LC$_{50}$ values (table 3) and MIC$_{80}$ values using less than 25% of the full fumigant concentration (table 4). Both MI:Pic (33:67) and MI:Pic (50:50) controlled 50% of *F. oxysporum* (155.3 and 172.5 µmol kg$^{-1}$, respectively) and *R. solani* (215.0 and 234.1 µmol kg$^{-1}$, respectively) (table 3). A full concentration of MI:Pic (98:2) was calculated to achieve 80% mortality of *F. oxysporum* and *R. solani* (table 4). According to MIC$_{80}$ values, MI:Pic (50:50) was more effective in controlling *V. dahliae* (862.4 µmol kg$^{-1}$) compared with MI:Pic (33:67) and MI:Pic (98:2) fumigants (2,007.0 and 914.7 µmol kg$^{-1}$, respectively; table 4).

**Chloropicrin formulations**

The pathogens *F. oxysporum*, *P. ultimum* and *T. semipenetrans* were relatively sensitive to Pic 99 and Pic-Clor 60. With Pic 99, LC$_{50}$ values for *F. oxysporum* and *T. semipenetrans* were 145.6, 196.0 and 196.0 µmol kg$^{-1}$, respectively; with Pic-Clor 60, LC$_{50}$ values were 311.0, 241.2 and 121.1 µmol kg$^{-1}$, respectively (table 3). Low values of LC$_{50}$ were also calculated for *R. solani* following Pic 99 and Pic-Clor 60 application (235.2 and 215.8 µmol kg$^{-1}$, respectively; table 3), and half the full rate controlled 80% of *R. solani* (940.8 and 1,066.2 µmol kg$^{-1}$, respectively; table 4). Neither Pic 99 nor Pic-Clor 60 (57:37) was effective in controlling *V. dahliae*, and MIC$_{80}$ values were 1,414.6 and 1,349.3 µmol kg$^{-1}$, respectively (table 4).

**Discussion**

Although some information is available on the efficacy of chloropicrin against soilborne pathogens, little is known about the efficacy of commercial formulations of DMDS:Pic and Mida. Results from this study indicate that, in several cases, effective control of some pathogens was achieved with these mixtures at dosages below the maximum label rate.

The fumigants DMDS:Pic and Pic-Clor 60 controlled almost all tested pathogens. The largest slope at the inflection point of the curve (b value) indicated that *F. oxysporum* and *R. solani* have greater susceptibility to pure MI (MI:Pic, 98:2) than to the other fumigants (table 2). Early dose-response studies evaluated the efficacy of pure MI and MBr to control a range of soilborne pathogens and found *P. ultimum* to be the most sensitive and *R. solani* to be the least sensitive (Hutchinson et al. 2000; Ohr et al. 1996), and only partial mortality of *F. oxysporum* and *V. dahliae* was achieved with these fumigants. Other studies have reported that MI and MBr controlled nematodes, including citrus nematode (Becker et al. 1998; Hutchinson et al. 1999; Luo et al. 2010). Also, a dose-response study on the efficacy of InLine (Klose et al. 2007) found that *P. ultimum* was the most sensitive and *V. dahliae* the least sensitive, and a partial mortality was achieved for *F. oxysporum*. In general, our results (table 4) indicate that *P. ultimum* was the most sensitive and *V. dahliae* was most resistant.

DMDS:Pic controlled *P. ultimum* and *T. semipenetrans* at low dosages. Ten percent of the full concentration (label rate of 5,494.9 µmol kg$^{-1}$) is equivalent to 645 kg ha$^{-1}$ or 576 lb ac$^{-1}$ was calculated to

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**TABLE 2. Values of the slope b at the inflection point of the dose-response curve following application of tested soil fumigants for 24 hours at 20°C**

<table>
<thead>
<tr>
<th>Soil fumigants*</th>
<th>Maximum dosage† (µmol kg$^{-1}$)</th>
<th>Fusarium oxysporum</th>
<th>Pythium ultimum</th>
<th>Rhizoctonia solani</th>
<th>Tyllichulis semipenetrans</th>
<th>Verticillium dahliae</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMDS:Pic (79:21)</td>
<td>5,494.9</td>
<td>388.4</td>
<td>11.1</td>
<td>313.9</td>
<td>17.8</td>
<td>NS</td>
</tr>
<tr>
<td>MBr:Pic (50:50)</td>
<td>2,448.8</td>
<td>313.6</td>
<td>NS</td>
<td>298.6</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>MI:Pic (33:67)</td>
<td>1,886.6</td>
<td>138.1</td>
<td>NS</td>
<td>278.7</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>MI:Pic (50:50)</td>
<td>1,612.3</td>
<td>155.9</td>
<td>NS</td>
<td>234.3</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>MI:Pic (98:2)</td>
<td>836.4</td>
<td>325.9</td>
<td>NS</td>
<td>219.2</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Pic 99</td>
<td>1,775.1</td>
<td>NS</td>
<td>NS</td>
<td>149.7</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Pic-Clor 60 (57:37)</td>
<td>2,004.7</td>
<td>101.4</td>
<td>NS</td>
<td>85.6</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* Soil fumigants: DMDS plus Pic (79% DMDS:21% Pic), Tri-Con (50% MBr:50% Pic), Midas Gold (33% MI:67% Pic), Midas Bronze (50% MI:50% Pic), Midas (MI, a.i. 97.8%), Pic (trichloronitromethane) (a.i. 99%) and Pic-Clor 60 (57% Pic:33% I,3-D).
† The maximum dose was 645 kg ha$^{-1}$ for DMDS:Pic (79:21), 336 kg ha$^{-1}$ for MBr:Pic (50:50), 336 kg ha$^{-1}$ for MI:Pic (33:67), 280 kg ha$^{-1}$ for MI:Pic (50:50), 140 kg ha$^{-1}$ for MI:Pic (98:2), 336 kg ha$^{-1}$ for Pic 99 and 336 kg ha$^{-1}$ for Pic-Clor 60 (57:37).
‡ NA = Not applicable. LC$_{50}$ values for *V. dahliae* could not be calculated from a probit model.

**TABLE 3. Values of lethal concentration (LC) calculated to control 50% of soilborne pathogens population following application of tested soil fumigants for 24 hours at 20°C**

<table>
<thead>
<tr>
<th>Soil fumigants*</th>
<th>Maximum dosage† (µmol kg$^{-1}$)</th>
<th>Fusarium oxysporum</th>
<th>Pythium ultimum</th>
<th>Rhizoctonia solani</th>
<th>Tyllichulis semipenetrans</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMDS:Pic (79:21)</td>
<td>5,494.9</td>
<td>1,095.5</td>
<td>507.0</td>
<td>1,068.3</td>
<td>388.5</td>
</tr>
<tr>
<td>MBr:Pic (50:50)</td>
<td>2,448.8</td>
<td>395.1</td>
<td>201.4</td>
<td>193.7</td>
<td>240.1</td>
</tr>
<tr>
<td>MI:Pic (33:67)</td>
<td>1,886.6</td>
<td>155.3</td>
<td>185.2</td>
<td>215.0</td>
<td>NA</td>
</tr>
<tr>
<td>MI:Pic (50:50)</td>
<td>1,612.3</td>
<td>172.5</td>
<td>191.0</td>
<td>234.1</td>
<td>172.5</td>
</tr>
<tr>
<td>MI:Pic (98:2)</td>
<td>836.4</td>
<td>91.5</td>
<td>104.5</td>
<td>39.2</td>
<td>NA</td>
</tr>
<tr>
<td>Pic 99</td>
<td>1,775.1</td>
<td>145.6</td>
<td>196.0</td>
<td>235.2</td>
<td>196.0</td>
</tr>
<tr>
<td>Pic-Clor 60 (57:37)</td>
<td>2,004.7</td>
<td>311.0</td>
<td>241.2</td>
<td>215.8</td>
<td>12.1</td>
</tr>
</tbody>
</table>

The values of LC$_{50}$ were calculated from the dose-response curve for each pathogen and each fumigant. Confidence interval estimates are in parentheses ($P < 0.05$, n = 8).

* Soil fumigants: DMDS plus Pic (79% DMDS:21% Pic), Tri-Con (50% MBr:50% Pic), Midas Gold (33% MI:67% Pic), Midas Bronze (50% MI:50% Pic), Midas (MI, a.i. 97.8%), Pic (trichloronitromethane) (a.i. 99%) and Pic-Clor 60 (57% Pic:33% I,3-D).
† The maximum dose was 645 kg ha$^{-1}$ for DMDS:Pic (79:21), 336 kg ha$^{-1}$ for MBr:Pic (50:50), 336 kg ha$^{-1}$ for MI:Pic (33:67), 280 kg ha$^{-1}$ for MI:Pic (50:50), 140 kg ha$^{-1}$ for MI:Pic (98:2), 336 kg ha$^{-1}$ for Pic 99 and 336 kg ha$^{-1}$ for Pic-Clor 60 (57:37).
‡ NA = Not applicable. LC$_{50}$ values for *V. dahliae* could not be calculated from a probit model.
control 50% of \textit{P. ultimum} and \textit{T. semipenetrans}. Good control of \textit{F. oxysporum} and \textit{R. solani} was achieved using 20% of the full DMDS:Pic concentration. In previous laboratory studies, DMDS:Pic was found to be effective against citrus nematode (Cabrera et al. 2010) and \textit{R. solani} (Fritsch et al. 2002) partially effective against \textit{F. oxysporum f. sp. radicis-lycopersici} (Abraham Gamliel, professor, ARO Volcani Center, Israel, unpublished data). Also in prior studies under field conditions, effective control was achieved for \textit{R. solani} and \textit{V. dahliae} at a rate of 600 kg ha\(^{-1}\) with VIF in France (Fritsch 2004). However, in our study, only 60% mortality of \textit{V. dahliae} was detected following full concentration application (645 kg ha\(^{-1}\)), which is equal to 5,494.9 \text{µmol kg}\(^{-1}\). Our results suggest that DMDS can provide satisfactory control of selected soilborne pathogens, but more field experiments are required.

The mixture of MBr:Pic (50:50) was used instead of the traditional MBr:Pic (67:33) mixture because of commercial formulation changes with the phaseout of MBr. In addition, the MBr:Pic (50:50) mixture served as a good benchmark against the MI:Pic (50:50) formulation. The MBr:Pic (50:50) mixture controlled \textit{P. ultimum} and \textit{T. semipenetrans} but was not effective on \textit{R. solani} and \textit{V. dahliae}. Only one-tenth of the full concentration was needed for 50% control of \textit{P. ultimum} and \textit{T. semipenetrans} (LC\textsubscript{50}), and 80% mortality was achieved using less than 25% of the full concentration (tables 3 and 4). \textit{F. oxysporum} mortality increased with increasing concentration of MBr:Pic (fig. 1 and table 3). \textit{R. solani} and \textit{V. dahliae} were controlled only by higher concentrations at 2,602.9 and 2,386.0 \text{µmol kg}\(^{-1}\), respectively (table 4).

Most MBr efficacy studies have assessed the dose response using pure MBr (98%) and found this compound very effective against a wide range of pests; however, the analog compound, MI, was found to be as effective as or more effective than MBr (Becker et al. 1998; Hutchinson et al. 1999; Hutchinson et al. 2000; Ohr et al. 1996; Zhang et al. 1997). In this study, the mixed fumigants MBr:Pic (50:50) and MI:Pic (50:50) both controlled \textit{T. semipenetrans}, \textit{P. ultimum} and \textit{F. oxysporum}, but MI:Pic was more effective in controlling \textit{R. solani} compared to MBr:Pic (tables 3 and 4).

The data for MI:Pic mixture efficacy is mainly assessed under field conditions and is measured by yield (Brown et al. 2006; Gilreath et al. 2003; Schneider et al. 2008). However, our study assessed the efficacy of the mixtures MI:Pic (33:67), MI:Pic (50:50) and MI:Pic (98:2) under controlled conditions. All three formulations controlled \textit{P. ultimum} and \textit{T. semipenetrans}. Only 12.5% of the full concentration was required to control half of \textit{P. ultimum} and \textit{T. semipenetrans} (LC\textsubscript{50} values, table 3), and 80% mortality (table 4) was achieved using less than 25% of the full concentration of each fumigant. Based on the LC\textsubscript{50} values, reduced concentrations of MI:Pic (33:67) and MI:Pic (50:50) controlled tested pathogens better than MI:Pic (98:2) (table 4), which may indicate that adding chloropicrin to MI improved the efficacy of MI:Pic mixtures. This result is consistent with research that found combining two fumigants may result in synergy or competitive relationships between the compounds in the mixture (Gamliel and Tricky-Dotan 2009; Hutchinson et al. 2000; Zheng et al. 2003).

Another reason to include Pic-Clor 60 in this study was to compare its efficacy with that of Pic 99. The additional 1,3-D in the Pic-Clor 60 mixture did not improve efficacy compared with Pic 99. Both fumigants had similar MIC\textsubscript{50} values, indicating effective mortality of \textit{F. oxysporum}, \textit{P. ultimum}, \textit{R. solani} and \textit{T. semipenetrans} (table 4). Neither chloropicrin formulation controlled \textit{V. dahliae}, and the MIC\textsubscript{50} values for Pic 99 and Pic-Clor 60 (1,414.6 and 1,349.3 \text{µmol kg}\(^{-1}\), respectively) were calculated assuming a linear relationship of increasing concentration and mortality (table 4).

Incomplete mortality of \textit{V. dahliae} (60% to 80%) was observed with all tested. 

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**TABLE 4. Values of the minimum 80% inhibitory concentration (MIC\textsubscript{50}) calculated to control 80% of soilborne pathogens following application of tested soil fumigants for 24 hours at 20°C**

<table>
<thead>
<tr>
<th>Soil fumigants*</th>
<th>Maximum dosage† (µmol kg(^{-1}))</th>
<th>Fusarium oxysporum</th>
<th>Pythium ultimum</th>
<th>Rhizoctonia solani</th>
<th>Tylenceulus semipenetrans</th>
<th>Verticillium dahliae</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMDS:Pic (79:21)</td>
<td>5,494.9 2,920.6 1,460.3 4,380.0 730.6 3,750.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBr:Pic (50:50)</td>
<td>2,448.8 1,301.4 650.7 2,602.9 325.4 2,386.0</td>
<td></td>
<td></td>
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<td>MI:Pic (98:2)</td>
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<td>1,775.1 470.4 235.2 940.8 235.2 1,414.6</td>
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<td>Pic-Clor 60 (57:37)</td>
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* Soil fumigants: DMDS plus Pic (79% DMDS:21% Pic), Tri-Con (50% MBr:50% Pic), Midas Gold (50% MI:50% Pic), Midas Bronze (50% MI:50% Pic), Midas (MI, a.i. 97.8%), Pic (trichloronitromethane) (a.i. 99%) and Pic-Clor 60 (57% Pic:33% 1,3-D).
† The maximum dose was 645 kg ha\(^{-1}\) for DMDS:Pic (79:21), 336 kg ha\(^{-1}\) for MBr:Pic (50:50), 336 kg ha\(^{-1}\) for MI:Pic (33:67), 280 kg ha\(^{-1}\) for MI:Pic (50:50), 140 kg ha\(^{-1}\) for MI:Pic (98:2), 336 kg ha\(^{-1}\) for Pic 99 and 336 kg ha\(^{-1}\) for Pic-Clor 60 (57:37).

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**Tarping fields helps to retain fumigants in soil.**
fumigants at full concentration except for MI:Pic (50:50), which achieved 80% mortality with half the full concentration (table 4). The multivariate analysis (ANOVA) for the effects of fumigants and the interactions between fumigants and rates on *V. dahliae* mortality were not significant (*P* < 0.05) (table 1). The resistance of *V. dahliae* may occur because its resting form in soil (microsclerotia) is difficult for fumigants to penetrate (Klose et al. 2007). Note that this study evaluated a fumigant dose-response over a 24-hour period. Earlier studies (Klose et al., 2007 and 2008) found that fumigants in a closed system reach equilibrium within minutes after application, and a 24-hour incubation period is sufficient to assess pathogen mortality following soil fumigant application. However, increasing exposure time of the pathogen to fumigants in combination with other disinfection methods and other fumigants may increase efficacy against this pathogen. For example, using TIF or VIF, the effective dose can be higher due to longer exposure times (Fennimore and Ajwa 2011).

The results indicate that the maximum application rate for commonly used fumigants may be insufficient to control important pathogens. For example, the maximum allowable application rate of MB:Pic (50:50), the most commonly used fumigant, is insufficient to inhibit more than 80% of *V. dahliae* (table 4). For this same pathogen, however, this study also suggests that an application rate of 226 kg ha⁻¹ of Pic-Clor 60 (1,349.3 µmol kg⁻¹ relative to the maximum label rate 2,004.7 µmol kg⁻¹) can control 80% of *V. dahliae* (table 4).

Although our results show that for certain pathogens, such as *P. ultimum*, the recommended maximum label rate was often higher than the minimum effective dose, the actual effective dose used under field conditions may vary widely, depending on soil type, soil preparation, soil temperature, soil moisture, type of pathogen complex in the soil, pathogen distribution in soil and the type of tarp used to seal in the fumigants. Maximum label rate is usually recommended to ensure the control of the diverse weed and pathogen populations in soils. However, pre-fumigation soil testing for pathogens and historic farm weed and pest pressure will aid growers in determining minimum application rates.

Results presented in this study can be used to compare the reactivity of the commercial formulations to each other for specific pathogens and show that application rates can be based on the type of pathogen and degree of infestation. However, extrapolating the results to field conditions should be done with caution. This study provides basic information to reduce pathogen populations to levels where natural biological feedback mechanisms can function to regulate disease outbreaks. However, further research is needed on fumigant efficacy as a function of soil type under field conditions for various crops and their cultivars.

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### References


Managing for soil health can suppress pests

by Amanda Hodson and Edwin Lewis

A “healthy” soil can be thought of as one that functions well, both agronomically and ecologically, and one in which soil biodiversity and crop management work in synergy to suppress pests and diseases. UC researchers have pioneered many ways of managing soil biology for pest management, including strategies such as soil solarization, steam treatment and anaerobic soil disinfestation, as well as improvements on traditional methods, such as reducing tillage, amending soil with organic materials, and cover cropping. As managing for soil health becomes more of an explicit focus due to restrictions on the use of soil fumigants, integrated soil health tests will be needed that are validated for use in California. Other research needs include breeding crops for disease resistance and pest suppressive microbial communities as well as knowledge of how beneficial organisms influence plant health.

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) defines soil health as the “continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans” (NRCS 2014), thus emphasizing that a healthy soil is one that yields both agronomic and ecological returns. Soil health emphasizes the dynamic, living nature of soil (van Bruggen and Semenov 2000), and encompasses biological attributes such as biodiversity, food web structure and ecosystem functioning (Pankhurst et al. 1997). These properties have been linked to important agronomic benefits such as disease and weed suppression, resilience to environmental stress and increased plant productivity (Berendsen et al. 2012; Brussaard et al. 2007; Lehman and Acosta-Martinez 2015; Pellkofer et al. 2016; van der Heijden et al. 2008; Wagg et al. 2014).

Precisely defining soil health can be a difficult task since it is determined by interactions among microbial communities, management decisions, and soil physical and chemical factors. Use of the term soil health has recently become more common (Farm Foundation NFP 2014; Ferris and Tuomisto 2015) and is used distinctly from soil quality, which describes agricultural productivity as well as a soil’s quantitative physical and chemical characteristics (Doran et al. 1996; Singer and Ewing 2000). However, use of the term can be problematic, because some soil organisms that contribute to biodiversity can make it difficult for crops to grow, and could be considered unhealthy for agricultural production (McKenry et al. 1994).

Growers have used various tools to address the challenge of soil pests, which include fungi, bacteria and nematodes and which cause billions of dollars in economic damage each year. In the past, soil pest management technologies relied heavily on resistant plants and cultural modifications such as crop rotation, tillage and hand weeding. While these were helpful in preventing pest outbreaks, and are still widely used today, increased use of soil fumigants since the 1950s has provided additional rapid, effective and inexpensive pest management. Methyl bromide was particularly useful in that a single treatment before planting could effectively control many types of soilborne pests, resulting in increased crop yields and quality.

In 1999, a phaseout of methyl bromide began under the Montreal Protocol, an international treaty that limits the production of substances that deplete stratospheric ozone, commonly referred to as the ozone layer. While this treaty has allowed for quarantine/preshipment and critical use exemptions in many crops that do not have effective or affordable fumigant replacements, such as strawberry, these exemptions will soon phase out almost entirely.
As the use of soil fumigants becomes more restricted by state and federal regulators, the question of how to sustainably manage agroecosystems to increase soil health has become more important. Recently, governmental organizations within California have taken more interest in managing for soil health, with the goal of simultaneously achieving high agronomic and ecological functioning without relying so heavily on fumigants (California Department of Pesticide Regulation 2014; NRCS 2014). While the University of California (UC) has historically been a leader in soil health research and fumigant alternatives, more research on soil health is needed to provide consistent pest control that manages the multiple economic and environmental tradeoffs involved. Here, we review research on managing soil health as a method of pest suppression, advances in soil health diagnostics and recommendations for future research priorities.

Soil solarization, steam and ASD

Soil solarization, steam and anaerobic soil disinfection (ASD) disinfect the soil by creating conditions inhospitable for microbes. For example, solarization and steam elevate temperatures above those tolerated by many microbes, while ASD deprives microbes of oxygen; all three methods volatilize organic compounds naturally present in soil that are toxic to soil microorganisms (Hewavitharana et al. 2014). The technique of soil solarization has been extensively studied by UC scientists and is most effective at controlling pests that live in the top 12 inches of soil (Hartz et al. 1993; Stapleton et al. 2000). A modification on this technique, bisolarization, combines covering and heating the soil with the incorporation of plant materials, which enhances pest suppression (Gamriel and Stapleton 1993; Stapleton and Duncan 1998; Villapudua and Munnecke 1986). ASD builds upon these principles by combining the addition of organic matter and covering of the soil with flooding to create anaerobic conditions where microbes cannot survive (Shennan et al. 2014).

When used under the right conditions, all three methods can be very effective. For example, in small-scale strawberry production, solarization effectively controlled weeds and was more cost effective than methyl bromide while providing similar yields (Stapleton et al. 2005). Steam and ASD treatments can also result in yields comparable to those produced in conventionally fumigated soils (Fennimore et al. 2013; Samtani et al. 2012). Steam treatments, long used in California nursery production to control nematodes and diseases (Baker 1948; Baker and Smith 1967), were previously limited for field use by their slow speed (Samtani et al. 2012). However, recent UC and USDA Agricultural Research Service (ARS) research on applicators that physically mix soil with steam are faster and have shown promising results, paving the way for commercially available models (Fennimore et al. 2014).

While these methods kill pests directly, they can also cause biological changes that contribute to pest control. Opportunistic species of nematodes and microbes quickly re-colonize after treatment and many of these groups are antagonistic to pests (Gamriel and Stapleton 1993; Mazzola et al. 2012; Simmons et al. 2014; Stapleton 2000), resulting in very different microbial communities than those found in either fumigated or nonfumigated soil (Drenovsky et al. 2005; Shennan et al. 2013). For ASD, steam and solarization, researchers continue to explore using different amendments (e.g., rice bran, brassica seed meal) to enhance pest control and optimize the carbon sources used to control specific pathogens (Fennimore et al. 2014; Shennan et al. 2013; Shennan et al. 2014; Simmons et al. 2013).

Cover crops and crop rotation

Using cover crops and crop rotation can inhibit pathogens and weeds, as well as stimulate beneficial soil microbes. Incorporating cover crops can also produce bioactive compounds that behave similarly to chemical soil fumigants (biofumigation), causing changes in microbial communities and suppressing pests (Hao et al. 2003; Koike and Subbarao 2000). In peaches, UC and USDA-ARS researchers found that short preplant rotations of sudangrass helped manage Prunus replant disease, improving calculated profits even when fruit prices were low (Browne et al. 2013).

To optimize the potential of cover cropping, more information is needed about which planting mixtures and sequences best suppress pests. This information, along with data on the yield benefits provided by various planting mixtures, must be integrated into existing crop management systems for several reasons. Certain cover crops can be incompatible with the agricultural practices used on the main crop (Ingels 1994); others can have allelopathic effects on crop plants (Summers et al. 2009); and cover cropping may not be desirable for some particularly high value crops, or in cases where the appropriate cover crops for...
managing soil biology are not themselves economically profitable.

**Organic amendments**

While organic amendments possess widely different characteristics, and their effects can vary between production batches, they generally enhance soil microbial activity by providing carbon in forms that are easy for microbes to digest (Cavigelli et al. 2012; Janvier et al. 2007). Over the years, UC research has focused on topics ranging from how mulches and composts can increase populations of nematode-trapping fungi (Jaffee 2004; Mankau 1959) to their effects on weeds and diseases (Jackson et al. 2003). The decomposition of organic amendments also increases soil temperatures, as in bio-solarization, and helps create anaerobic conditions, as in ASD (Shennan et al. 2014; Stapleton and Banuelos 2009).

Amendments likely suppress pathogens and weeds by both producing biocidal or allelopathic compounds and by altering microbial communities, but the exact mechanisms of how this occurs remain unknown. Amendment with brassica seed meal residue, a byproduct of biodiesel production, controlled nematode pests and diseases in a study of two Washington state apple orchards, and resulted in higher yields compared to fumigated soil (Mazzola et al. 2015). In orchard soils, brassica seed meal can also suppress weed growth by modifying resident soil microbial communities (Hoagland et al. 2008). Treatments based on organic amendments can be optimized through research that examines their effects singly and in mixtures across different crops and soil types. However, care must be taken to eliminate risks of crop contamination with human pathogens. Useful research will also characterize and monitor soil microbial communities associated with plant disease suppression after the application of amendments (Mazzola 2004).

**Tillage**

Growers till soil to prepare seedbeds and kill weeds, but this also disturbs soil microbial communities (Cavigelli et al. 2012), which can have negative consequences for natural enemies of pests (Warde 1995). UC research on the effects of no-till agriculture in cotton and processing tomatoes has found that sustained management of no-till practices can achieve yields comparable to standard tillage (Mitchell, Klonsky et al. 2012; Mitchell et al. 2015) and can reduce seed banks of weeds (Shrestha et al. 2008). Benefits of this method include lower labor costs (Mitchell, Klonsky et al. 2012; Mitchell, Singh 2012), reduced particulate matter emissions (Baker et al. 2005) and less evaporative water loss (Mitchell, Singh et al. 2012), as well as increased soil carbon (Veenstra et al. 2007). While these results have served as a proof-of-concept, further studies on the commercial feasibility of this technique are needed to determine whether it can be widely adopted by California processing tomato growers.

**Inoculation**

The previous practices could be considered methods of conservation biological control, which modifies agricultural practices and the environment to promote the establishment and survival of native organisms antagonistic to pests (Eilenberg et al. 2001). Another approach to biological control is inoculation, where natural enemies are released directly via soil, seeds or planting materials with the expectation that they will continue to provide control as they reproduce in the environment (Eilenberg et al. 2001). Past work in this area by UC scientists found that inoculation with certain species of root-colonizing bacteria (termed fluorescent pseudomonads or plant growth-promoting rhizobacteria) increased plant growth and suppressed diseases such as vascular wilt and take-all (Kloepper et al. 1980a; Kloepper et al. 1980b; Suslow et al. 1979). Recent work has identified new strain-specific genes in fluorescent pseudomonads that produce antibiotics, expanding potential avenues of disease suppression (Loper et al. 2012).

The strategy of inoculating soil with beneficial microorganisms requires further research in multiple areas. While inoculation with microbes can confer traits such as resistance to nematode pests (Flor-Peregrin et al. 2014) and environmental stress (Coleman-Derr et al. 2014), they often do not survive when introduced into a new environment and so are unable to control pathogens effectively (Mazzola 2004). For example, UC researchers found that the microbial communities of soil where commercial inoculants were applied were similar to uninoculated soils, and that inoculants had no effect on tree vigor (Drenovsky et al. 2005). Advancing knowledge of how plants and microbes communicate and how key beneficial organisms function to influence plant health and/or repel pathogens may mitigate these constraints and improve the effectiveness of inoculated products. Inoculating crops with an assemblage of complementary microorganisms may also control diseases more effectively than inoculations with a single group. Such compatible microbial communities, or consortia, could also help restore diversity, leaving fewer available resources for pathogens to become established (Bakker et al. 2012).

**Breeding**

One long used strategy to control belowground pests has been the breeding of cultivars and rootstocks resistant to specific pests and diseases. UC research has been instrumental in identifying and evaluating genetic material resistant to a variety of soil pests and diseases, such as root knot nematodes (Kaloshian et al. 1996; Yaghoobi et al. 2005), Fusarium wilt (Scott et al. 2012) and Armillaria (Baumgartner et al. 2013). Recent field research evaluating experimental rootstocks for almond and stone fruit has found that some hybrids are markedly less sensitive to Prunus replant disease than others, which may result in less need for chemical controls (Browne et al. 2013). Molecular advances are also enabling the genes for resistance to be mapped and marked for easy identification, facilitating the development of improved germplasm in crops such as walnuts (Kluepfel et al. 2014).

Instead of breeding directly for disease resistance, another approach is to breed crops for root exudate characteristics that suppress pests, either by producing bioactive compounds or by recruiting disease-suppressive microbes. The question of how plants and microbes communicate chemically and what plant exudates are important in shaping the microbial community has been examined for some plant species in the laboratory (Badri et al. 2009), but research remains sparse for agricultural crops.
While we know that existing crop cultivars differ in their associated microbial communities (Smith and Handelsman 1999), breeding programs have rarely, if ever, taken an active approach to manipulate them (Mendes et al. 2013). On the contrary, modern crop breeding may have inadvertently selected against traits that led beneficial microbes and encouraged their establishment. The theory of plant–microbiome co-adaptation holds that crop plants grown close to areas where they were originally domesticated had the opportunity to form close associations with microorganisms over long time periods. As these crop plants were brought into new locations, though, they encountered microbial communities to which they were not adapted. Signals that may have triggered a beneficial response in the native community would then go “unheard” by microbes in the new cropping system (Bakker et al. 2012). Such a mismatch between the root microbial community and the plant could create an opportunity for pathogen infection. Since pathogens compete with other microbes for food and physical space on the root, a tight association with beneficial microbes may leave little room for pathogens to establish.

**Soil health diagnostics**

The soil health tests available at this time mostly focus on chemical and physical indicators (for example, water infiltration rate and plant-available nutrients) since these are generally straightforward to measure and interpret. As soil microorganisms and fauna intimately relate to soil physical properties and immediately affect ecosystem processing, their presence, abundance and diversity have often been proposed as bioindicators of soil health (Nielsen and Winding 2002; Visser and Parkinson 1992), but these indicators also require taxonomic expertise. Currently in California, several tests related to soil health are available. The UC Davis Analytical Laboratory measures soil physical and chemical factors like organic matter, carbon and bulk density, while the California Department of Food and Agriculture (CDFA) provides diagnostic services for plant pests, weeds and diseases. These resources are largely limited to those affiliated with university or government agencies, but private companies also identify many nematode species and other plant pathogens and perform soil analyses. Despite these assets, no specific soil health test is available in California that integrates multiple factors.

Other publically available soil health tests in the United States provide indices that combine different suites of indicators. The Haney Soil Health Test, available through the USDA-ARS, gives a soil health score in addition to measuring plant-available nutrients. The score is calculated based on overall microbial activity, the food resources available to microbes (in the form of water-extractable carbon and nitrogen) and the ratio of carbon and nitrogen in the sample. The Comprehensive Assessment of Soil Health (offered through the Cornell University Nutrient Analysis Laboratory) provides indicators of many soil processes, including disease presence, microbial activity and nutrient storage and release. For both of these tests, adjusting the soil health scores and management recommendations to local crops, soils and management practices, as well as on-farm validation, will improve their relevance and accuracy for use in California.

**Future directions**

Particularly relevant research for the future will examine integrative systems that combine multiple strategies, for example, experiments that combine techniques such as bioactive soil amendments with solarization. Such new management strategies and combinations must be feasible and relevant to existing systems if they are to be implemented. Confirming the commercial viability of new innovations, such as the use of no-till techniques in commercial processing tomatoes, will also contribute to their success. Valuable UC research is in progress focusing on breeding for direct resistance to soilborne pests using advances such as molecular marker–assisted identification of resistance genes. Less well studied though, is the idea of breeding for indirect resistance by recruiting beneficial microbes or repelling pests via root exudates.

Lastly, in working to manage soil health for pest suppression, more work is needed on diagnostics to determine what constitutes a “healthy” soil. As a step towards future testing for beneficial organisms, databases of microbial communities could be expanded, relating them to management practices and disease presence. Soil health tests developed outside California will require validation in local cropping systems, and the relationship between soil health scores and desired outcomes such as increased yields and nutrient retention will need to be confirmed. With future advances in UC research, managing for soil health could become an integral component of pest management, resulting in more resilient and productive cropping systems that provide multiple agronomic and environmental benefits.

### References


Fennimore SA, Serohijos R, Samtani JB, et al. 2013. TIF "distance-breaking" nematodes identified in California toma-
Jaffee BA. 2004. Do organic amendments enhance the
inglassic soil disinfection technique for strawberry pro-
Hewavitharana SS, Ruddell D, Mazzola M. 2014. Carbon
cosystem criteria as indicators of soil health. In: Wahl DH, et al.
microbial communities promote temporal stability and spe-
O'Neill MN, Winding A. 2002. Microorganisms as in-
Nielsen MN, Singh PN, Wallender WW, et al. 2012. No-
Nelson RE, Technical Report No. 388. Roskilde, Denmark:
Kloeper JW, Leong J, Teintze M, Schroth MN. 1980a. En-
Kloeper JW, Leong J, Teintze M, Schroth MN. 1980b. Pseudo-
Kloeper JW, Doube BM, Gupta VVSR. 1997. Biological
Mazzola M, Muramoto J, Shennan C. 2012. Transforma-
Mitchell JP, Singh PN, Wallender WW, et al. 2012. No-
Mitchell JP, Singh PN, Wallender WW, et al. 2012. No-
Stapleton JJ, Duncan RA. 1998. Soil disinfection with cruciferous amendments and sublethal heating: effects on Meloidogyne incognita, Sclerotium rolfsii and Py-
Doran JW, Sarrantonio M, Liebig M. 1996. Soil health and
Shennan C, Muramoto J, Lamers J, et al. 2014. Anaerobic soil disinfection for soil borne disease control in straw-
Shennan C, Muramoto J, Lamers J, et al. 2014. Anaerobic soil disinfection for soil borne disease control in straw-
Simmons CW, Claypool JT, Marshall MN, et al. 2014. Char-
Stapleton JJ, Duncan RA. 1998. Soil disinfection with cruciferous amendments and sublethal heating: effects on Meloidogyne incognita, Sclerotium rolfsii and Py-
Suslow TV, Kloeper JW, Schroth MN, Burr TJ. 1979. Ben-
van Bruggen AHC, Semenov AM. 2000. In search of bio-
Yaghoobi J, Yates JL, Williamson VM. 2005. Fine mapping of the nematode resistance gene Mi-3 in Solanum peru-
viurn and construction of a S. lycopersicum DNA con-
Inconsistent food safety pressures complicate environmental conservation for California produce growers

by Patrick Baur, Laura Driscoll, Sasha Gennet and Daniel Karp

Controlling human pathogens on fresh vegetables, fruits and nuts is imperative for California growers. A range of rules and guidelines have been developed since 2006, when a widespread outbreak of E. coli O157:H7 was linked to bagged spinach grown in California. Growers face pressure from industry and government sources to adopt specific control measures on their farms, resulting in a complex, shifting set of demands, some of which conflict with environmental stewardship. We surveyed 588 California produce growers about on-farm practices related to food safety and conservation. Nearly all respondents considered both food safety and environmental protection to be important responsibilities for their farms. Responses indicate that clearing vegetation to create buffers around cropped fields, removing vegetation from ditches and ponds, and using poison bait and wildlife fences are commonly used practices intended to reduce wildlife movements onto farm fields. The survey also revealed that on-farm practices vary substantially even among farms with similar characteristics. This variability suggests inconsistencies in food safety requirements, auditors’ interpretations or growers’ perception of the demands of their buyers. Although site-specific considerations are important and practices should be tailored to local conditions, our findings suggest growers, natural resources and food safety would benefit from clearer, more consistent requirements.

California leads the nation in production of vegetables, fruits and nuts (CDFA 2014) and its fresh produce industry is composed of an exceptional diversity of crops and farm types. Beginning in the late 1990s and accelerating after prominent incidents such as the 2006 outbreak of E. coli O157:H7 linked to bagged spinach, new rules and best practice guidelines to mitigate foodborne pathogen contamination propagated rapidly through the fresh produce industry (Stuart 2010). The multiple layers of rules and guidance developed over the past decade present growers with a complex landscape of pressures to adopt and intensify on-farm practices intended to improve food safety, some of which may conflict with efforts to conserve natural resources.

Alongside continually developing expectations for food safety, growers are also expected to conserve water and soil and are legally obligated to protect water quality as well as wildlife and its habitat. Many of the state’s major agricultural regions, such as the San Joaquin, Sacramento, Santa Clara and Salinas River valleys are located in or near ecologically sensitive river corridors and floodplains. These ecosystems host fertile soils, are sources of fresh water, and also provide habitat for many species of birds, amphibians and other wildlife. On-farm practices, including those related to food safety, can have direct and indirect consequences to the benefits provided from these ecosystems (Karp et al. 2015; Karp et al. 2016; Karp, Baur et al. 2015; Letourneau et al. 2015).

Food safety measures and impacts

Early evidence suggested that pressures to improve food safety after 2006 led growers to adopt on-farm practices with substantial economic and environmental costs (Lowell 2010). Surveys
and interviews of Central Coast growers conducted in 2007 (Beretti and Stuart 2008) and 2009 (Beretti 2009; Lowell et al. 2010) revealed that “as a condition to sell their produce, growers report yielding to tremendous pressure exerted by auditors, inspectors, and other food safety professionals to take measures that are potentially damaging to the environment” (Lowell et al. 2010). Such measures included clearing vegetation (including removing existing vegetated conservation practices), removing ponds or water bodies, setting poison bait traps for wild animals and installing extensive wildlife exclusion fences. In a separate study of land use change using aerial imagery, Gennet et al. (2013) confirmed that approximately 13% of the remaining riparian habitat in the Salinas Valley was removed between 2005 and 2009.

There is no clear evidence that on-farm practices to reduce animal intrusions are effective at enhancing food safety (Langholz and Jay-Russell 2013). Further, emerging evidence suggests that removal of non-crop vegetation fails to reduce, and may even increase, pathogen prevalence on leafy-green vegetable farms in the California Central Coast (Karp et al. 2015), while degrading important ecosystem benefits such as natural pest control services (Letourneau et al. 2015, Karp et al. 2016). Removing vegetation is expensive and at times conflicts with landowners’ acknowledged environmental stewardship responsibilities (Crohn and Bianchi 2008; Gennet et al. 2013, Hardesty and Kusunose 2009; Stuart 2009). Furthermore, such approaches may conflict with California’s regulatory targets for surface water quality. They may also conflict with standards for USDA’s Natural Resources Conservation Service conservation practices, limiting growers’ access to Farm Bill or other federal sources of funding. In addition, activities specifically adopted to remove or deter wildlife from entering fields — such as poison bait, trapping and extensive wildlife exclusion fences — may expose growers to criticism from wildlife conservation interests and public expectations of farmers to protect native plants, animals and environmental quality.

### Many layers of pressure

The pressures on growers to improve food safety originate from government regulators such as the Food and Drug Administration (FDA), from private third-party auditors and certifiers, and from retail and foodservice companies that purchase produce. The cumulative effect of these multiple layers of pressure on growers and the food safety measures they feel obligated to implement has not been assessed industry-wide.

Food safety regulation at the farm level is a recent development. Before FDA finalized its Produce Safety Rule (80 Fed. Reg. 74353) in 2015 pursuant to the Food Safety Modernization Act of 2011, there was no direct federal oversight. The rule was written in general terms to provide growers with the flexibility to adopt the food safety measures that they deem most appropriate for their farm. For example, with respect to how growers should manage animal intrusion, the rule only requires that growers visually monitor the growing area prior to harvest and take “measures reasonably necessary” in case an animal does find its way into the field. It leaves precise interpretation of what those measures should entail open to the discretion of growers, inspectors, auditors and produce buyers. The rule sets more specific standards for detectable amounts of bacteria in biological soil amendments and agricultural water. But while it does detail approved composting and pathogen testing methodologies, the rule gives growers latitude to choose their own irrigation and soil amendment practices and technologies. FDA, USDA and various partner organizations are actively developing additional guidance and training resources to assist growers in interpreting and implementing the rule, but it will take years to reach everyone. In the meantime, it is unclear precisely how growers will respond.

That said, while much attention has been given to the *minimum* legal requirements set by government regulators, it is critical to understand that government oversight will not account for all, or even necessarily the primary, pressure on growers to improve food safety on their farms. Because food safety rules as written are frequently open-ended and regulators have very limited resources to monitor or enforce compliance, many produce buyers seek additional assurance by requiring their growers to receive certification to one or more private standards. Maintained by third-party certifiers, these private standards add an additional burden of compliance to government regulation (Bain et al. 2013; Henson and Humphrey 2009).

Regulations and private standards are generally publicly available, but there are
two further layers of more opaque pressure. First, government inspectors and third-party auditors decide whether or not the on-farm practices used by a given grower comply with regulations or private standards, respectively. Inspectors and auditors thus shape the ways in which growers put rules and standards into practice, yet it is very difficult to gauge their consistency and level of influence. Second, produce buyers may impose additional, case-specific production specifications on their suppliers through purchasing contracts or even verbal communication.

From pressure to practice

Little scholarship has examined how these varied and dynamic pressures have played out on California farms since 2009 or assessed whether and to what extent pressures and practices vary by crop type and farm size. Several developments in the past 7 years lend urgency to the need for updated and expanded data in these areas. First, in response to the reported tension between managing for food safety and managing for environmental quality (Crohn and Bianchi 2008; Stuart 2009), UC Cooperative Extension in collaboration with USDA’s Natural Resource Conservation Service and others has developed guidance for and sought to raise awareness of co-management, an adaptive strategy that seeks to reduce food safety risks without impairing environmental goals (ANR 2015; FFSCN 2015). Second, the aforementioned Produce Safety Rule now requires growers to meet national standards for agricultural water, soil amendments (specifically compost) and preventive programs to mitigate contamination risk from wildlife and livestock. Third, the ongoing drought in California and heightened water quality control regulations for agriculture — such as the Central Coast Water Quality Control Board’s Conditional Waiver of Waste Discharge Requirements (Agricultural Order No. R3-2012-0011) under California’s 1969 Porter-Cologne Act, the first order that does not allow waivers for agricultural contamination to waterways — may give new impetus for growers to preserve riparian and wetland vegetation that helps reduce nutrient contamination and implement other water conservation practices. Lastly, public health officials and media continue to draw attention to the persistent risk of foodborne illness associated with fresh produce (Bakalar 2015; FDA 2014; Painter et al. 2013).

As these ongoing developments intensify scrutiny of field-level production, there is a pressing need to assess the current state of on-farm practices and grower perspectives for food safety and conservation. To help address the need for such data, we collaborated with the California Farm Bureau Federation (CFBF) in 2014 to survey growers across the state.

Survey design and implementation

The survey (ucanr.edu/u.cfm?id=141) was designed to produce baseline information about ongoing food-safety practices for industry, policymakers, regulators, the Cooperative Extension community, conservation interests and academic researchers. In developing the survey instrument, we examined the questions asked in the 2007 and 2009 surveys and gathered suggestions on further questions to include from stakeholders at the CFBF and the Farm Food Safety and Conservation Network. We aimed to assess (1) the current prevalence of various on-farm practices for food safety and conservation in California; (2) the effect of farm size and organic status on whether growers use a certain practice; (3) where and how growers access information about food safety and conservation; and (4) growers’ broader perspectives on food safety and environmental management.

The first draft of the survey instrument was shared with a focus group of five CFBF members for comment. Based on feedback from the focus group, the instrument was revised and piloted with 28 members of the CFBF’s Specialty Crop Commodity Advisory Committee. After a final round of revisions, CFBF staff delivered the survey instrument electronically to the CFBF email listserv. Responses were collected during the month of October 2014, and one reminder email was sent two weeks after the initial recruitment email.

Survey limitations

To preserve privacy and with the understanding that on-farm practices can be a sensitive subject for growers, responses to this survey were collected anonymously. In addition, the identity and job title or operational role of specific respondents were not controlled or recorded. As with all surveys, responses reflect the personal interpretations and attitudes of respondents. There is thus a possibility of false or incorrect answers. Respondents were allowed to skip individual questions, opening the possibility for underreporting on sensitive topics. For example, some growers may have chosen not to disclose whether they currently use poison bait or copper sulfate, or whether they clear vegetation in or near riparian areas, as these management practices may exist in a legal gray area depending on the area of production. That said, we did not observe the response rates for these practices to be markedly lower than for the less sensitive practices queried.

Survey respondents

The survey yielded responses from 588 produce growers who reported more than $25,000 annual sales for their operation. Of these respondents, 536 reported growing fruits and nuts and 118 reported growing vegetables and melons (66 respondents reported growing at least one crop in each category). About one-fifth (21%) of respondents reported growing at least some certified organic produce, with 7% reporting growing exclusively certified organic produce.

To estimate our survey response rate, we compared our respondents to the subpopulation of CFBF members growing fruits and nuts or vegetables and melons, who have operations with annual sales above $25,000. When the survey was sent in 2014, CFBF had 29,519 agricultural members, 10,905 of whom were on the organization’s email listserv. Fruit and nut growers represented 41% of CFBF members on the listserv, while vegetable and melon growers represented 15%. We therefore estimate the survey instrument was emailed to 4,471 fruit and nut growers and 1,636 vegetable and melon growers.

CFBF does not track its members’ annual sales. Additionally, the survey did not indicate the percentage of sales by commodity for each respondent. However, we estimate response rates by assuming that the distribution of
operations by annual sales is similar between CFBF members and the full population of California growers as reported in the 2012 census of agriculture (USDA 2014). This would mean the survey was distributed to approximately 2,618 fruit and nut growers and 684 vegetable and melon growers with annual sales above $25,000, yielding estimated response rates of 20% for fruit and nut growers and 17% for vegetable and melon growers.

The CFBF membership is not necessarily representative of all California growers, and as such our respondents should be conservatively interpreted as a convenience sample. To assess the potential selection bias resulting from this non-probabilistic sample, we compared the proportion of respondents by crop type and annual sales to the statewide proportions reported in the 2012 census of agriculture (USDA 2014). Statewide, the ratio of fruit and nut operations to vegetable and melon operations with more than $500,000 in annual sales is approximately 9:1. The statewide ratio of produce operations (fruit, nut, vegetable and melon) with annual sales between $25,000 and $500,000 to those with annual sales greater than $500,000 is about 3:1. Among our respondents, the ratios are about 4:1 and 1:1, respectively, meaning that our sample over-represents both vegetable and melon growers and farm operations with more than $500,000 in annual sales.

**Farm categories**

In our analysis, we compare respondents by the annual sales reported for their farms. Based on FDA’s definitions of farm size used in the Produce Safety Rule (21 CFR §112.3), we define “large” farms as respondents who reported annual sales of $500,000 or more per year and “small” farms as those who reported annual sales between $25,000 and $500,000 per year; we excluded respondents reporting sales under $25,000 per year. Different market channels represent different clusters of consumer demand, and thus may be associated with different types and intensities of food safety pressure. In our sample, respondents reporting annual sales of at least $500,000 per year also reported selling primarily to broker, wholesaler, packer/shipper and processor market channels, while respondents reporting annual sales under $500,000 per year were more likely to report selling primarily to farmers market and community supported agriculture (CSA) channels.

In addition to annual sales, different crops are associated with different agonomic practices and present different food safety risk profiles. In recognition of these differences, we analyze respondents who reported growing vegetable and melon crops separately from those who reported growing fruit and nut crops (including strawberries).

**On-farm practices**

The survey asked respondents to indicate when, if ever, they had used any of a list of 11 on-farm practices specifically because of a food safety concern. Respondents were also asked to indicate use of a list of 22 conservation practices on land they farm. We implemented generalized linear mixed models (GLMMs) to assess whether and to what extent farm size and organic status affect the likelihood that a grower uses on-farm practices for food safety (fig. 1) or conservation (fig. 2).

Fruit and nut growers were analyzed separately from vegetable and melon growers. Predictor variables (fixed effects) included whether growers operated a large versus small farm, and whether

![On-farm practices for food safety among California produce growers.](http://calag.ucanr.edu/u.cfm?id=142)

Fig. 1. On-farm practices for food safety among California produce growers. Points are mean model-predicted probabilities that a respondent reported using the on-farm practice for food safety. The left panel reports probabilities for fruit and nut growers ($n = 282$ to 306), while the right reports probabilities for vegetable and melon growers ($n = 74$ to 79). For each type of grower, the second column compares organic versus conventional producers and the second column compares large farms versus small farms. Lines are confidence intervals, asterisks (*) denote significance under likelihood ratio tests after multiple test correction, and plus signs (+) denote significance without multiple test correction. Too few vegetable and melon growers reported using copper sulfate to model the effect of organic status or farm size. Model parameters, practice-specific $n$-values, and $P$-values are presented in table S1 (ucanr.edu/u.cfm?id=142).
they grew organically versus conventionally. The primary market channel for each grower was accounted for as a random effect. We first built separate models with binomial errors and logit links for each on-farm practice. We then used likelihood ratio tests to assess the significance of predictor variables, comparing nested models with and without each predictor variable (Zuur et al. 2009). Because each on-farm practice was modeled individually, we used false discovery rates to account for multiple tests.

### Practices for food safety

Most respondents (88%, n = 314) reported using at least one of the 11 on-farm practices for food safety queried in the survey, with about half (48%) reporting using at least four such practices (data not shown). Among fruit and nut growers (n = 282 to 306, see tables 1 and S1 [ucanr.edu/u.cfm?id=142] for detailed results), 53% reported using nonpoison traps and 52% reported using poison bait because of a food safety concern. Rates were similar across organic/conventional status and farm size, although our models show that large farms growing fruits and nuts were more likely than small farms to use poison bait (60% vs. 45%).

A higher proportion of vegetable and melon growers reported using nonpoison traps (68%), but fewer overall reported using poison bait (47%). However, among vegetable and melon growers (n = 74 to 79), our models show that large farms were significantly more likely than small farms to report using nonpoison traps (80% vs. 47%) and poison bait (63% vs. 18%).

Reported use of wildlife fences was relatively low among fruit and nut growers (26%), but 48% of vegetable and melon growers reported using wildlife fences. No significant difference was detected across organic status or farm size for either group.

Similarly, less than half of fruit and nut growers (38%) reported removing vegetation from ditches or farm ponds;...
large farms were slightly more likely to report removing vegetation than were small farms. The majority of vegetable and melon growers (56%) reported removing vegetation from ditches or farm ponds; no significant difference was detected across organic status or farm size.

A total of 40% of fruit and nut growers and 45% of vegetable and melon growers reported clearing vegetation to create buffers; no significant differences were found across organic status or farm size. Very few respondents (<20%) in either produce category reported stopping use of, draining, or filling ditches or farm ponds because of a food safety concern. One in four fruit and nut growers and 17% of vegetable and melon growers reported using copper sulfate due to a food safety concern. One in three fruit and nut growers, less than a quarter reported currently using a fully composted soil amendment (i.e., compost), heat-treated soil amendments (e.g., chicken manure pellets), or tailwater recovery ponds.

The most commonly reported conservation practice in both groups was integrated pest management (IPM), with 74% of fruit and nut growers and 80% of vegetable and melon growers reporting currently using IPM. Our models show that large farms in both groups were significantly more likely to use IPM than were small farms. Most vegetable and melon growers also reported using cover crops (66%) and crop rotation (88%).

Despite low overall use, significant differences in reported use between small and large farms were found for many conservation practices. Among fruit and nut growers (n = 280 to 305), our models show that large farms were significantly more likely than small farms to use biocontrol agents (44% vs. 21%), sediment or stormwater basins (34% vs. 17%), tailwater recovery ponds (26% vs. 10%), crop rotation (40% vs. 18%), and physically heat-treated soil amendments (31% vs. 9%).

Among vegetable and melon growers, large farms were significantly more likely than small farms to use sediment or stormwater basins (55% vs. 14%) and tailwater recovery ponds (49% vs. 11%). However, among these growers (n = 72 to 80), small farms were significantly more likely than large farms to use native bee nest boxes (35% vs. 9%), vegetated strips for native pollinators (60% vs. 28%), and fully composted soil amendments (50% vs. 19%). Not surprisingly, organic growers in both categories were more likely than conventional growers to report using biocontrol agents and vegetated strips

### TABLE 1. On-farm practices for food safety among fruit/nut and vegetable/melon growers reported by farm size (annual sales)

<table>
<thead>
<tr>
<th>Conservation practice</th>
<th>More than $500,000 annual sales</th>
<th>Less than $500,000 annual sales</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Use</td>
<td>Don’t use</td>
<td>Use</td>
</tr>
<tr>
<td>Planted low-risk crops or fallowed land</td>
<td>141 82%</td>
<td>18%</td>
<td>154 93%</td>
</tr>
<tr>
<td>Removed vegetation from ditches or farm ponds</td>
<td>149 55%</td>
<td>45%</td>
<td>157 69%</td>
</tr>
<tr>
<td>Stopped use, drained, or filled ditch or farm pond</td>
<td>141 87%</td>
<td>13%</td>
<td>155 92%</td>
</tr>
<tr>
<td>Treat irrigation water</td>
<td>142 82%</td>
<td>18%</td>
<td>155 91%</td>
</tr>
<tr>
<td>Wildlife fences</td>
<td>144 72%</td>
<td>29%</td>
<td>158 77%</td>
</tr>
<tr>
<td>Falconers or owl boxes</td>
<td>148 48%</td>
<td>52%</td>
<td>160 62%</td>
</tr>
<tr>
<td>Depredation (removed pest animals)</td>
<td>142 54%</td>
<td>47%</td>
<td>161 60%</td>
</tr>
<tr>
<td>Nonpoison traps</td>
<td>146 45%</td>
<td>55%</td>
<td>166 48%</td>
</tr>
<tr>
<td>Poison bait</td>
<td>151 40%</td>
<td>60%</td>
<td>168 55%</td>
</tr>
<tr>
<td>Copper sulfate</td>
<td>145 63%</td>
<td>37%</td>
<td>161 85%</td>
</tr>
<tr>
<td>Cleared vegetation to create or expand buffers</td>
<td>150 62%</td>
<td>38%</td>
<td>165 58%</td>
</tr>
</tbody>
</table>
for native pollinators and pest predators. Organic fruit and nut growers were also more likely than their conventional counterparts to use cover crops, crop rotation and physically heat-treated organic soil amendments.

Access to information
The survey asked respondents to indicate from whom they get information about best practices for food safety and for conservation. We summarize the responses ($n = 336$, undifferentiated by size or crop) in figure 3. It should be noted that these questions were asked at the end of the survey, and the response rate is lower most likely due to survey fatigue. It is possible that respondents might not have

<table>
<thead>
<tr>
<th>Conservation practice</th>
<th>Fruits and nuts</th>
<th></th>
<th></th>
<th>Vegetables and melons</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>More than $500,000 annual sales</td>
<td>Less than $500,000 annual sales</td>
<td>All</td>
<td>More than $500,000 annual sales</td>
<td>Less than $500,000 annual sales</td>
<td>All</td>
</tr>
<tr>
<td>Bird nest boxes</td>
<td>n</td>
<td>Use</td>
<td>Don't use</td>
<td>n</td>
<td>Use</td>
<td>Don't use</td>
</tr>
<tr>
<td>Constructed wetland</td>
<td>139</td>
<td>9%</td>
<td>91%</td>
<td>161</td>
<td>5%</td>
<td>95%</td>
</tr>
<tr>
<td>Release of biocontrol agents</td>
<td>144</td>
<td>44%</td>
<td>56%</td>
<td>164</td>
<td>21%</td>
<td>79%</td>
</tr>
<tr>
<td>Native bee nest boxes</td>
<td>142</td>
<td>16%</td>
<td>85%</td>
<td>160</td>
<td>21%</td>
<td>79%</td>
</tr>
<tr>
<td>Beetle banks</td>
<td>140</td>
<td>2%</td>
<td>98%</td>
<td>153</td>
<td>4%</td>
<td>96%</td>
</tr>
<tr>
<td>Integrated pest management (IPM)</td>
<td>155</td>
<td>85%</td>
<td>16%</td>
<td>165</td>
<td>64%</td>
<td>36%</td>
</tr>
<tr>
<td>Flower or native plant strips to attract natural pest predators</td>
<td>141</td>
<td>28%</td>
<td>72%</td>
<td>163</td>
<td>26%</td>
<td>74%</td>
</tr>
<tr>
<td>Flower or native plant strips for native pollinators</td>
<td>145</td>
<td>32%</td>
<td>68%</td>
<td>162</td>
<td>28%</td>
<td>72%</td>
</tr>
<tr>
<td>Hedgerow or windbreak</td>
<td>144</td>
<td>30%</td>
<td>70%</td>
<td>163</td>
<td>21%</td>
<td>79%</td>
</tr>
<tr>
<td>Grassed waterways or roads</td>
<td>143</td>
<td>25%</td>
<td>76%</td>
<td>161</td>
<td>21%</td>
<td>79%</td>
</tr>
<tr>
<td>Riparian/stream bank restoration</td>
<td>141</td>
<td>21%</td>
<td>79%</td>
<td>159</td>
<td>15%</td>
<td>86%</td>
</tr>
<tr>
<td>Sediment or stormwater basin</td>
<td>144</td>
<td>34%</td>
<td>66%</td>
<td>161</td>
<td>17%</td>
<td>83%</td>
</tr>
<tr>
<td>Tailwater recovery ponds</td>
<td>139</td>
<td>26%</td>
<td>74%</td>
<td>160</td>
<td>10%</td>
<td>90%</td>
</tr>
<tr>
<td>Vegetated filter or buffer strips</td>
<td>141</td>
<td>29%</td>
<td>71%</td>
<td>159</td>
<td>22%</td>
<td>78%</td>
</tr>
<tr>
<td>Vegetated treatment system</td>
<td>136</td>
<td>6%</td>
<td>94%</td>
<td>159</td>
<td>9%</td>
<td>91%</td>
</tr>
<tr>
<td>No-till agriculture</td>
<td>150</td>
<td>52%</td>
<td>48%</td>
<td>163</td>
<td>42%</td>
<td>58%</td>
</tr>
<tr>
<td>Cover cropping</td>
<td>149</td>
<td>45%</td>
<td>55%</td>
<td>163</td>
<td>37%</td>
<td>63%</td>
</tr>
<tr>
<td>Crop rotation</td>
<td>145</td>
<td>40%</td>
<td>60%</td>
<td>160</td>
<td>18%</td>
<td>82%</td>
</tr>
<tr>
<td>Physically heat treated soil amendments containing animal manure</td>
<td>144</td>
<td>31%</td>
<td>69%</td>
<td>160</td>
<td>9%</td>
<td>91%</td>
</tr>
<tr>
<td>Fully composted, not physically heat treated, soil amendments containing animal manure or animal products</td>
<td>144</td>
<td>28%</td>
<td>72%</td>
<td>162</td>
<td>21%</td>
<td>79%</td>
</tr>
<tr>
<td>Raw manure, green waste or other non-composted soil amendment containing animal products</td>
<td>140</td>
<td>10%</td>
<td>90%</td>
<td>161</td>
<td>8%</td>
<td>93%</td>
</tr>
</tbody>
</table>
answered these questions because they felt uncomfortable with the topic, but no concerns were raised on these questions during either phase of piloting.

Respondents reported receiving information on food safety and conservation (“any information” category in fig. 3) primarily from other growers (75% of respondents), government agencies (74%), Cooperative Extension advisors (70%) and trade associations (69%). For information exclusively about food safety, however, more respondents rely on their buyers (42%), third-party auditors/inspectors (28%) and trade associations (24%) than on government agencies (18%) or Cooperative Extension advisors (13%). Furthermore, respondents with large farms were significantly more likely ($P < 0.01$ using a Z-test to compare proportions) than respondents with small farms to rely on third-party auditors/inspectors (46% vs. 11%) and their buyers (50% vs. 34%) exclusively for food safety information (data not shown).

For information about conservation, conversely, Cooperative Extension and government stand out, with 57% and 55% of all respondents seeking some form of conservation information from them, respectively (“Only conservation” category in fig. 3). There was no statistically significant difference between large and small farms for information only about conservation (data not shown).

The survey also asked growers to rank the factors of importance in resolving their buyers’ food safety concerns. Respondents with large farms were much more likely to rank certification more important and to rank the length of the relationship with their buyer and buyer site visits less important than were growers with small farms (fig. 4).

Respondents were also asked how they prefer to get information and what topics are of most use to them. On a scale of 1 (most) to 6 (least) useful, respondents ranked in-person workshops (2.6) and written guidance available either online (2.7) or in paper format (2.8) significantly higher than online webinars/trainings (3.9) or videos (4.1). Using a bootstrap method with case resampling to estimate 95% confidence intervals for the rankings, no significant differences were observed across crop type or farm size (data not shown).

Most respondents ($n = 374$, undifferentiated by size or crop) wanted information on regulatory requirements (82%), detailed best practice guidance (72%), what technologies and tools are available (69%), implementation costs (63%), and evidence of the effectiveness of tools and practices for managing food safety hazards (62%). Around half of respondents felt that information about how to co-manage food safety and agricultural conservation (59%), how to prepare for a food safety audit (52%), and guidance/tools for developing good agricultural practices (GAPs) (52%) would be useful. Only 39% felt that information about available consulting services would be of use. No significant differences were observed across crop type or farm size.

### Grower perceptions, opinions

The survey asked respondents whether they agreed or disagreed with a set of statements about food safety and conservation. Again,
response rates for these questions are lower (data not shown), most likely due to survey fatigue.

Past surveys have indicated that many on-farm practices for food safety are both costly (Hardesty and Kusunose 2009) and pose an ethical dilemma for growers (Stuart 2009). Among our respondents, however, most fruit and nut growers (78%, n = 279) and vegetable and melon growers (71%, n = 77) believed that their on-farm practices for food safety are compatible with their environmental stewardship goals; only 8% and 16%, respectively, perceived a conflict.

Most respondents were confident that they had or could easily get information on food safety; only 17% of fruit and nut growers (n = 273) and 16% of vegetable and melon growers (n = 77) responded that they could not.

Furthermore, the overwhelming majority of fruit and nut growers and vegetable and melon growers agreed or strongly agreed that it is their responsibility to protect food safety (92%, n = 305, and 96%, n = 82, respectively) and water quality and the environment (93%, n = 309, and 95%, n = 81, respectively) on their farm.

That said, many respondents perceived problems with the auditing process. Only 42% of fruit and nut growers (n = 187) and 50% of vegetable and melon growers (n = 62) reported that they agree with government or third-party auditors when those auditors identify potential food safety risks. Moreover, just 16% of fruit and nut growers (n = 191) and 18% of vegetable and melon growers (n = 62) agreed that auditors are consistent.

When asked if they agreed that their products are safer following food safety certification, 39% of fruit and nut growers (n = 170) and 39% of vegetable and melon growers (n = 61) disagreed or strongly disagreed. The response rate for questions asking about auditors and certification was markedly lower; we presume this is because many respondents do not maintain third-party certification and so skipped these questions as not applicable to their operations. A majority of respondents agreed that buyers cooperate with them to address food safety concerns (71% of fruit and nut growers, n = 237, and 69% of vegetable and melon growers, n = 67), and that they can adequately address their buyers’ food safety concerns (76%, n = 246, and 80%, n = 69, respectively).

**Tension and inconsistency persist**

The results of our survey suggest that on-farm practices for food safety that target wildlife and potentially impact natural communities and ecosystem services via vegetation and habitat removal are still used in produce agriculture in California. Past surveys of on-farm practices used by leafy greens growers in the Central Coast found that the most common practices were buffers around cropped fields and poison bait (>50% respondents), followed by wildlife trapping and wildlife exclusion fencing (~40%) (Beretti and Stuart 2008; Lowell et al. 2010). Respondents to our survey reported similar if not higher rates of use for these same practices, suggesting that practices have remained constant within the leafy greens sector over the past 6 years and that, possibly due to expanding food safety regulations, food safety pressures and practices now reach into other sectors of the produce industry, as well.

As discussed above, many of these legacy practices have not been shown to reduce food safety risk, and growing evidence points to their impacts on ecosystem services and other public goods and benefits (Karp et al. 2015; Karp et al. 2016; Karp, Baur et al. 2015; Letourneau et al. 2015). Nevertheless, we found that many growers still use these and similar practices, suggesting that the on-farm practices which growers perceive to be required of them do not yet reflect available scientific information.

The impact of requiring on-farm practices for food safety depends upon how and by whom rules are written and enforced, and the scale of the farm. Future field-based research should address whether this difference is due to the greater resources available to large farms or to different levels of risk and oversight associated with different market channels and supply chains.

Our survey suggests that food safety and conservation are practiced and interpreted differently by growers of different size and crop type. Farms in our sample with annual sales over $500,000, for example, were more likely than farms with annual sales under $500,000 to report practicing some form of animal intrusion prevention, such as fencing or trapping. However, even among farms of similar size growing similar crops, we found a wide range of variation. Rather than converging as scientific evidence and experience grow, on-farm practices for food safety are highly heterogeneous across produce agriculture in California, suggesting that either requirements, or grower interpretations of those requirements, are inconsistent.

Inconsistency in real or perceived food safety pressures raises several concerns. Our results show that many growers rely on each other for both food safety and conservation information, but perceptions of practices for food safety and knowledge of regulations varied greatly among growers. Mixed messages from their peers could lead to uncertainty over legal requirements and the potential consequences of noncompliance. In the face of uncertainty, growers may take what seems to be a conservative approach by adopting wildlife deterrence and vegetated habitat removal practices that have not been scientifically shown to reduce risk. While open-ended or flexible regulation may aim to give farmers more freedom, inconsistencies in food safety pressures can also make it more difficult to provide guidance on strategies to co-manage food safety and sustainability goals.

In addition, the majority of our survey respondents reported that auditors are inconsistent in their assessments. A high degree of inconsistency may make food safety requirements appear arbitrary to growers, especially if evidence is not provided along with the justification for decisions or recommendations. A significant proportion of our respondents also did not believe that food safety certification has made their products safer, despite the high importance of certification in securing access to larger buyers. Lastly, the higher the degree of inconsistency in interpreting and responding to food safety pressures, the higher the degree of difficulty for regulators — and the consuming public — to know whether the produce industry has effectively made food safer.

**Finding the right balance**

Taken together, our findings highlight that discrepancies remain among California produce growers with respect to their access to current, relevant food safety
and economic costs. Safety while minimizing environmental on-farm practices that actually improve extent to which that flexibility will lead to modifications, but it is necessary to evaluate the Rule acknowledges this need by providing a degree of flexibility to growing operations, but it is necessary to evaluate the extent to which that flexibility will lead to on-farm practices that actually improve safety while minimizing environmental and economic costs.

Our results suggest that in some cases pressures from third-party auditors and produce buyers may lead to inconsistency in the interpretation and implementation of food safety regulations and guidance, but our survey was conducted prior to the finalization of the Produce Safety Rule. In light of this significant regulatory development since the survey was administered, additional survey and interview-based research is needed to determine the extent to which growers adopt practices based on their own goals or perceived pressures from their buyers, third-party certifiers/auditors or government regulators. Future research should investigate who has the power to decide what practices are best for food safety, and whether and in what ways the distribution of decision-making authority affects the balance between consistency and flexibility.

Greater alignment and collaboration between environmental and food safety science is needed to establish a more comprehensive catalogue of practices that can help growers mitigate pathogen risks while also protecting the environment and ecosystem services. A call for consistent rules and enforcement must allow a responsive flexibility in implementing food safety guidelines. A balance is necessary. While we cannot say what that balance should be, it is apparent from our survey that any discussion of balance can only improve with better understanding of extant food safety pressures and the ways in which they are perceived and put into practice by growers. More transparent information on what practices growers adopt in the name of food safety, and why growers adopt those practices, is urgently needed. It would improve consistency and help promote food safety efficiently and without unnecessary impacts on the environment. That would benefit both farmers and consumers.

References


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Soil testing for P and K has value in nutrient management for annual crops

by Daniel Geisseler and Gene Miyao

Adequate nutrients in forms available to plant roots are essential for sustainable crop production. Soil testing for phosphorus and potassium availability allows growers and crop advisers to determine whether a soil is likely to respond to fertilization. As yields have risen with improved management and production systems, crop nutrient demand and the removal of nutrients with harvested crops have increased. An in-depth discussion of soil tests for phosphorus and potassium and their use in California cropping systems is clearly needed. We review how these nutrients become available to plant roots, how samples are taken and test results interpreted, complementary ways to assess the adequacy of supplies and what research is needed to improve soil testing for phosphorus and potassium.

Phosphorus (P) and potassium (K) are essential nutrients required in rather large amounts by crops. The application of fertilizers is often required to meet the crops’ demand, with the application rate depending on the availability of nutrients in the soil. Insufficient application rates result in lower yields and may reduce soil fertility over time as the availability of nutrients decreases. In contrast, the application of excess nutrients increases production costs and may cause environmental problems.

Soil testing is one of the most cost-effective nutrient management tools available to growers and crop advisers. It can guide fertilization decisions for individual fields, and it can assess whether a soil is likely to respond to fertilization (Cox 1994). Soils differ in their capacity to supply nutrients to crops.

Early research has shown that many soils in California do not supply sufficient P to annual crops, and P fertilization has often been found to be highly beneficial (Jenny et al. 1946). Tree crops, in contrast, are less likely to have a yield response to P fertilizer. Few cases of K deficiency were reported in the first half of the 20th century (Jenny et al. 1946). With a few exceptions, K has not received much attention since then. We focus on P and K here, but our discussion applies to other nutrients, such as calcium or magnesium, as well. One exception is soil sampling for residual soil nitrate-N. Nitrate is directly plant available, but much more mobile in the soil than P and K and thus easily lost.

An in-depth discussion of soil tests and their use with a focus on California cropping systems is currently missing, but clearly needed. Improved management and varieties have increased productivity considerably in California. Most recently, the shift to semipermanent drip irrigation systems has further increased crop yield. As a result, nutrient removal is higher and soil nutrient depletion faster because of the more confined root zone. A positive response to P and K fertilization is now much more likely even on soils that have long been considered sufficiently fertile. For these reasons, and because environmental concerns with overfertilization are being raised more
frequently, the value of soil testing has increased.

**Soil tests as tools**

To be useful, the results of a specific soil test need to be calibrated with the yield response (Mikkelsen 1955). Critical yield response values commonly used in California are given in table 1 for select annual crops. The calibration is done by comparing the yields of a fertilized plot and an unfertilized control. The yield response from many fields is then plotted against the soil test values of those fields, and the soil test values at which a yield response is likely versus unlikely are determined (fig. 1). Based on these results, fertilization recommendations can be developed in rate trials on responsive sites.

For meaningful test results and their correct interpretation, it is important to take a representative sample of the field and to be aware of what soil tests measure and what their limitations are.

**Misconceptions about soil tests**

Many growers and crop advisers lack confidence in soil test results — at least partly due to prevailing misconceptions about what information they provide and how it should be interpreted.

For example, soil tests do not represent all pools of nutrients available to crops, which may limit their accuracy in some soil types. Furthermore, soil test values are an index of nutrient availability and cannot be used to calculate the amount of available nutrients in pounds per acre.

Nonetheless, with a good understanding of soil chemistry and laboratory methodology, soil test values can be interpreted correctly for specific fields and cropping systems and can be combined with other tools and approaches to make informed decisions about P and K fertilization rates.

**Soil P pools and availability**

Phosphorus exists in soil in many different forms, which greatly differ in their plant availability (Fixen and Grove 1990). Plant roots take up P in the form of phosphate ($\text{H}_3\text{PO}_4^-$ or $\text{HPO}_4^{2-}$) from soil solution. Generally less than 1 pound per acre, or less than 1% of the total quantity of P in the soil, is in soil solution (Pierzynski 1991). Therefore, soil solution P needs to be replenished constantly during the growing season to meet the demand of crops.

Phosphate in soil solution is in equilibrium with phosphate adsorbed to the surface of minerals or bound to cations. Depending on solution P concentrations, reactions with minerals and cations may replenish the solution P pool or bind solution P. The strength of the interactions between phosphate and minerals varies. Weakly bound P equilibrates rapidly with the soil solution and replenishes solution P. This pool is often called labile P. Over time, labile bonds may be transformed into stronger bonds resulting in precipitation of low-available P minerals. In contrast, P may be released from the nonlabile pool and become plant available (Pratt and Lippert 1986).

The primary cations involved in these reactions with phosphate are calcium ($\text{Ca}^{2+}$), aluminum ($\text{Al}^{3+}$) and iron ($\text{Fe}^{3+}$). In neutral and alkaline soils, different forms of Ca-phosphate most strongly determine P concentration in solution, and thus P availability. In acidic soils, P solubility is mainly controlled by interactions between phosphate, Al and Fe ions (Pierzynski et al. 2005). Phosphorus availability is generally highest in slightly acidic soils with a pH around 6.5 (Stevenson and Cole 1999).

One- to two-thirds of the P in mineral soils is in the organic form (Condron et al.)
Mineralization of organic P is mediated by soil microorganisms and can significantly contribute to the P nutrition of plants (Oehl et al. 2001). Many different forms of organic P are found in soil, their availability ranging from very labile to highly recalcitrant.

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Soil P tests

Because of the low solubility of major P forms, the concentration of P in soil solution is generally low and not a good measure of P availability. Soil P tests aim to extract solution P and the labile inorganic P pool. Due to the complexity of the soil P pools, it is not possible to determine the exact amount of P that will become plant available during the season. Instead, soil tests provide an index of the labile plant-available P in a soil (Fixen and Grove 1990) by extracting a fraction of the P in the soil that has been found to be correlated with the yield response of crops to P fertilization (fig. 1). As this fraction is not identical to plant-available P, soil test results cannot be used to calculate the available P in pounds per acre and compare this value with the P demand of a crop.

The two most commonly used soil tests in California are the Olsen and Bray-P1 tests. Both tests measure solution P and extract labile fractions of phosphates of Ca, Al, and Fe. The contribution of these different pools to the P extracted differs due to differences in pH and chemical composition of the extractant (Beegle 2005).

The Olsen P method uses a sodium bicarbonate solution adjusted to a pH of 8.5 (Olsen et al. 1954). This test is widely used in soils with a mildly acidic to alkaline pH (Gavlak et al. 2005). The Bray-P1 test uses an acidified ammonium fluoride solution with a pH of 2.6 to extract P (Bray and Kurtz 1945). The Bray-P1 soil test is often used in acid to neutral soils (Gavlak et al. 2005).

For both tests, however, the optimal pH range is soil-specific. Some studies have reported that the Olsen P test performed reasonably well in acidic soils (John et al. 1967; Smyth and Sanchez 1982). Similarly, in some alkaline soils, the Bray-P1 test is well correlated with the Olsen P test (Ebeling et al. 2008). In California, the Bray-P1 test is generally used in soils with a pH below 6.0 and the Olsen P test in soils with a pH of 6.0 or higher (CPHA 2002).

As these soil tests extract different fractions of the labile P pool, it is best to use the same test over the years for the same field, so that the results can be compared with the values of previous years. With both tests extracting adsorbed inorganic forms of P, they tend to underestimate P availability in soils with a high soil organic matter content, where the mineralization of organic P may contribute considerably to the available-P pool (Steffens et al. 2010).

Soil K pools and availability

Plants take up K in the form of K+ from soil solution. Soluble K is only a small pool that is constantly replenished by exchangeable K and to some degree by stable, or nonexchangeable, K (Römheld and Kirkby 2010). Potash (K2O), which is used for fertilizer application rates, is not a form of K found in soil. Elemental K is converted to K2O by a multiplication factor of 1.2.

Exchangeable K is held on negatively charged sites of clay minerals and soil organic matter. It is in equilibrium with K in soil solution, being released when the concentration of K in solution is low, for example, due to plant uptake (Römheld and Kirkby 2010). The capacity of a soil to exchange K and other cations such as Ca2+, sodium (Na+) and magnesium (Mg2+) is reflected in its cation exchange capacity (CEC). Solution K and exchangeable K represent the available-K pool.

Most K in soil is present as a component of primary minerals (structural K) or fixed in clay minerals and not immediately available. Available K may be fixed in some soils by clay minerals and thus made unavailable. In California, K fixation occurs in some soils formed from Sierra Nevada alluvium, located on the east side of the San Joaquin Valley. In contrast, soils formed in Coastal Range alluvium do not fix K, except to a small extent in deeper horizons. In general, K-fixing soils are either weakly developed soils with high mica content or intermediately developed soils with high vermiculite clay mineralogy (Pettygrove and Southard 2003).

As much as 80% of applied K can be fixed and become temporarily unavailable to plants (Cassman et al. 1990; Hartz et al. 2002). Nonexchangeable K becomes only slowly plant available. However, there is no clear boundary between exchangeable and nonexchangeable K (Öborn et al. 2005). Depending on the minerals present and their weathering stage, nonexchangeable K can contribute significantly to plant supply (Kuhlmann and Wehrmann 1984; Öborn et al. 2005; Wang et al. 2011).

Potassium is readily available from crop residues, as it is not incorporated into organic molecules in plant tissue. It can be released from residues even before they decompose.

Soil K tests

In California, soil K availability is most often determined from soil samples by extraction with an ammonium acetate solution at neutral pH (Allen et al. 1994). This procedure extracts soil solution K, exchangeable K and possibly a small proportion of the nonexchangeable pool (Haby et al. 1990). While soil solution K and exchangeable K can be determined accurately, soil tests may not always extract the fraction of the nonexchangeable K that becomes crop available (Rengel and Damon 2008; Römheld and Kirkby 2010). Soil tests measuring exchangeable K are a significantly less precise measure for yield response in K-fixing soil (Cassman et al. 1990; Rees et al. 2013).

Soil test sampling

One of the most challenging aspects of soil testing is to ensure that the sample taken is representative of the field. A test result from a nonrepresentative sample has little value.

Taking a representative sample

Most commonly, soil cores are taken from the entire area of the field or management area in a W-shaped sampling pattern or by walking a zigzag course around or through the area (fig. 2). Atypical areas, such as corners or edges of former fields or fencerows that are now in the field, should be excluded (Pennock
et al. 2008). To capture the variability within fields, it is generally recommended to take 20 to 30 cores from random locations within each field (James and Wells 1990). The composites cores should be thoroughly mixed and submitted for laboratory analysis following instructions of the lab where samples are submitted (Pennock et al. 2008).

Soil test results can vary depending on the time of the year the samples are taken (Childs and Jencks 1967). Samples for P and K are best taken in late fall or early spring. They should not be taken when fertilizer has been applied recently. To monitor trends in nutrient availability over the years, it is important to always take samples during the same season and from the same depth. In annual crops, the top 12 inches are generally sampled. Taking samples to the same depth is especially important for P because P moves very slowly down the profile due to its immobility in soils (Beegle 2005).

**Spatial variability**

Even when care is taken to collect a representative sample, the results of the soil test may still not be very useful when the field is not uniform. When soil properties, past management, plant development or yield history differ within a field, the field should be divided into different management areas with similar characteristics, and a sample from each area should be taken (fig. 2). A convenient way to check for differences in soil properties is to use the interactive application SoilWeb (available at casoilresource.lawr.ucdavis.edu/soilweb/).

The immobility of P also means that banded P can result in fairly long lasting zones of high P test values in no-tillage systems (Beegle 2005). If the location of the band is known, it is generally recommended to take one core from the band for every 20 cores taken. More often than not, the exact location of the bands is not known. In this case, twice as many cores from random locations in the field should be taken compared to the number taken from a field without fertilizer bands.

**Sampling drip-irrigated fields**

Some special considerations apply to drip-irrigated fields. With subsurface drip irrigation, the active root zone from which crops draw most nutrients is confined to the region wetted by the drip tape. With the soil volume explored by roots being limited, the potential for a positive response to nutrient application is increased (Hartz et al. 2005; Hartz and Hanson 2009). Therefore, critical soil test values may be higher for drip systems than for furrow-irrigated fields.

Due to the restricted soil volume roots have access to, nutrient concentrations can vary considerably across the bed with distance from the drip line. Depending on the amount of nutrients applied relative to crop uptake and their mobility in soil, nutrients may accumulate or be depleted around the emitters (Carrijo and Hochmuth 2000; Hartz 2008; Palacios-Díaz et al. 2009).

A recent study in drip-irrigated tomato fields found that the variability across the bed can be captured by taking more than one core from the top 20 inches at each sampling location within a field — for example, taking three cores at a distance of 5, 10 and 20 inches from the drip tape in the center of a 60-inch bed (Lazcano et al. 2015). The cores can be pooled for analysis.

**Limitations of soil tests**

Soil tests cannot capture all the factors that determine the efficiency with which crops acquire nutrients from the soil, such as crop species, variety and the effects of soil properties on root growth (Cassman, Roberts, et al. 1989; White 2013). For example, rooting depth and root density determine how well a plant can access the pool of potentially available nutrients in the tested layer and in the subsoil (Gahoonia and Nielsen 2004; Richardson et al. 2011; Samal et al. 2010).

Depending on the distribution of nutrients in the soil profile and rooting depth, crops may take up a considerable proportion of nutrients from the soil below the sampled layer. Winter wheat, for example, has been found in one study to acquire 50% of its K from the subsoil (Kuhlmann...
and Barraclough 1987). Furthermore, nutrient availability, especially that of P, depends on soil temperature, decreasing in cool soils (Johnstone et al. 2005). Phosphorus values in soil taken after a crop of lowland (flooded) rice are not reliable because drainage of flooded soils increases amorphous iron oxide levels and P immobilization (Sah and Mikkelsen 1986). A field study on major rice soils in California found that wheat and barley grown following lowland rice may suffer P deficiency despite soil test values above the critical level (Brandon and Mikkelsen 1979).

### Differences among labs

Test results and fertilization recommendations obtained for a field sample may differ considerably among labs (Follett et al. 1987; Jacobsen et al. 2002). Proficiency testing programs allow labs to monitor the accuracy of their analytical methods, but test results can be affected by sample handling and preparation before analysis.

The amount of P extracted is affected by the speed and time of shaking, as well as the temperature of extraction. This may contribute to some differences among soil test labs (Schoenau and O’Halloran 2008). In the case of K, shaking time may affect the amount of K extracted with ammonium acetate (Haby et al. 1990). Exchangeable K is generally determined on air-dried soils. Air drying and how the samples are dried may have a variable effect on soil test K values (Haby et al. 1990; Khan et al. 2013).

Preparation of samples, including drying, grinding and extraction can be time consuming, so soil test labs may use procedures that reduce processing time, which in turn may lead to significant differences in the test values among labs. Furthermore, some soil test labs use multi-element extractants that allow a determination of P, K and other nutrients in the same extract (Allen et al. 1994). An equation is then used to convert the results to Olsen P or ammonium acetate extractable K. While the correlation between two soil tests may be quite good across a large number of samples, some fields may not follow the general trend (Burt et al. 2002).

The variability among labs makes it hard to detect long-term trends in nutrient availability when labs are changed repeatedly over the years. However, reliable labs should be consistent within and among years.

### Using soil tests with other tools

Because of the limitations of soil tests described above, nutrient management decisions should not be based solely on test results. Soil tests are a valuable tool for assessing nutrient availability in annual crops, but to accurately evaluate the nutrient availability in a field and to determine optimal fertilizer rates, they are best combined with other tools, such as plant tissue analysis, nutrient budgets and on-farm strip trials.

### Plant tissue analyses

While soil testing identifies potential nutrient deficiencies before planting, plant analysis allows in-season monitoring and, depending on the time of sampling, adjustments to the fertilizer program (Westfall et al. 1990).

As is the case with soil testing, the validity and usefulness of plant tissue analyses rely on representative sampling and proper sample handling (Jones and Case 1990). Furthermore, the concentration of elements can change rapidly with time and plant developmental stage, so tissue samples need to be taken at a stage for which critical values have been established (Munson and Nelson 1990). The concentration of elements is also affected by cultivar, cultural practices and environmental conditions (Munson and Nelson 1990; Westfall et al. 1990).

Plant tissue tests do not detect excess soil P supplies (Mallarino 1995; Mallarino UC Davis researcher Patricia Lazicki takes a soil sample from a field in the fall after harvest of the crop. To obtain a representative sample, it is generally recommended to take 20 to 30 cores from random locations within a field.
and Higashi 2009). In contrast, they do show excess soil K: vegetative tissue K concentrations tend to increase in the presence of excess soil K, a process known as luxury consumption (Hawkesford et al. 2012).

**Nutrient budgets**

Large amounts of P and K can be removed with harvested crops. To maintain adequate nutrient availability over the years, the input of nutrients needs to balance nutrient exports. A nutrient budget, in its simplest form, compares fertilizer inputs with the amount of nutrients removed with harvested crops (output). The nutrient concentrations in harvested plant parts and the amounts of P and K removed from the field at harvest are listed in tables 2 and 3 for select annual crops.

Nutrient budgets are less reliable for soils where large losses may occur or for high-fixation soils. In general, losses of P and K are minor. There are some exceptions where losses can be significant. Phosphorus is lost from fields with surface runoff or when erosion takes place (Sharpley et al. 2000). Phosphorus leaching losses can be significant in fields with a history of high manure or fertilizer applications, which lead to an accumulation of P in the profile (Brock et al. 2007; Fortune et al. 2005; Hartz and Johnstone 2012; McDowell et al. 2013).

Potassium can be leached in soils with a very low CEC (Wulff et al. 1998). The CEC of a soil mainly depends on its clay content, the dominant clay minerals present and the soil organic matter content. In California, with the exception of very sandy soils with a low soil organic matter content, the CEC is generally sufficient to prevent K leaching even when large amounts of fertilizer are applied. Potassium may also be leached in very clay-rich soils when cracks are present, allowing K in soil solution to bypass exchange sites (Alfaro et al. 2004).

**On-farm trials**

For some crops, on-farm trials have led to the development of optimal fertilizer application rates based on soil test results (e.g., Miller et al. 1996). On-farm trials give growers the opportunity to evaluate different application rates on a limited area under field- and farm-specific conditions, such as soil types, climate, crop variety and crop management (Hicks et al. 1997).

Based on the results, growers can then decide whether to adopt these rates on part or all of the acreage (Hicks et al. 1997).

Application rates can be tested in small plots or field strips. Field strips are generally more convenient to establish and manage (Hancock 1992). A uniform and representative part of the field needs to be chosen for the trial. The field should not be deficient in other nutrients. Except for the different fertilizer rates, the strips are managed identically. The strips should be large enough so that field equipment can be used for all operations. The strips should also be wide enough to permit harvesting, soil testing and plant tissue sampling from an area that is not affected by the management in the rest of the field (Hancock 1992). For fertilizer trials in row crops, it is generally suggested that the strips be at least two rows wider on each side than the harvested area. When the comparison includes foliar fertilizers, the border area may need to be wider.

The simplest trial includes two treatments, the new application rate and the normal practice, which serves as the control. When the goal of the trial is to determine whether P and K fertilization is beneficial, fertilizer is applied to a

## TABLE 2. Phosphorus and potassium concentrations in harvested plant parts of select annual crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>Plant part harvested</th>
<th>Phosphorus % of dry matter</th>
<th>Potassium % of dry matter</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter wheat</td>
<td>Grain</td>
<td>0.25–0.49</td>
<td>0.33–0.66</td>
<td>van Duivenbooden et al. 1996</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0.03–0.08</td>
<td>1.06–1.92</td>
<td>van Duivenbooden et al. 1996</td>
</tr>
<tr>
<td>Barley</td>
<td>Grain</td>
<td>0.34–0.56</td>
<td>0.49–0.61</td>
<td>Arvidsson 1999; Saskatchewan Ministry of Agriculture 2012</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0.06–0.08</td>
<td>1.51–1.73</td>
<td>Tarkalson et al. 2009; Saskatchewan Ministry of Agriculture 2012</td>
</tr>
<tr>
<td>Corn</td>
<td>Grain</td>
<td>0.21–0.40</td>
<td>0.20–0.53</td>
<td>van Duivenbooden et al. 1996</td>
</tr>
<tr>
<td></td>
<td>Whole plant</td>
<td>0.14–0.21</td>
<td>1.00–1.40</td>
<td>Wortmann et al. 2009</td>
</tr>
<tr>
<td>Cotton</td>
<td>Seeds, lint</td>
<td>0.44–0.45</td>
<td>0.90–1.10</td>
<td>Halevy 1976; Cassman, Kerby, et al. 1989</td>
</tr>
<tr>
<td>Sunflower</td>
<td>Seeds</td>
<td>0.57–0.87</td>
<td>0.46–0.92</td>
<td>Deibert and Utter 1989; Gholamhoseini et al. 2013</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>Fruit</td>
<td>0.025–0.035†</td>
<td>0.20–0.30†</td>
<td>Christou et al. 1999; de C. Carmello and Anti 2006; Hartz and Hanson 2009</td>
</tr>
</tbody>
</table>

* Values for these and other crops can also be found online in databases by the Natural Resources Conservation Service (plants.usda.gov/rpk/main) and the International Plant Nutrition Institute (ipni.net/app/calculator/home).
† Concentrations in % of fresh fruit.
‡ Assuming a harvest index (grain yield divided by total aboveground biomass) of 0.5.
The value of testing in soils with a high organic matter content and in production systems where mineralization of organic P amendments, such as animal manures and composts, contribute significantly to the plant-available P pool.

Standard soil K tests are not accurate predictors of fertilizer K availability in K-fixing soils. Much progress has been made recently identifying K-fixing soils in California. A soil test that can accurately and reliably determine the K fixation potential of a soil, yet is simple enough to be adopted by commercial soil test labs, still needs to be developed. An improved understanding and quantification of the capacity of different crops to access nonlabile K would further improve the value of soil testing, not just in K-fixing soils.

Under drip irrigation, the wetting pattern and thus the zone where roots have access to nutrients is more limited than under furrow- or flood-irrigated systems. To ensure appropriate interpretation of soil test values in drip-irrigated fields, current critical soil test values may need to be reevaluated. In addition, there is a need to refine nutrient response curves to soil test values to ensure appropriate application rates.

**Future research**

Research addressing the following issues will help increase the value of the soil testing. Current soil tests extract inorganic forms of labile P. Development of tests that can assess the mineralization potential of organic P would greatly improve the value of testing in soils with a high organic matter content and in production systems where mineralization of organic P amendments, such as animal manures and composts, contribute significantly to the plant-available P pool.

Test procedures and resulting values among commercial labs may differ, making it difficult for growers to compare the results with published critical values. The industry might benefit from routine comparisons of soil test values reported by different commercial labs: the samples would be taken from selected field sites, require sample preparation before analysis and preferably be blind submissions. Such a program might increase standardization of methods and raise awareness of differences among labs.

Soils differ in their capacity to supply nutrients to crops. Despite its limitations, soil testing is a cost-effective way to assess nutrient availability for specific fields. With the information provided in this article, growers and crop advisers can use soil testing for fertilizer decisions that result in efficient and sustainable use of fertilizers.

**References**


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Time: All day
Location: Sequoia Conference Center, Eureka
Contact: Yana Valachovic yvala@ucanr.edu (program); Sherry Cooper slcooper@ucanr.edu (logistics)

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Time: All day
Location: UC Cooperative Extension Placer County, Auburn
Contact: Roger Ingram rsingram@ucdavis.edu

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Date: November 15, 2016
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Location: UC Davis Conference Center, Davis
Contact: Elise Gornish egornish@ucdavis.edu