Nonfumigant Strawberry Production Working Group **Action Plan**

APRIL 2013

CALIFORNIA DEPARTMENT OF PESTICIDE REGULATION

California's strawberry industry urgently needs practical and cost-effective ways to grow strawberries without soil fumigants. Growers have been using fumigants for good reason: they are extremely effective in reducing damage—or worse, devastation—caused by soilborne fungi and nematodes. The strawberry industry has a long history of funding research on soilborne pests and integrated pest management (IPM), but it is imperative to speed up the timetable for developing more production tools in the face of tougher fumigation restrictions and increasing urban development near agricultural land.

The Department of Pesticide Regulation, perhaps more than any other agency, is in a unique position to help move this forward, and that is why I dedicated some of my staff and resources to bring together and motivate a diverse group of stakeholders to converge on this issue. We set the goal for the group: to accelerate change in strawberry production away from reliance on soil fumigants without sacrificing the ability to economically manage soilborne pests. The end product would be an action plan that describes the priorities for researching innovative technologies and adopting new practices.

Our pest management scientists understand the place fumigants and other pesticides have in modern agriculture and the difficulties that often arise when pesticide use is limited without new technologies or practices to fill the gap. I also have a personal understanding of this challenge. During my years as an organic rice farmer in California, I saw that farm production practices can only change when farmers have an array of viable options to select from.

The experts I recruited for the working group unquestionably answered the call. They made time in their very busy lives to meet with us to formulate, draft, and refine this action plan—I am very grateful for the dedication they showed throughout the process. The proposals contained in the action plan are a road map to guide the research required to find production practices and tools necessary to maintain a viable strawberry industry without fumigants. It is a road map for change that will serve to better protect people and the environment.

Brian R. Leahy

Brian R. Leahy
Director
Department of Pesticide Regulation

Acknowledgments

The Department of Pesticide Regulation would like to thank the following individuals and groups for their input, guidance, and support on the Action Plan and Report:

- Members of the Nonfumigant Strawberry Production Working Group for their time, collaboration, expertise, and dedication to seeing this process through to the recommendations.
- Matt Rodriquez, Secretary of the California Environmental Protection Agency, for the idea to address this challenge through a working group.
- California Strawberry Commission for their logistical support of the Working Group field tour and photographs.
- Ag Innovations Network, Joseph McIntyre, President and Tim Griffin, Director of Consulting Services, for their facilitation and expertise in guiding the discussion and process.
- Bill Chism, U.S. Environmental Protection Agency biologist, for his contributions to the discussion early in the Working Group process.

DPR EDITORIAL TEAM

Nan Gorder, Marshall Lee, Matt Fossen, Paul Verke, & Nita Davidson

Table of Contents

Acknowledgments ii
Table of Contents iii
Executive Summary 1
Working Group Biographies 3
Project Background 5
Section I: Discovery 8
Focus Area #1: Breed for genetic resistance to soilborne pests 8
Focus Area #2: Monitor and manage soil microbes to promote plant health 9
Focus Area #3: Evolve production protocols 11
Section II: Research and Evaluation 12
Focus Area #1: Improve viability of management options 12
Focus Area #2: Determine how nonfumigant options might function in IPM programs 13
Focus Area #3: Improve and expand opportunities for research collaboration 14
Section III: Demonstration and Adoption 15
Focus Area #1: Ensure rapid and effective dissemination of information 15
Focus Area #2: Develop approaches to mitigate risk from early adoption 16
Focus Area #3: Identify avenues to encourage and evaluate early adoption 17
Appendix: Research Reports on Existing Options 19

DPR = California Department of Pesticide Regulation
UC = University of California
UCCE = UC Cooperative Extension
UC IPM = UC Statewide Integrated Pest Management Program
USDA = United States Department of Agriculture
U.S. EPA = United States Environmental Protection Agency

Executive Summary

Strawberries are an important agricultural commodity in California. In 2011, they represented 88 percent of the U.S. domestic crop with 2.3 billion pounds harvested for a value of $2.4 billion. Owing to potentially devastating soilborne pests, strawberry growers have relied on soil fumigation treatments for many years. The use of methyl bromide, the fumigant of choice, was to be phased out by 2005 due to its impact on stratospheric ozone under the terms of an international treaty. A critical-use exemption allows limited use on California strawberry acreage. While this exemption requires annual renewal and may expire in 2015, the strawberry industry currently substitutes the fumigants chloropicrin, 1,3-dichloropropene, and metam-sodium for methyl bromide. However, these other fumigants have questionable long-term viability due to rising costs, limited efficacy, and use restrictions, which could include expanded buffer zones to protect health.

In light of these circumstances, Director Brian Leahy of the California Department of Pesticide Regulation convened in April 2012 a working group of industry and scientific leaders to develop an action plan of research priorities for developing cost-effective management tools and practices for soilborne pests of strawberries in the absence of conventional fumigants.

The Working Group recognized that over the last 20 years, many studies focused on breeding disease-resistant plants and testing soil treatments such as anaerobic soil disinfestation, biopesticides, biofumigants, soilless substrate, steam, and solarization. The studies have developed and tested alternatives singly on a small-to-medium scale. Any one of the alternatives, when considered by itself, currently lacks the cost effectiveness, broad efficacy, and reliability of methyl bromide, and will require further work. However, methyl bromide's effectiveness and availability delayed the need to undertake extensive long-term, coordinated research studies to develop alternatives. As a result, growers do not have information and tools needed to grow strawberries without fumigants. Yet to be done is testing combinations of alternatives in extensive field trials and on-farm demonstrations. Collaborative research in the future could elucidate combinations of alternatives that could ultimately replace methyl bromide.

The Working Group's action plan, with its focus areas and priority actions, will inform a diverse group of stakeholders that include growers, academics, commodity groups, environmental organizations, and government agencies. Full implementation of the action plan will require a major commitment of time and resources by a broad range of groups in the private and public sectors, such as researchers, funding institutions, growers, grower organizations, farmworker advocates, community and environmental organizations, and consumers. These commitments would build upon the considerable investment and effort that has gone into research over the last 20 years.

Even with full commitment to implement this action plan, the strawberry industry will need to continue its use of fumigants for years to remain viable in California. The Working Group believes that these recommendations, if embraced, can build on past efforts and lead to the refinement, further development, and adoption of alternative options to reduce reliance on fumigants. The Working Group hopes that growers will increasingly incorporate use of these options as they transition away from fumigants.

FOCUS AREAS AND PRIORITY ACTIONS

DISCOVERY

1. Expand breeding for genetic resistance to soilborne pests

- Screen wild and cultivated clones for resistance to major strawberry pathogens in California.
- Expand research on identifying genetic markers for disease resistance.
- Explore grafting as a possible shortcut to disease resistance.

2. Monitor and manage soil microbes to promote plant health

- Identify and evaluate soil microbes that influence plant health and develop ways to monitor their populations.
- Explore interactions between soil microbial ecology and the cropping environment.
- Develop treatments for managing soil microbial populations.
- Develop a collection of microorganisms isolated from strawberry roots.

3. Evolve production protocols

- Track how soil microbial communities change over time in unfumigated fields.
- Evaluate effects of short- and long-term crop rotations.
- Evaluate the effects of nutrient and water-use strategies on microbial communities.
- Develop databases and GIS software to map and predict disease and pest pressure.

RESEARCH AND EVALUATION

1. Improve viability of management options

- Increase scale of research.
- Develop mechanical equipment to support nonfumigant options.
- Explore geographical and temporal limitations.

2. Determine how nonfumigant options might function in integrated pest management (IPM) programs

- Improve understanding of combining nonfumigant options with IPM practices.
- Explore IPM practices that combine both fumigants and nonfumigant options.

3. Improve and expand opportunities for research collaboration

- Expand gatherings to foster research collaboration and collective action on nonfumigant options.
- Increase number of facilities focused on collaborative strawberry research.
- Promote collaborative research.

DEMONSTRATION AND ADOPTION

1. Ensure rapid and effective dissemination of information on fumigant alternatives

- Develop easy-to-access information.
- Create a comprehensive and producer-oriented online resource.
- Expand on-farm training and education opportunities for growers.
- Strengthen communication and collaboration with public and private groups supporting growers.

2. Develop approaches to mitigate risk during early adoption

- Increase grower knowledge about existing grants and develop new grants to support new approaches.
- Explore opportunities to cover nonfumigant options under crop insurance.

3. Identify avenues to encourage and evaluate early adoption

- Identify regions with early adopters and a high density of potential early adopters.
- Develop strategies to promote nonfumigant options among potential early adopters.
- Track progress of early adopters over time.

WORKING GROUP BIOGRAPHIES

WORKING GROUP SPONSOR

Brian R. Leahy, Director, Department of Pesticide Regulation, Sacramento.
Brian was appointed director in February 2012 by Governor Brown. He previously served as assistant director for the California Department of Conservation's Division of Land Resource Protection and as executive director, respectively, for the California Association of Resource Conservation Districts and California Certified Organic Farmers. Brian is a former organic farmer who has held many leadership roles in agriculture and has a strong history of working collaboratively with environmental organizations, agricultural groups, trade associations, local government officials and other stakeholders. He grew up in Southern California and has a juris doctorate degree from Creighton University School of Law in Omaha, Nebraska.

MEMBERS

Greg Browne, Research Plant Pathologist and Director, U.S. Department of Agriculture's Western Areawide Program for Methyl Bromide Alternatives, Davis.
Greg's research includes examining the etiology of *Prunus* replant disease and other soilborne diseases of deciduous fruit and nut crops and improving integrated pest management strategies for these diseases. His work emphasizes development of almond and walnut rootstock germplasm with improved resistance to soilborne pathogens. He has a bachelor's in plant science and a master's and a doctorate in plant pathology from UC Davis.

Steve Fennimore, Specialist in Cooperative Extension, Department of Plant Sciences, U.S. Agricultural Research Station, Salinas, University of California, Davis.
Steve specializes in weed management in vegetable crops and small fruits as well as weed seed physiology and seed bank ecology. His research and extension interests are in the development of integrated strategies for weed management in cut flower, vegetable crops, and strawberries. The management of weeds in most of these crops is complicated by the limited number of herbicide and fumigant options. Steve's research program is divided into soil disinfestation with steam, mechanical weed removal, and weed management with herbicides. His outreach activities focus on providing educational materials on the management of weeds in California, cut flowers, vegetable crops, and strawberries. He has a bachelor's in public affairs from the University of Oregon, a master's in weed science from UC Davis and a doctorate in weed science from Purdue University.

Anne Katten, California Rural Legal Assistance Foundation, Sacramento.
Anne is an industrial hygienist who has worked with the California Rural Legal Assistance Foundation for the past 20 years. Her work includes analysis of pesticide illness episode investigations, pesticide risk assessments and regulatory proposals, and advocating for improved enforcement and policy changes to reduce farmworkers' exposure to pesticides and other work hazards. Earlier in her career, she worked as a research assistant at a seed company. She has a bachelor's in plant pathology and a master's in public health, both from UC Berkeley.

Karen Klonsky, Specialist in Cooperative Extension, Department of Agricultural and Resource Economics, University of California, Davis.
Karen has been a specialist in agricultural and resource economics at UC Davis since 1981. Her research includes the economic feasibility of alternative and organic farming practices and the size and growth of organic agriculture in California. She is an associate editor for California Agriculture and the Journal of the American Society of Farm Managers and Rural Appraisers and an associate director of the University of California Agricultural Issues Center. She serves as a member of the California Organic Products Advisory Board to the Department of Food and Agriculture and the California Certified Organic Farmers Management Committee. She received her doctorate in agricultural economics from Michigan State University.

Rod Koda, Strawberry Grower, Watsonville.
Rod is a third-generation strawberry farmer. In 1985, Rod and his wife, Gwen, took over the family farm, Shinta Kawahara, that was established when his grandmother-in-law started growing strawberries in 1959. The Kodas continue to farm both organic and conventional strawberries on more than 27 acres along the Monterey Bay coast. Rod has an associate degree from Cal Poly, San Luis Obispo.

Dan Legard, Vice President of Research and Education, California Strawberry Commission, Watsonville.
Dan manages the Commission's efforts related to production research and grower education. His work includes developing research initiatives on fumigant-emission reduction and farming without fumigants. Before his role at the Commission, Dan led the strawberry pathology research program at the University of Florida as associate professor of plant pathology. While there he gained expertise in the epidemiology of strawberry diseases, biology and population genetics of fungal pathogens of strawberries, and integrated management of strawberry diseases through the use of chemical, biological, and cultural control practices. Dan has bachelor's and master's degrees in plant pathology from Colorado State University and a doctorate in plant pathology from Cornell University in New York.

Pam Marrone, Founder and Chief Executive Officer, Marrone Bio Innovations, Davis.
Pam started Marrone Bio Innovations in 2006 to discover and develop effective and environmentally responsible natural products for pest management in agriculture, water, and other markets. She has raised $60 million in venture capital to fund the company, which has commercialized three products and has several more in development across all pest categories. Pam earlier founded AgraQuest, where she served as its CEO, chair and president, raised $60 million in venture capital and commercialized seven biopesticides. Before AgraQuest, she was founding president of Entotech Inc. and led the Insect Biology group at Monsanto. She is past president of the Association of Applied IPM Ecologists and is board member–treasurer of the Organic Farming Research Foundation. She founded the Biopesticide Industry Alliance, a trade association of more than 60 biopesticide companies, and is a member of the UC Davis Ag & Environmental Sciences Dean's Advisory Council. Pam has a bachelor's in entomology from Cornell University and a doctorate in entomology from North Carolina State University.

Gary Obenauf, Agricultural Research Consultant and Chair of the Methyl Bromide Alternatives Conference, Fresno.
Gary is the owner of Agricultural Research Consulting. Areas of expertise are fruit and nut crop production and postharvest handling, including normal production and postharvest handling practices, and pesticides, food safety, regulatory and other technical issues relative to the fruit and nut industries. He has administered and coordinated research projects for the dried fruit and nut industries for almost 20 years and is responsible for the Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. Gary has a bachelor's from the University of Georgia and a master's from Michigan State University.

Carol Shennan, Professor of Agroecology at the University of California, Santa Cruz.
Carol has been a professor in the Environmental Studies Department at UC Santa Cruz since 1997 and served as director of the Center for Agroecology and Sustainable Food Systems there for 10 years. She previously served on the faculty at UC Davis in the Department of Vegetable Crops. Her research focuses on questions of agricultural sustainability in contrasting contexts: high input, high capital intensive vegetable and strawberry production in California, resource-poor systems in sub-Saharan Africa, and most recently in avocado plantations in Chile. In California, her research targets the development of alternatives to soil fumigants for soilborne disease management, strategies for improved nutrient use and disease suppression of strawberry and vegetable rotation systems, and the potential for landscape diversification to enhance biological control of arthropod pests. She has a doctorate in botany from the University of Cambridge, U.K.

John Steggall , California Department of Food and Agriculture, Sacramento.
John began working for CDFA in 1998 after four years at the Department of Pesticide Regulation. At CDFA, he analyzes impacts of pesticide regulatory decisions, pesticide alternatives, and trends in pest management. John has a bachelor's in biology from Colorado College, a master's in aquatic biology from the University of Michigan, and a doctorate in entomology from UC Berkeley. His dissertation research at UC Berkeley was on resource allocation and tolerance of strawberry to herbivory.

Project Background

Strawberries are a highly valued crop in California and are consumed across the United States and well beyond its borders. Strawberries were first introduced to the West in the 1830s. By the 1950s, California had become one of the world's premier growing areas. Working in partnership with scientists at the University of California (UC), strawberry growers pioneered advanced cultivation technologies. Over the next 20 years, UC scientists introduced new strawberry cultivars, annual planting systems, high-elevation nurseries, wide plant beds, and drip irrigation. By the 1970s California emerged as the world's leading strawberry producer. In 2011, 2.3 billion pounds of strawberries were harvested in California, worth $2.4 billion, representing 88 percent of the United States strawberry crop.[1]

THE PHASEOUT OF METHYL BROMIDE

Methyl bromide is an odorless and colorless gas, historically used as a soil fumigant to manage pests across a wide range of agricultural sectors. It is labeled by U.S. EPA as a Restricted Use Pesticide due to acute toxicity. Because methyl bromide depletes the stratospheric ozone layer, the amount used in the U.S. was reduced incrementally until it was phased out January 1, 2005, pursuant to obligations under the *Montreal Protocol on Substances that Deplete the Ozone Layer* (Protocol) and the Clean Air Act. Currently, use is prohibited except for allowable exemptions such as critical-use exemptions, which must be renewed annually and agreed to by the Protocol.

But this industry is now at a crossroads. For years the industry has relied on preplant soil fumigation as the primary tool to manage soilborne pests that include weeds, nematodes, and diseases. Methyl bromide, the fumigant of choice in strawberry production, was technically phased out in 2005 under an international treaty to protect the earth's ozone layer. The challenge of finding suitable replacements for methyl bromide led to approval of critical-use exemptions that give growers prescribed access to it. The exemptions require annual renewal and are based on extensive analysis of alternatives by the USDA, U.S. Environmental Protection Agency (U.S. EPA), and parties of the Montreal Protocol, and highlight the economic and technical challenges facing the strawberry industry to find suitable alternatives to methyl bromide.

Strawberry growers have managed methyl bromide's phaseout[2] primarily by switching to other fumigants (Figures 1 and 2), which of all agricultural pesticides used in California, have the highest use in pounds. From 2010 to 2011, fumigant use increased in some crops (Figure 3). Although the fumigants chloropicrin, 1,3-dichloropropene, and metam-sodium only partially manage soilborne pests, without methyl bromide, strawberry growers must depend on these to produce a viable crop. However, these fumigants are subject to increased use restrictions.

Fumigants are volatile by nature, so their high volatility, high use, and toxicity cause potential health risk to bystanders, workers, and residential neighbors. Since 2003, DPR has documented hundreds of acute illnesses caused by accidental fumigant exposure to agricultural workers as well as people living near fumigated fields[3].

[1] ERS 2011 strawberry data http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1381; www2.econ.iastate.edu/classes/econ496/lence/spring2004/strawberries.pdf

[2] For more information, go to the U.S. EPA Web site at www.epa.gov/ozone/mbr/

[3] www.cdpr.ca.gov/docs/whs/pisp.htm

Fumigants can impact the environment by polluting ground-level air from emissions as volatile organic compounds—and in the case of methyl bromide, stratospheric ozone depletion. Because of their acute toxicity and volatility, fumigants are among the most highly regulated pesticides used in California today. Requirements include regional use limits (township caps), buffer zones, application method restrictions, and personal protective equipment for workers.

Methyl iodide, a recently registered fumigant, was voluntarily withdrawn from the California market in March 2012 and the rest of the U.S. in November 2012. Dimethyl disulfide is registered in other states, but not in California due to insufficient data. Limited availability of fumigants, rising costs, and increasingly stringent mitigation measures have reduced the long-term feasibility of soil fumigant use in California's strawberry industry.

In the face of this uncertainty, nonfumigant options need further development. For over 20 years, the USDA, UC, and the California strawberry industry have made a considerable investment in research on nonfumigant options. Although many of these have been evaluated, no single option has emerged as the best replacement for methyl bromide. Several options have shown promise in small-scale studies, but years of successful commercial-scale research trials are necessary before widespread adoption can happen. No single alternative treatment currently provides the same combination of cost effectiveness and efficacy as soil fumigants and additional collaborative research is needed to develop new integrated approaches.

In the wake of these challenges, the Department of Pesticide Regulation convened a group of industry and scientific leaders to develop recommendations that if followed, could accelerate development and adoption of management tools that manage soilborne pests in strawberry effectively and economically, and reduce the need for conventional fumigants. These recommendations are aimed at a diverse group of stakeholders including growers, academics, commodity groups, environmental organizations, and government agencies. The hope is that if these recommendations are embraced, in five years the current nonfumigant options will have been extensively tested and implemented where viable to reduce fumigant use, and that additional effective and economical options will be in development.

In the 1970s, the collaborative effort between growers and researchers laid the foundation for what is today a multibillion dollar California strawberry industry. Today, that same spirit of partnership and innovation among all industry stakeholders is needed to ensure that California continues to provide safe, affordable, high-quality strawberries well into the future.

Figure 1. Strawberry acres treated with soil fumigants and total acres harvested from 2000 to 2011. Strawberry fields are frequently treated with more than one fumigant, so total acres are shown as harvested instead of treated to avoid double-counting. Fumigant data are from DPR's pesticide use reports database. Data for 2011 are draft. Harvested acres data are from the National Agricultural Statistics Service. Fumigants include chloropicrin, methyl bromide, 1,3-dichloropropene (1,3-D), and metam-sodium (metam).

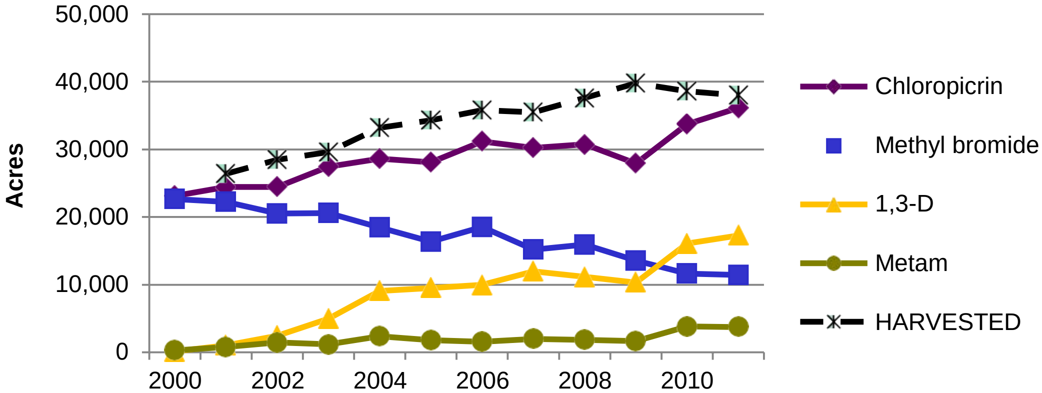


Figure 2. Amount of soil fumigants applied to strawberry fields from 2000 to 2011. Data are from DPR's pesticide use reports database. Data for 2011 are draft.

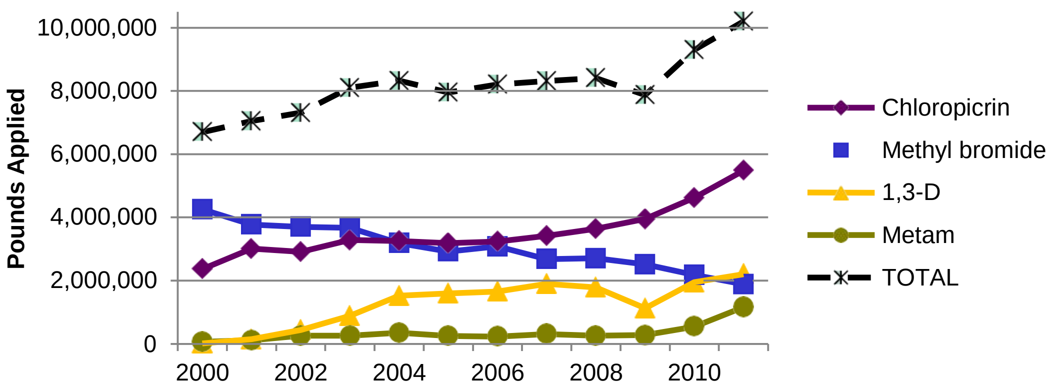
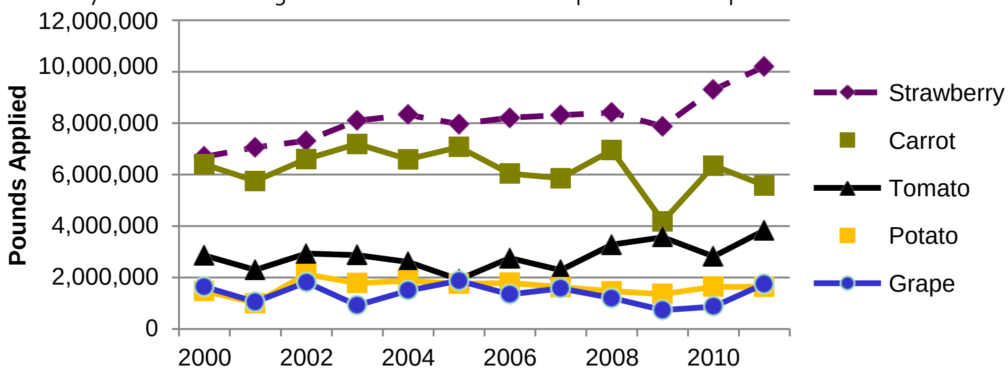


Figure 3. Crops treated with soil fumigants from 2000 to 2011. Remaining crops, including soil fumigation/preplant, comprise approximately one-third of fumigant use. Data are from DPR's pesticide use reports database. Data for 2011 are draft.



Section I: Discovery

Since the phaseout of methyl bromide began, there has been funding of research to grow strawberry or other crops without fumigants. Promising options have emerged, but their commercial efficacy is still being examined in terms of economic viability and ability to manage the same range of pest problems as fumigants. Since evaluation is now in progress there is no guarantee that all of the options will prove viable. Some may only work in specific regions or with access to certain equipment and will need further research.

Working group members recommend that additional resources be devoted to exploratory research. New research should address gaps in basic knowledge, technologies required to produce strawberries without fumigants, and creating a foundation for long-term applied research.

Examples of discovery topics include innovative breeding or propagation programs to develop strawberry cultivars or scion and rootstock combinations with broad resistance to soilborne pathogens. Other topics include an examination of microbial communities and treatments that support their effective management.

Focus Area #1: Expand breeding for genetic resistance to soilborne pests

An ideal coastal climate, combined with focused breeding efforts and intensive cultural practices have made California's strawberry industry the most productive in the world. Yet, without fumigation, soilborne pests remain a primary limiting factor for California strawberry production. The soilborne challenges can be addressed by discovery research on genetic improvement, including genetic engineering, conventional breeding, and development of disease-resistant strawberry rootstocks. There is little industry support for genetic engineering at this time due to negative public perception and limits on exports to many countries.

Modern strawberry cultivars have a relatively narrow germplasm base. Opportunities lie in integrating disease-resistant wild and unimproved clones into breeding or grafting programs. Researchers have made extensive efforts to collect and maintain clones from all over North and South America. They have also reconstructed cultivated strawberry from wild relatives, screening these crosses for disease resistance.

Between the 1950s and mid-1990s, researchers tried to understand resistance and screen for genetic resistance to pathogens such as *Verticillium*, although disease resistance was not a primary focus of breeding efforts. When the methyl bromide phaseout began, UC scientists and private sector breeders focused more attention on resistance breeding. Breeders have made some advances, but believe that further progress is possible, although this may take years. Several recent developments—such as the collection of potentially resistant wild plants and development of genetic tools to quickly identify and incorporate resistance genes into commercial cultivars—have set the stage for future breeding efforts.

Priority Actions for Focus Area 1

- **Screen wild and cultivated clones for resistance to major strawberry pathogens in California.** Breeders have searched North and South America for wild and improved strawberry plants and assembled an extensive collection at Oregon State University. Within this collection, breeders have found substantial possibilities for breeding for resistance to many major strawberry diseases, including anthracnose crown rot, Verticillium wilt, charcoal rot, Fusarium wilt, powdery mildew, bacterial angular leafspot disease, and Phytophthora. Screening wild and cultivated clones for priority strawberry pathogens in California should be a primary target of funding. Emphasis should also be placed on refinement of disease resistance screening techniques for single and multiple pathogens.

- **Expand research on identifying genetic markers for disease resistance.** Recently, plant geneticists have sequenced the strawberry genome and marked genes of interest, such as those for anthracnose resistance. Also, USDA sponsored a $5 million effort (RosBREED) to develop marker-assisted breeding tools for crops in the Rosaceae, including strawberry. The RosBREED program has resulted in development of molecular breeding tools and collaboration between breeders. A notable effort was the collection and distribution for disease screening of 900 genotypes to researchers in California, Michigan, Florida, and New Hampshire. Further research on identifying genetic markers for disease resistance will accelerate breeding results.
- **Explore grafting as a possible shortcut to disease resistance.** No formal academic work has been done on grafting of strawberry plants onto disease-resistant rootstocks. Vegetable grafting has recently been adapted on a commercial scale, in part to combat soilborne diseases. It is possible to graft strawberry scions onto strawberry rootstocks, although nothing is known about commercial potential for the practice. All five strawberry breeders contacted thought this idea is worth pursuing, although difficulties are expected in commercializing the practice and serious questions remain about the economics of this approach.

Focus Area #2: Monitor and manage soil microbes to promote plant health

Previous research has documented efficacy of soil fumigants and fumigant application technologies for boosting strawberry production and reducing populations of pathogenic fungi, oomycetes, nematodes, and weeds in soil. The focus of these studies was largely limited to monitoring impacts on survival of soilborne pathogens, but the research also afforded glimpses into effects of the treatments on the broader culturable soil microbial communities. For example, researchers determined incidences of fungi, oomycetes, and bacteria associated with diseased strawberry roots in unfumigated soil and healthy strawberry roots in fumigated soil. In addition, attempts were made, with some success, to identify and exploit organisms that may stimulate strawberry growth through disease suppression. Researchers are testing organic soil amendments for their potential to induce favorable shifts in soilborne microbial communities in strawberry fields. Recently, anaerobic soil disinfestation (ASD) has shown promise in managing soilborne pathogens without soil fumigation. ASD provides readily available organic amendments and high soil moisture levels to shift microbial communities, stimulate temporary anaerobic conditions, and thereby reduce pathogen populations and suppress strawberry diseases. Modification of fertility management with ASD is needed to prevent undesirable nutrient loss, water quality impacts. or greenhouse gas emissions.

Protocols based upon the polymerase chain reaction (PCR) methods were developed for *Phytophthora cactorum* and *Verticillium dahliae*. The methods may be improved and additional pathogen-specific detection protocols are needed. Finally, rapidly advancing DNA-based technologies now offer detailed views into soil microbial communities, and these should be exploited.

Despite these important advancements, the soil microbiology of strawberry fields is still poorly understood and a better understanding is critical for improving nonfumigant options. Discovery research is needed to provide a sound foundation for advances in soil microbiology and plant pathology.

Priority Actions for Focus Area 2

- **Identify and evaluate soil microbes that influence strawberry plant health and develop ways to monitor their populations**. Systems are needed to identify, quantify, and assess the importance of soil microbial organisms and complexes on strawberries. Recent advances in DNA-based methods, such as improved PCR-based DNA amplification and quantification systems and expanded DNA-sequence databases, may facilitate discovery.

- **Explore interactions between soil microbial ecology and the cropping environment.** Soil microorganisms interact with their environment to affect strawberry growth and disease. The strawberry cultivar, the local microclimate, and the cropping system are among the environmental factors that interact with microbial communities to influence plant health. Research topics include the development of treatment thresholds for disease organisms using refined understanding of sampling and diagnostic methods as well as the use of DNA-based deep-sequencing technologies to understand the microbial ecology of strawberry growth responses and disease suppression.

EXAMPLES OF RESEARCH TOPICS FOR EXPLORING MICROBIAL POPULATIONS

- Identification and characterization of previously undiscovered microorganisms that can suppress disease and stimulate strawberry growth
- Development of specific quantitative PCR (qPCR) detection methods and qPCR primers specific for all important known soilborne pathogens of strawberry
- Development of soil and root sampling and extraction protocols appropriate for DNA-based diagnostics of soilborne pathogens of strawberry
- Rigorous statistical assessment of soil sampling methods for 1) DNA-based risk assessment and diagnostics for soilborne strawberry disease and 2) characterization of soil microbial communities

- **Develop treatments for managing soil microbial populations.** Research may identify environmentally friendly treatments that favorably alter soil biology to allow strawberry production without soil fumigation. Previous research led to current practices such as soil inversion by deep plowing, the application of brassica seed meals or other antimicrobial crop residues, crop rotations, and ASD. ASD shifts populations of soilborne microbial organisms to favor strawberry growing without fumigants. ASD is now used on a limited scale in organic production and may be used in buffer zones for conventional production, but further work is needed to improve its cost-effectiveness and reduce any potential environmental impacts.

EXAMPLES OF RESEARCH FOR MANAGING MICROBIAL POPULATIONS

- Investigation of tractor-applied soil inversion technologies
- Evaluation of cropping rotations and soil amendments that support optimal strawberry growth without soil fumigation
- Identification of economically viable ASD substrates that can be managed to avoid emissions of greenhouse gases and leaching of nitrates
- Characterization of the physical, chemical, or microbial dynamics of ASD treatments in different soils and with different substrates
- Modeling ASD responses using results of the characterizations above
- Evaluation of in-season drip delivery of substrates and microbial complexes to suppress disease
- Evaluation of combinations of ASD and in-season additions of substrates and microbial complexes

- **Develop a collection of microorganisms isolated from strawberry roots.** Locate soils where growers have reported little to no disease and isolate microorganisms from those soils and roots of strawberry plants.
    - Conduct in vitro tests to screen the isolated microorganisms of major strawberry diseases.
    - Select the microorganisms that show the best in vitro inhibition of strawberry pathogens and set up greenhouse and field tests.
    - If the microorganisms show potential management or suppression of pathogens, develop and commercialize as a U.S. EPA–registered biocontrol agent (biopesticide).
    - Screen potential biocontrol microorganisms in collaboration with companies, universities, and public institutions.

Focus Area #3: Evolve production protocols

The transition away from conventional fumigants will require a combination of cultural practices and rotational cycles to optimize production and limit disease pressure. Research is needed to evaluate these new combinations through time and assess how microbial communities and pathogenic species respond. As more acreage is subject to restrictions that require unfumigated buffer zones, there is an opportunity to conduct side-by-side studies to compare fumigated and unfumigated fields.

Priority Actions for Focus Area 3

- **Track how soil microbial communities change over time in unfumigated fields.** Moving away from using fumigants will stimulate changes in the soil microbial communities, including the pathogens within them. Understanding these changes will help us find ways to promote the growth of beneficial soil microorganisms and manage new pests to produce a viable crop. For example, new pathogens, e.g., *Macrophomina phaseolina*, have caused problems in fields treated with fumigants other than methyl bromide. Though populations of beneficial microorganisms should proliferate after a shift to farming without fumigants, pathogens may need increased management. It will be essential to identify how constituents in microbial communities change through time and develop strategies to manage them for optimal plant health.
- **Evaluate effects of short- and long-term crop rotations.** Many strawberry growers, especially those who use organic practices, rotate fields with broccoli and other crops to keep pest pressure down. In addition, land owned by vegetable growers is planted with vegetable crops for 2–3 years, and then rented to a strawberry grower, who fumigates before planting. Without the use of fumigants, this rotation may change as vegetable growers would no longer benefit from the fumigated soil. There is much to learn about managing new problems when strawberries and vegetable crops are grown in rotation without fumigants, including economic impacts. Some such studies are already underway.
- **Evaluate the effects of nutrient and water-use strategies**, especially those that might be regulated by the State's Irrigated Lands Regulatory Programs, on microbial communities. Optimum nutrition sometimes helps plants tolerate infections with secondary pathogens and outgrow disease symptoms. Managing nutrient inputs is also critical to avoid runoff into surface water or leaching into groundwater.
- **Develop databases and GIS software** to map and predict soilborne disease and pest risk to strawberries, allowing growers to choose appropriate management options. More work is needed to predict incidence of primary strawberry diseases and weed problems, but predictive modeling tools that account for local conditions would be helpful for management of all soil pathogens.

Section II: Research and Evaluation—Nonfumigant Options Used on a Commercial Scale

Over the last 20 years, the development of stand-alone, replacement nonfumigant options for managing soilborne diseases has had some success. A number of options have yet to be tested on a large scale through on-farm demonstrations or incorporated into programs that use multiple rather than stand-alone approaches. Recent results with some options have increased optimism; however, conventional growers remain skeptical of the long-term, commercial-scale suitability without additional large-scale, on-farm demonstration and use in more growing regions. The development of effective options will likely require the development of new, more integrated approaches.

Working group members recommend continuing to research the most promising options that focus on fitting these into an integrated pest management (IPM) program.

Focus Area #1: Improve viability of management options

Ways to improve commercial viability and remove barriers to commercial adoption need further research and evaluation. One or more of these options could be combined with long-standing cultural practices such as removal of old plants, crop rotation, and other preventive practices.

The strawberry crop is economically valuable, but is highly susceptible to several soil pests. Current conventional strawberry production is based on soil fumigation with methyl bromide and combinations of other fumigants. Methyl bromide fumigation is a well-understood process with minimal yield risks. Most efforts have tried to replace methyl bromide with other combinations of fumigants. These replacements have not been satisfactory from pest management or public health perspectives, and they have shown how difficult it will be to manage soilborne pests effectively without fumigants. The continued use of fumigants may not be sustainable. Thus, it is imperative to focus the development of options that will reduce the need for fumigants without threatening the economic viability of the strawberry industry.

Management options for strawberry production are outlined below and described in detail in the appendix.

- **Production of Strawberries in Soilless Substrate Systems.** The California Strawberry Commission funded adaptation of this physical pest-exclusion system from Europe. Troughs are cut into traditional strawberry beds, which are then lined with landscape fabric and filled with a substrate such as peat, coir, or mixtures of these and other materials. The trough has a limited rooting volume and thus plant nutrition and water status must be carefully monitored on a daily basis. Current versions of this system are not economically practical in the United States. A variation is used on limited acreage in Belgium and other European countries where higher returns for strawberry are possible.
- **Use of Biological Pesticides.** Various biologically based pesticides are available to help manage soilborne pests. These include both microbial biopesticides—products derived from microbes or their metabolites—and biochemical biopesticides, which are naturally occurring compounds or synthetically derived compounds that are structurally similar and functionally identical to their naturally occurring counterparts. Not enough large-scale, on-farm demonstrations have been conducted to determine their full potential as fumigant alternatives. Nor have combinations of active ingredients or combinations with lower levels of fumigants been tested extensively.
- **Anaerobic Soil Disinfestation (ASD)**. ASD suppresses soilborne pathogens by using organic amendments and water to create temporary anaerobic soil conditions. The process involves incorporating a carbon source into the soil, irrigating the soil to field capacity,

and maintaining an anaerobic environment for up to three weeks. ASD has been shown to manage many soilborne pathogens, but not weeds under most coastal conditions.

- **Steam.** Steam treatments effectively manage pathogens and weeds, but only in soil directly contacted by the steam. Current steam delivery systems using hoses and pipes are labor intensive and expensive. Automatic steam application equipment is used on a limited scale in Italy and is much more economical, but has the disadvantage of being slow. Soil that has been disinfested with steam can be used for strawberry production using the same practices as fumigated soil. Questions remain about the economic and environmental practicality of this approach. To reduce the cost and limitations, steam could be combined with other options such as biopesticides, but these combinations must also be evaluated.
- **Solarization**. Soil solarization uses plastic sheets to trap solar energy and kill soilborne organisms with heat. The heat kills weed seeds near the surface, but fails to reach organisms deeper in the root zone. Strawberries are primarily produced in coastal regions where solarization temperatures are too low to be effective. It may be possible to improve efficacy by combining solarization with other treatments, such as mustard meal applications.

Priority Actions for Focus Area 1

- **Increase scale of research**. Researchers should conduct experiments on increasingly larger-scale, on-farm plots. Research should include growers and economists to ensure that the common field variables and constraints are examined, and that cost data are accurately captured.
- **Develop mechanical equipment to support nonfumigant options.** Research and engineering are needed to develop machinery that increases the scalability, ease of implementation, and consistency of using nonfumigant options.
- **Explore geographical and temporal limitations.** Strawberry has geographical and seasonal limitations based on climatic requirements of the crop, seasonal variations, and nursery plant availability. We need a better understanding of how these factors may impact the efficacy of nonfumigant options.

Focus Area #2: Determine how nonfumigant options might function in IPM programs

Still unknown is the effectiveness of combining nonfumigant options with other pest management practices. IPM (defined in the box below) maintains plant health by including various preventive practices. Additional research is needed to explain what makes these practices effective and how they might be used with nonfumigant programs.

IPM can also include the judicious use of synthetic pesticides, including fumigants, and additional research is needed to explore how rotating nonfumigant options with fumigants might work under short-term field conditions.

DEFINITION OF IPM
(University of California)

Integrated pest management (IPM) is an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of practices such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties. Pesticides are used only after monitoring indicates they are needed according to established guidelines, and treatments are made with the goal of removing only the target organism. Pest management materials are selected and applied in a manner that minimizes risks to human health, beneficial and nontarget organisms, and the environment.

Priority Actions for Focus Area 2

- **Improve understanding of combining nonfumigant options with IPM practices.** IPM is enhanced by developing healthy, disease-suppressive soils that reduce the prevalence of pests. Common practices include removing old strawberry plants from the field, rotating crops, incorporating soil additives such as compost and seed meals that suppress soil pathogens, and manipulating the soil microbial community with inocula. Research is needed to determine what makes these practices effective and how they function in unfumigated fields.

- **Explore IPM practices that combine fumigants and nonfumigant options.** IPM includes both conventional soil fumigants and nonfumigant options. These combined approaches may provide an additional degree of protection in fields with very high disease pressure and as a way to transition to emerging nonfumigant options. Additional research is needed to explore the potential of these combined approaches.

Focus Area #3: Improve and expand opportunities for research collaboration

A number of meetings and conferences on fumigant options focus on information sharing, typically in the form of research presentations. Information sharing is useful, but given the interdisciplinary nature of managing cropping systems, creative discussion and collaboration among researchers would illuminate research blind spots and foster breakthrough thinking. Additionally, researchers would benefit from expanding prime public research facilities or properties to collaboratively develop management options.

Priority Actions for Focus Area 3

- **Expand gatherings designed to foster research collaboration and collective action on nonfumigant options**. Research would benefit from venues designed to encourage collaboration among academics, growers, and other industry stakeholders. This would include collaboratively designing trials, analyzing research findings, and discussing results with growers. Such meetings and workshops might consider including working groups that could investigate and report on promising new research topics.

- **Increase number of facilities focused on collaborative strawberry research.** Researchers would benefit from access to long-term, stable research locations in major strawberry production regions. Currently, most research is done on farms, which presents logistical challenges and limits the ability for researchers to collaborate with other researchers. These research stations should accommodate trials by numerous researchers and span many disciplines. The box below highlights key design recommendations for such collaborative research stations.

DESIGN RECOMMENDATIONS FOR COLLABORATIVE RESEARCH STATIONS

- Locate in main strawberry-growing area in California
- Allow back-to-back strawberry crops as well as rotation with other crops
- Include natural build-up of pathogens such as *Verticillium, Macrophomina, Colletotrichum, and Fusarium*
- Set up to allow testing and demonstration of individual practices such as ASD, but also practices combined with other biological tools such as pre-plant dips, soil-applied microbials, and other biological products such as Induced Systemic Resistance and Systemic Acquired Resistance extracts or compounds
- Allocate a section for organic production

- **Promote and expand collaborative research**. Researchers commonly rely on grant funding to conduct their projects. For the most part, the requirements of funding from government agencies include collaborative, interdisciplinary work. Research projects have benefitted from collaborative research and this should continue into the future. New sources for funding might come from DPR pest management research grants, foundations, and private companies.

Section III: Demonstration and Adoption

As new practices emerge and current promising options are refined, researchers, industry and government representatives, and nonfumigant advocates must develop strategies that will support growers transitioning to nonfumigant options.

Working group members emphasize the importance of ensuring that growers understand how nonfumigant options work in theory and under field conditions. This will require online resources, more demonstration and grower test plots, and effective strategies for communicating with growers, pest control advisers, and farm advisors. Also important is encouraging businesses to offer services, supplies, and technical support that will help growers adopt nonfumigant options.

Working group members also recommend proactive measures to interest growers in adopting nonfumigant options and reduce the risks involved when trying new management practices. They recommend targeting information about nonfumigant options to potential early adopters.

Focus Area #1: Ensure rapid and effective dissemination of information on fumigant alternatives

Priority Actions for Focus Area 1

- **Develop easy-to-access information**, including reliable economic and efficacy data on nonfumigant options for growers, pest control advisers, academics, agribusiness groups, and other stakeholders. For this information to be useful to a wide audience, it should be available in a variety of ways (e.g., written material, online resources, and field demonstrations).
- **Create a comprehensive and producer-oriented online resource.** An easy-to-use resource that allows data sharing and collaboration is essential to ensure information transfer and good communication. The primary objective of such an online platform should be to explain relevant research results through grower-oriented outreach. Ideally, this information would be available in several languages, including English, Hmong, and Spanish. The box below highlights sample content that such a Web site could include.

  A successful Web site would require coordination among governmental agencies, academic and industry organizations, private businesses, and growers. Many of these groups already have online sites that provide strawberry growers with information (e.g., the California Strawberry Commission, UC Cooperative Extension, UC IPM). The resource could grow out of an existing platform.

SAMPLE CONTENT FOR ONLINE RESOURCES

- ✓ Research on promising practices (e.g., field trial results)
- ✓ Manuals for using specific practices
- ✓ Case studies of growers working with new practices
- ✓ Regional maps of growers, businesses, extension agents, and others supporting new practices
- ✓ Periodic e-newsletters highlighting cutting-edge research, recent successes, and other relevant data
- ✓ Video segments of field demonstration days and grower accounts of experience with practices

- **Expand on-farm training and education opportunities for growers related to nonfumigant options.** An important complement to providing access to new and relevant information for growers is seeing firsthand how new practices work in the field.

Many growers prefer to learn about new practices at demonstration plots and field days where they can see the systems in the real-world settings. Growers will benefit from additional training and educational events that highlight new practices and span several growing regions.

Growers play an important role during the evolution of new practices by identifying efficiencies and adapting them to different field conditions and equipment. On-farm innovations often improve efficacy, predictability, and affordability and accelerate adoption by other growers. Consequently, growers should be supported in their efforts to test new practices on their own farms.

- **Strengthen communication and collaboration with public and private groups supporting growers.** Most growers interact with various groups that support the strawberry industry. Close communication and partnership between core institutions, including county agricultural commissioner offices, the Farm Bureau, UC Cooperative Extension, and UC IPM will ensure that groups that frequently interface with strawberry growers stay up to date on nonfumigant options.

  Additionally, agribusiness groups may be interested in staying current with development and refinement of nonfumigant options. Private enterprises that offer farm support services might find attractive opportunities to expand business prospects and provide services to growers who want to implement promising new nonfumigant options. Such services might include supplying necessary key materials (e.g., carbon sources for ASD) or leasing high-cost equipment (e.g., industrial steamers). Businesses have emerged that sell carbon sources and provide technical support to growers for ASD (see box below).

  Businesses in the supply-chain—many of which feature products that supply sustainable farms—may also be interested in the possible marketing advantages of certain production practices. Lenders should also be aware of progress to ensure they understand capital investment opportunities.

One farmer-owned distribution, marketing, and research company sells cover crop seeds, different varieties of mustard seed meal, and other carbon sources as soil amendments. The company offers growers high-quality carbon sources for use in anaerobic soil disinfestation (ASD) and field consultation to teach them how to use and monitor ASD treatments. In 2012, 130 acres at 20 different sites were treated.

Focus Area #2: Develop approaches to mitigate risk during early adoption

Risk is one of the biggest challenges for growers adopting new pest management practices. High production costs, susceptibility to pests, perishability of fresh strawberries, and market volatility will all influence a strawberry grower's readiness to adopt new practices. Growers of specialty crops such as strawberries are especially at risk since they do not benefit directly from government price supports.

Effective incentives and safety nets that protect growers can help them more confidently face increased risk incurred when transitioning to nonfumigant options. Incentives should include promoting and expanding grants and other programs designed to support growers in transition, and exploring how crop insurance might protect growers using nonfumigant options.

Priority Actions for Focus Area 2

- **Increase grower knowledge about existing grants and develop new grants**

and other incentive programs to support new crop production approaches. Given the high production costs of strawberries, the effectiveness of soil fumigants, and the devastating threat that soilborne diseases pose, growers may be reluctant to try nonfumigant options, especially if they must learn a new production system or use new equipment. Incentives or safety nets that reduce the burden of transition to new approaches could increase growers' willingness to experiment.

A number of such programs already exist, including grant programs through USDA's Environmental Quality Incentives Program (EQIP) and Sustainable Agriculture Research and Education,[4] although these have proven so far to be of limited value to strawberry growers. Strategies are needed to better tailor existing programs and develop new grant programs and other incentives specifically for strawberry growers interested in nonfumigant options.

- **Explore opportunities to better cover nonfumigant options under crop insurance.** Crop insurance helps growers manage risk by safeguarding their crop against unforeseen events, usually related to weather. When losses beyond the farmer's control reduce revenue, crop insurance can provide indemnities that compensate for these losses.

  The government's Federal Crop Insurance program[5] is currently piloting a California strawberry policy, available to growers in Fresno, Merced, Monterey, Santa Barbara, Santa Cruz and Ventura counties. However, very few strawberry growers have purchased policies; only six were sold in 2012 and seven in 2013, possibly owing to the high cost. Greater numbers of strawberry growers may be insured privately.

  This current federal pilot program will not serve as a safety net for growers transitioning from fumigant use to nonfumigant options unless they transition to organic production, because loss from plant disease is only compensable if no registered pesticides are available for use. While the current insurance program model does not adequately promote nonfumigant adoption, the overall insurance concept as a risk-mitigating safety net holds promise as a potential tool. With further research and exploration, a new insurance contract and economic model could be developed to help growers reduce the revenue risks associated with switching from fumigants to nonfumigant options.

Focus Area #3: Identify avenues to encourage and evaluate early adoption

- Growers may want to try new nonfumigant options if their fields are close to schools or other sensitive sites requiring large buffer zones, or who face more stringent fumigant use restrictions due to unfavorable local weather conditions.
- Once researchers identify regions where growers are best situated to try new nonfumigant options, a strategy can be developed to raise awareness and encourage growers to experiment. If possible, surveys should be conducted to capture and analyze key data and track progress in numbers of farms and acreage using new practices. This information will enhance growers' and other key stakeholders' understanding of the performance of practices under different management scenarios.

[4] www.sare.org/grants
[5] www.rma.usda.gov/data/sob.html and www.rma.usda.gov/tools Also see USDA Federal Crop Insurance Corporation Actual Revenue History Strawberry Pilot Crop Provisions: www.rma.usda.gov/policies/2012/12-154.pdf and www.rma.usda.gov/fields/ca_rso/2012/caarhstrawberries.pdf

Priority Actions for Focus Area 3

- **Identify regions with early adopters and a high density of potential early adopters**. As a first step, an effort should be made to identify and locate growers who may be likely to implement new approaches. These could include growers who produce both organic and conventional strawberries. Other factors might also influence the likelihood of early adoption (e.g., fields are adjacent to sensitive areas such as residences). This information may help focus efforts to grower education efforts to where they would have the greatest impact.
- **Develop strategies to promote nonfumigant options among potential early adopters.** Once prospective early adopters are identified, strategies should be developed to promote nonfumigant options for them. For promotion efforts to be effective, key stakeholders should be engaged to ensure the nonfumigant option's benefits and shortcomings are addressed. It is also necessary to inform other stakeholders about nonfumigant options, especially those who may influence adoption, such as certifiers of organic producers, pest control advisers, farm advisors, and county agricultural commissioners who issue fumigant use permits.
- **Track progress of early adopters over time.** As early adopters begin to use new practices in their fields, information should be collected and monitored on key parameters (e.g., acres, cost, or yield) over time. Understanding how these parameters change over time will provide a more complete picture of how these practices are functioning in the field. This should include capturing early adopters' experiences using new practices and allowing researchers to monitor the performance of practices over time and under different management scenarios and environments.

Appendix: Research Reports on Existing Options

ANAEROBIC SOIL DISINFESTATION: RESEARCH REPORT

Description: Anaerobic soil disinfestation (ASD) suppresses soilborne pathogens by using organic amendments and water to facilitate the development of temporary anaerobic soil conditions.

What We've Learned

- Requires a carbon source to be mixed into the soil
  - Primarily used rice bran to date, although not enough rice bran for universal use in strawberry industry
  - Other potential sources include molasses, grape pomace, and other materials; ethanol is used in Japan
  - Application rates need more fine-tuning and nitrogen management issues addressed
- Take soil to field capacity and keep it there for 3 weeks
  - Uses approximately 3 acre-inches of water
  - Add 1.5 inch at first, then add more as needed
- How it works
  - Still unsure exactly how it works, but the process requires strong anaerobic conditions and soil temperatures above 65°F for at least the first 1–2 weeks
  - Organic acids and volatiles released during process, and possibly production of ferrous ions (Fe^{2+}), any of which can be toxic to pathogens
  - Competition between new soil life and existing bacteria and fungi: ASD results in increased numbers of bacteria and fungi overall as well as in specific types, which may be disease suppressive
- Results
  - 80 to 100% reduction of *Verticillium* in sandy loam to clay loam soils
  - Tested in Watsonville, Salinas, Ventura, and Santa Maria locations
  - All trials were on farmers' fields
  - Findings in Florida and Japan say it can control *Fusarium* and *Macrophomina* as well as nematodes
  - Compares favorably to conventional costs depending on carbon source used—more exploration on numbers needed
  - Unpleasant smell in treated areas, which indicate anaerobic conditions
  - Encourage farmers to try ASD on a small area initially
  - Standard plastic works well—can be clear, green, or black
  - Doesn't manage weeds effectively under coastal conditions—options to use black plastic or herbicides
  - Treatment time is about 3 weeks of anaerobic decomposition before punching planting holes to reaerate the soil—timing is consistent with fumigant treatments
  - Currently suggest waiting about 3–4 days before planting

APPENDIX

What we still need to know about anaerobic soil disinfestation

DISCOVERY	▪ Identify and test additional carbon alternatives (e.g., molasses, other agricultural byproducts, summer cover crops) and optimize application rates ▪ Optimize N management depending on C source used	▪ Determine if ASD can work in very sandy soils or sloped fields ▪ Determine if summer cover crops can provide adequate carbon for early fall ASD
EVALUATION & RESEARCH	▪ Trial in sandy soil ▪ Trial on steeper slopes ▪ Trial ASD with other technologies ▪ Conduct field scale (≥ 0.5 acres) trials/evaluations simultaneously with research. Test different tarp applications for weed management in warmer regions ▪ Generate information on relative costs of ASD for multiple locations and different carbon sources, including summer cover crops ▪ Evaluate consistency of the effect on the microbial community ▪ Strengthen understanding of how soil temperature figures into process	▪ Track nitrogen release following ASD and refine N management to account for N input from ASD to meet water quality concerns ▪ Determine how deep in the soil the treatment works effectively ▪ Evaluate consistency versus fumigant treatments in large-scale plantings ▪ Determine how soon planting can happen after ASD process complete. ▪ Develop grower-friendly technologies (electrodes) to help ensure anaerobic conditions established ▪ Identify the range of pest and pathogens controlled. ▪ Explore equipment options needed to effectively scale technology
DEMONSTRATION & ADOPTION	▪ Identify best vehicles to deliver information to growers ▪ Develop information on comparative performance, costs, and use guidelines of various practices	▪ How to best support UCCE, UC IPM and others in promoting adoption ▪ Identify creative ways to support growers in using the new practices (commercialize technology support, provide insurance)

Research

Shennan, C., J. Muramoto, S. T. Koike, and O. Daugovish. 2011. Optimizing anaerobic soil disinfestation for non-fumigated strawberry production in California. Pgs 111–123 in California Strawberry Commission Annual Production Research Report: 2010–2011.

Report on performance of anaerobic soil disinfestation (ASD) as a nonfumigant alternative for soilborne disease management in field trials of strawberry production in coastal California. ASD involves incorporation of an organic carbon source into the soil of strawberry beds, followed by application of a plastic tarp and irrigation to soil saturation. The beds are then left for 3 weeks, during which time anaerobic conditions (no oxygen) are created which in other studies have been shown to control a number of pathogens and nematodes. Holes are then punched into the tarp to allow oxygen to return to the soil and transplants then planted 5–7 days later.

In multiple locations ASD performed as well as fumigants, generally increasing yields significantly above untreated controls. The report provides evidence that ASD reduces *Verticillium dahliae* in the soil by 85–100%, again comparable to fumigants. Preliminary economic analysis from another site shows that ASD compares well with fumigant use: these data are in a later report to be published shortly. Issues remaining include how to optimize the system in terms of carbon source additions and nitrogen management, to determine how effective ASD is against other pathogens like *Fusarium oxysporum* and

Macrophomina phaseolina, and issues involved in scaling the technique up to full field scale. Trials are underway to address all of these questions.

Blok, W.J., J.G. Lamers, A.J. Termorshuizen, and G.J. Bollen. 2000. Control of soilborne plant pathogens by incorporating fresh organic amendments followed by tarping. Phytopathology 90: 253–259.

This is the earliest study showing the potential for what has become known as ASD or BSD (see below). The work was done in the Netherlands and is notable for showing control of a number of pathogens by the technique. The study looked at *Fusarium oxysporum* f. sp. *asparagi*, *Rhizoctonia solani*, and *Verticillium dahliae* suppression by burying inoculum samples before treatment. The study showed that irrigating and either adding organic material or tarping alone did not lead to control, but the combination did, and resulted in creation of strongly anaerobic conditions. Soil temperatures during the study were much lower than typically found in California and the tarping period used was 15 weeks. Subsequent work a 3-week tarping period seems to work well in coastal California.

Momma, N. 2008. Biological soil disinfestation (BSD) of soilborne pathogens and its possible mechanisms. Jarq-Japan Agricultural Research Quarterly 42: 7-12.

Biological soil disinfestation (BSD) is similar to ASD in principle but is typically used as a flat field treatment with higher water use than ASD, which has been developed as a bed application technique for California strawberries. BSD also features addition o an organic amendment, irrigation, and covering the soil surface with plastic film for a period of time. Momma shows that BSD effectively killed *Fusarium oxysporum* f. sp. *lycopersici* and *Ralstonia solanacearum*. Much of the paper is dedicated to discussion of the potential mechanisms behind BSD such as production of organic acids and changes in the bacterial community.

Goud, J.C., A.J. Termorshuizen, W.J. Blok, and A.H.C. van Bruggen. 2004. Long-term effect of biological soil disinfestation on Verticillium wilt. Plant Disease 88(7): 688–694.

BSD was evaluated in the Netherlands for control of *V. dahliae* and the nematode *Pratylenchus fallax* in nursery production of two tree species. Using Italian ryegrass as a carbon source, BSD was compared at two locations with an untreated control. After treatment, plots were cropped with *Acer platanoides* and *Catalpa bignonioides* and grown for 4 years. Relative to the control, soil inoculum levels of *Verticillium dahliae* were reduced by 85% after BSD and did not increase for 4 years. Populations of *Pratylenchus fallax* in the soil and roots were reduced by 95 to 99%. The incidence of infection by *V. dahliae* was reduced by 80 to 90%. Verticillium wilt severity was significantly reduced in *A. platanoides* in all 4 years at one location and for the first 2 years at the other location. Market value of the crop in BSD plots was up to € 140,000 ha-1 higher for *A. platanoides* and € 190,000 ha-1 higher for *C. bignonioides* than in the untreated control. The authors conclude that BSD is an effective, economically profitable, and environmentally friendly disease control method for tree nurseries. While the conditions and specific application methods of BSD differ from coastal California, this paper is important for showing long-term control of *V. dahliae* by BSD.

BIOPESTICIDES: RESEARCH REPORT

Description: Biopesticides fall into two categories: microbials and biochemicals. Microbial biopesticides are products derived from various microscopic organisms. Microbial products may consist of the organisms themselves and/or the metabolites they produce. Biochemical biopesticides are naturally occurring compounds or synthetically derived compounds that are structurally similar and functionally identical to their naturally occurring counterparts. Serenade® and Actinovate® are examples of microbials.

In general, biochemical biopesticides are characterized by a nontoxic mode of action that may affect the growth and development of a pest, its ability to reproduce, or pest ecology. They also may have an impact on the growth and development of treated plants including post-harvest physiology. Regalia® and phosphite products such as Fungi-phite® are examples of biochemical biopesticides.

What we've learned

- There are potentially some viable biopesticide products for alternatives to fumigants for fungal disease and nematode management.
- Companies producing these have field data showing good results, but growers have limited experience with these products.
- There is skepticism that these products work, but incorporated with other tools they do have potential.

What we still need to know about biopesticides

DISCOVERY

- Ask companies for their field trial data

EVALUATION & RESEARCH

- Need to design integrated programs with multiple tools
- Research plots with key influencers (PCAs and land grant extension specialists)
- Multiple locations in California
- Multiple treatments
- Combine with ASD

DEMONSTRATION & ADOPTION

- While doing research trials, conduct parallel on-farm demos of integrated programs

Research

Biopesticide resources and case studies:

www.biopesticideindustryalliance.org/index.php

riseofbiopesticides.com

Highland, H. B. 2010. MeloCon®WG and SoilGard®12 G used in a Program as a Fumigant Alternative. Internal Certis presentation.

Bionematicide Melocon® (*Paecilomyces lilacinas* and *Gliocladium*) and fungal biocontrol (Soilgard®) combination—provided yields as good as commercial standard and better than untreated in strawberries

Holden Research and Consulting. 2012. Application of Regalia to Control Soil-borne Diseases and Enhance Plant Establishment of Strawberries, plus production. Internal Holden Research and Consulting data.

APPENDIX

Marrone, P. 2012. Regalia® Biofungicide. Internal Marrone Bio Innovations presentation.

Regalia,® an extract of giant knotweed, induces systemic resistance in strawberry plants, leading to disease management. For soil applications, trials show better vigor, root growth, and marketable yields than untreated and similar to grower standard in Florida and California strawberry trials. One Regalia rate appeared to beat the grower standard in a trial in California. Fungi-phyte in this trial was exceptional, far out-producing the grower standard.

Natural Industries, Inc. 2011. Actinovate® AG Biological Fungicide. Natural Industries product fact sheet. www.naturalindustries.com

Actinovate® (*Streptomyces lyticus*) used on strawberries showed good yields compared to untreated controls in field trials.

AgraQuest. 2012. Serenade Performance Data. serenadesoil.com/performance-data

AgraQuest. 2012. SERENADE SOIL® Fungicide Offers New Soil Disease Control for Strawberries. Press Release. agraquest.com/news/2012/05/serenade-soil®-fungicide-offers-new-soil-disease-control-alternative-for-strawberries/

Serenade®—*Bacillus subtilis* strain 713. Recently got a soil label for strawberries. Could not find strawberry data however, but they must have it as it's registered in California.

Plant Protectants, LLC. Fungi-phite®—A Systemic Fungicide for the Suppression and Control of Phytophthora, Pythium and Downy Mildew. Product Label.

UC IPM Online. 2012. Strawberry—2012 Fungicide Efficacy and Treatment Timing. www.ipm.ucdavis.edu/PMG/r734902111.html

Fungi-phite—Mono- and di-potassium salts of Phosphorous Acid—Labeled for strawberry. This product is a biochemical biopesticide.

BIOFUMIGANTS: RESEARCH REPORT

Description: Biofumigants are biological products that produce compounds such as isothiocyanates that act as local fumigants in the soil. Biofumigants include mustard seed meals, DMDS (dimethyl disulfide, a synthetic version of a naturally occurring compound), or *Muscodor* spp., a fungus that produces volatile compounds that can kill nematodes, insects, and plant pathogens.

What we've learned

- Mustard seed meals have shown potential, but specific meals must be used at high rates in combination with other practices since results vary due to field activity. A limited number of systems have been studied in depth, with the best information available for apple replant disease, a complex of *Rhizoctonia solani*, *Phytophthora cambivora*, *Pythium* spp and *Pratylenchus* spp. Studies by Mazzola et al. found that the mustard species used was important and a blend of species proved to be the best option. This is because *Sinapis alba* and *Brassica napus* can increase levels of *Pythium* spp, whereas inclusion of B*rassica juncea* prevents this increase. Conversely *B. juncea* does not control *Rhizoctonia solani* as effectively as the other species and does not control *Phytophthora cambivora*, which is effectively controlled by *S. alba*. A mixture of *B. juncea* and *S. alba* is recommended for broadest control of the complex. Other work showed potential for weed control with high rates of mustard seed meal application. A further study showed a significant benefit of high temperature exposure before mustard seed meal application for control of *Macrophomina* and *Fusarium oxysporum*. Issues of the particle size of the seed meal and the importance of good mixing in the soil have also been raised. Preliminary results for California strawberries were not promising, but may be due to the specific material used. A recent trial using a mix of *B. juncea* and *S. alba* from a different commercial source showed significant yield improvements over untreated controls at a site in Watsonville and suggests that further study is warranted.
- DMDS is currently pending approval in California.
- *Muscodor* is not developed or registered yet, but will likely enter the market in 2–3 years.

What we still need to know about biofumigants

DISCOVERY

- Mustard seed meal (MSM)—mechanisms of suppression of different pathogens by various species and mixes
- DMDS
- *Muscodor* species as biofumigants

EVALUATION & RESEARCH

- Identify the best mixes of MSMs to manage the range of pathogens of interest for strawberry.
- For MSM, look at rates of application, particle size of the material used, and degree of mixing in soil to find the optimal treatments. Investigate the importance of soil temperature, especially for management of *Macrophomina* and *Fusarium*.
- Address nitrogen dynamics following MSM application
- Test combinations of biofumigants with ASD and other nonfumigant options

DEMONSTRATION & ADOPTION

- Develop field-scale demonstrations of promising MSM mixes and combinations of practices

Research

Paladin® Soil Fumigant. 2012. Arkema Inc. Web site. paladin.com/default.aspx

Dimethyl disulfide (DMDS) is an effective, natural product but is also volatile and explosive. DMDS could be a viable alternative to conventional soil fumigants.

Ezra, W., M. Hess, and G. A. Strobel. 2004. New endophytic isolates of *Muscodor albus*, a volatile antibiotic-producing fungus. Microbiology 150: 4023–4031.

Hoagland, L., Carpenter-Boggs, L., Reganold, J., and Mazzola, M. 2008. Role of native soil biology in brassicaceae seed meal induced weed suppression. Soil Biol. Biochem. 40:1689–1697

Marrone, P. 2005. Muscodor™: A new biofumigant as an alternative to methyl bromide. Presentation for 2005 Annual International Research Conference on Methyl Bromide Alternatives and Emission Reductions.

Marrone, P. 2005. A New BioFumigant as an alternative to synthetic chemical fumigants. Internal AgraQuest presentation.

Marrone, P. 2006. An overview of microbial nematicides. Internal Marrone Organic Innovations presentation.

Mazzola, M. and J. Brown. 2010. Efficacy of brassicaceous seed meal formulations for the control of apple replant disease in conventional and organic production systems. Plant Disease 94:835–842.

Brassicaceous seed meals, such as mustard meal, have potential for nematode and pathogen control, but not weeds. However, results are inconsistent from trial to trial. These treatments are not stand-alone but could be part of an integrated system.

Mazzola, M., Brown, J., Izzo, A, and Cohen, M. F. 2007. Mechanism of action and efficacy of seed meal-induced suppression of pathogens inciting apple replant disease differ in a Brassicaceae species and time-dependent manner. Phytopathology 97:454–460.

Riga, E., L. A. Lacey, and N. Guerra. 2008. Muscodor albus, a potential biocontrol agent against plant-parasitic nematodes of economically important vegetable crops in Washington State, USA. Biological Control 45: 380–385.

Muscodor is a new genus of endophytic fungi discovered by Dr. Gary Strobel (Montana State University). AgraQuest worked on commercializing a strain of *Muscodor albus* but abandoned it in 2011. Marrone Bio Innovations (MBI) acquired a license from Strobel and has begun to develop a new strain effective on a broad range of plant pathogens, nematodes, and insects. MBI intends to submit this product to U.S. EPA in 2013. Expected market entry is 2015 in California. Work done under Pam Marrone at AgraQuest showed *M. albus* to be as effective at preserving and increasing yields as chemical fumigants. Producing the fungus was cost-competitive to chemical programs. The fungus could be used as a soil granule in an integrated program.

APPENDIX

PLANT BREEDING: RESEARCH REPORT

Description: Selective breeding of strawberry cultivars for disease resistance

What we've learned

- Breeding is highly effective for increasing yield and marketable traits
- Modest efforts for breeding disease resistance have yielded modest success in California
- Breeding programs outside California put more emphasis on disease resistance
- Strawberry genome has been recently mapped
- New molecular techniques are available now and more are being developed by USDA programs
- Genetic sources of resistance are being actively pursued
- Breeding for increased disease resistance is possible but will take many years

What we still need to know about plant breeding

DISCOVERY

- Which pathogens affect yield (organic fields, unfumigated soil)?
- Basic soil ecology
- Mechanisms of disease resistance
- Root stocks (crown-crown grafting)

EVALUATION & RESEARCH

- Mass screening of wild and improved genotypes for multiple pathogens
- Pathogen screening in different regions, environmental conditions
- Refine pathogen screening techniques
- Marker-assisted breeding techniques

DEMONSTRATION & ADOPTION

- Cultivar performance in organic and unfumigated fields

Research

Gordon, T.R., S.C. Kirkpatrick, J. Hansen, and D.V. Shaw. 2006. Response of strawberry genotypes to inoculation with isolates of *Verticillium dahliae* differing in host origin. Plant Pathology 55: 766–769.

Strawberry genotypes represented the largest source of variation in these experiments, with variance components approximately 10-fold greater than those associated with either isolate or the isolate × genotype interaction. The results suggest it should be possible to develop resistance to Verticillium wilt in strawberry that is broadly effective against isolates of diverse host origin.

Hancock, J.F., P.W. Callow, A. Dale, J.J. Luby, C.E. Finn, S.C. Hokanson, and K.E. Hummer. 2001. From the Andes to the Rockies: Native strawberry collection and utilization. HortScience 36:221–225.

The commercial strawberry has a narrow germplasm base, even though its progenitor species have an extensive geographical range. The majority of the genes in modern North American cultivars still comes from only seven nuclear and 10 cytoplasmic sources, even though at least eight native clones have been incorporated into cultivars in the last half century. Since the germplasm base of strawberries remains narrow, native germplasm can be injected into the lineage of cultivars relatively easily. Identification of more wild clones and their use in strawberry improvement would be beneficial. Researchers have spent the last decade cataloging horticulturally useful traits in native populations and using that variability.

Iezzoni, A., C. Weebadde, J. Luby, C.Y. Yue, C.P. Peace, N. Bassil, and J. McFerson. 2010. RosBREED: Enabling marker-assisted breeding in Rosaceae. Acta Horticulturae 859: 389–394.

Genomics research has not yet been translated into routine practical application in breeding Rosaceae fruit crops. A wealth of genomics resources has accumulated, including EST libraries, genetic and physical maps, quantitative trait loci (QTL), and whole genome sequences. The potential of genomics approaches to enhance crop improvement, particularly through marker-assisted breeding, is enormous, but unfulfilled. The U.S. Rosaceae genomics, genetics, and breeding community, with strong international involvement, has united behind the goal of translational genomics and collaborated on the development of large-scale USDA grant proposals. RosBREED. See also: USDA's RosBREED Project, www.rosbreed.org.

J. Luby, James & Hancock, James & Dale, Adam & Serce, Sedat. 2008. Reconstructing Fragaria X ananassa utilizing wild F. virginiana and F. chiloensis: inheritance of winter injury, photoperiod sensitivity, fruit size, female fertility and disease resistance in hybrid progenies. Euphytica 163:57–65.

Results indicate that substantial breeding progress can be made by reconstructing *F.* X *ananassa* if care is taken to select elite, complementary genotypes of *F. virginiana* and *F. chiloensis*.

Sargent, D. J., T. Passey, N. Surbanovski, E. Lopez Girona, P. Kuchta, J. Davik, R. Harrison, A. Passey, A.B. Whitehouse, and D.W. Simpson. 2012. A microsatellite linkage map for the cultivated strawberry (*Fragaria* X *ananassa*) suggests extensive regions of homozygosity in the genome that may have resulted from breeding and selection. Theoretical and Applied Genetics 124:1229–1240.

The complex nature of the cultivated strawberry genome has made genetic analysis of quantitative traits and development of markers for MABS a challenging process. An understanding of the genome structure of the cultivated strawberry at the molecular level is an essential prerequisite to the identification of molecular markers linked to agronomic traits within the species, and the development of well-characterized linkage maps is crucial to this process. Linkage mapping investigations in the cultivated strawberry have identified major genes and quantitative trait loci (QTL) for a number of agronomic traits, including disease resistance.

Shaw, D.V., T.R. Gordon, K.D. Larson, D. Gubler, J. Hansen, and S.C. Kirkpatrick. 2010. Strawberry breeding improves genetic resistance to Verticillium wilt. California Agriculture 64:37–41.

Testing is needed in naturally infested soils to determine whether resistance outside the range presently observed will be required for adequate performance of cultivars. Opportunities for such tests have been limited by the common practice of preplant soil fumigation; opportunities for widespread testing in naturally infested soil simply do not exist at present. A better understanding of the mechanisms of resistance may facilitate the development of screening procedures.

SOILLESS SUBSTRATE: RESEARCH REPORT

Description: The use of soilless substrate in strawberry production systems as an alternative to pre-plant soil fumigation for management of soilborne diseases

What we've learned

- We can produce strawberry fruit in soilless substrates
- A wide range of media can be used to produce strawberry fruit
- Peat and coconut coir are the primary substrates used
- Marketable yields can meet or exceed those of conventional production systems
- There are economic limitations on using soilless substrates for producing strawberry fruit
- The relative high cost of substrates is a primary limitation
- There are significant infrastructure costs associated with producing in substrates
  - One acre of strawberries requires 140 cubic yards of substrate
  - Mechanical installation methods are needed
- Some substrates are not sustainable
- Production in substrates requires an increased level of management
- Require more careful management of watering
- Require more careful management of nutrients
- Not possible without complex automated systems

What we still need to know about soilless substrate

DISCOVERY

- Reducing the high cost of substrate production
- Environmental impacts of substrate production system

EVALUATION & RESEARCH

- Disinfestation of reused/recycled substrates
- Nutrient and water management in substrate systems
- Impact of planting date, fertility program and cultivar in substrate systems

DEMONSTRATION & ADOPTION

- Grower demonstration of substrate production
- Large scale installation of substrate production systems
- Use of continuous feed fertilization programs and pulse irrigation

Research

Wang, D., J. Gartung, J. Gerik, A. Cabrera, M. Gabriel, M. Gonzales, T. Sjulin, and D Rowe. Evaluation of a raised-bed trough (RaBeT) system for strawberry production in California. Pp 125–131 in California Strawberry Commission Annual Production Research Report: 2010–2011.
(www.calstrawberry.com/fileData/docs/Wang_2010_11_RaBeT.pdf)

Field trials of a raised-bed trough (RaBeT) production system at three locations evaluated 6 different substrate-based treatments (peat, coir, and amended soil) and compared them to the standard grower production in preplant fumigated soil. Different irrigation regimes were also evaluated (100, 150, and 200% ET). Some of the substrate treatments performed equivalent to the grower standard treatment at two of the locations, but none performed as well as the grower standard at one of the sites. The use of landscaping fabric to separate the underlying soil from the substrate production system was effective at limiting nematode and pathogen incidence in the substrate grown plants.

P. Lieten. 2005. Substrates as an alternative to methyl bromide for strawberry fruit production in northern Europe in both protected and field production. Pgs 41–46 in Proceedings of International Conference on Alternatives to Methyl Bromide. Lisbon, 2004.

ec.europa.eu/clima/events/0014/proceedings_en.pdf

Overview of the development of strawberry substrate culture systems in Europe. In 2004, the author estimated that there were 1,270 ha of strawberries produced in Europe (2.7% of total European production) with most of the production located in central and southern Europe. Peat moss was the primary substrate being used with some use of coconut coir, rockwool, pine bark, perlite, and compost. The development of soilless systems in Europe began with the use of peat bags in the 1970s, and shifted to containers, buckets and pots during the 1980s through today. There are increased costs associated with using substrate production systems but potentially increased revenue from them.

Thomas, H., D. Legard, S. Fennimore, R. Serohijos, T. Sjulin, D. Rowe, S. Reddy, and C. Low. 2011. Production of strawberry in substrates. In Proc. 2011 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions, San Diego, Calif., 43:1–4.

www.mbao.org/2011/Proceedings/43ThomasH.pdf

Results from two field trials of a raised bed trough substrate production systems found that substrate production systems can produce equivalent yields to a fumigated grower standard. All the substrates tested produced higher yields than a nonfumigated grower standard and the coir and peat–perlite treatments were more productive than an amended soil treatment. The production curves for the substrate treatments were similar to the fumigated grower standard throughout the production season.

STEAM: RESEARCH REPORT

Description: Disinfests the soil through the application of steam.

What we've learned

- Physically mixing steam and soil results in rapid heating of soil (e.g., 90 seconds), whereas steam application to static soil takes hours to heat.
- Strawberry yields in steamed soils are generally equal to strawberry yields from fumigated soils.
- Weed and pathogen management is good with steam and equal to fumigants.
- Steam only kills pathogens in the soil zone where steam is applied.
- Traditional steam application methods such as sheet steaming or injection through hoses or pipes are labor intensive and expensive. Automatic steam applicators such as the Ferrari Sterilter are used commercially in Italy and are labor efficient.
- Using the concept of an automatic steam applicator we designed a prototype, which slowly applies steam to raised beds in strawberry. We are confident that we can build a machine that covers area more rapidly.
- Water hardness is a problem for traditional boiler steam generators. Traditional steam generators can calcify or scale up if hard water is not treated.
- Downhole steam generators are a new technology used in the petroleum industry to generate steam in oil wells for heavy oil extraction. These generators are potentially a game changer with regard to in-field steaming.
- Downhole steam generators can use hard or soft water and still make large quantities of steam with a compact machine.
- Downhole steam generators are an alternative to traditional boiler steam generators.
- Because of their compact design, a multi-bed applicator could be designed to treat land more rapidly than existing prototype steam applicators.
- Steam applicators will likely be used by custom operators rather than growers as they will likely be expensive pieces of equipment that are only viable in the hands of professional operators much like today's fumigation operators.
- Large growers could also own and operate their own steam applicators.
- Strawberries grown on steam-treated soil can be grown with the same cultural practices that are used now for strawberries grown on fumigated soils.

APPENDIX

What we still need to know about steam

DISCOVERY	▪ Design a steam applicator that adopts downhole steam generators used in the petroleum industry to apply steam in the field. Downhole steam generators are capable of using hard or soft water.	▪ Design and build a steam applicator that treats several acres per day ▪ Given current technology (includes downhole steam generators), what is the limit for the speed and area that can be covered per day? ▪ What can be done to maximize economy of steam?
EVALUATION & RESEARCH	▪ What is the soil depth in the raised bed that must be treated to protect strawberry roots? ▪ Does steaming enhance the possibility of ammonium toxicity? ▪ Maximize the fuel use efficiency of the steam applicator by heating soil only to the minimum temperature necessary to kill soil pests. ▪ Evaluate aerated steam to minimize harm to beneficial organisms especially nitrifiers, but still kill soil pathogens.	▪ Test steam applicators in combination with exothermic compounds such as CaO that can enhance fuel use efficiency. ▪ Mustard seed meal appears to enhance or complement steam efficacy. Is this because of the biofumigants in mustard meal or because of the fertility contribution of mustard seed meal? ▪ What are the economics of steam treatments?
DEMONSTRATION & ADOPTION	▪ Develop use recommendations based on soil type and soil moisture. ▪ Train applicators to use steam equipment.	▪ Communicate with potential custom operators to make them aware of the potential value of steam for soil disinfestation. ▪ Determine the commercial cost and value of steam for soil disinfestation.

Research

Samtani, J.B., C. Gilbert, J.B. Weber, K.V. Subbarao, R.E. Goodhue, and S.A. Fennimore. 2012. Effect of steam and solarization treatments on pest control, strawberry yield and economic returns relative to methyl bromide. HortScience 47:64–70.

Steam and solarization treatments were evaluated as an alternative to fumigation in California strawberry. Strawberry yields in soil disinfested with steam were as good as strawberry yields from soils that had been fumigated. Weed control with steam was as good as fumigation. Steam killed *Verticillium* where it came in contact with the pathogen. Steam was delivered by stationary hoses in this work which required a lot of labor, hence the costs were high. Based on these high costs we pursued development of a self-propelled automatic steam applicator which has lower labor costs.

Baker, K.F. and C.N. Roistacher. 1957. *In*:Baker, K.F. The U.C. system for producing healthy container-grown plants. Calif. Agric. Exper. Sta. Ext. Serv. Manual 23.

This classic manual for soil steaming was published in 1957, but is still in use by greenhouse managers. The manual lists the correct procedures to treat soils with steam for the purpose of killing soil pests. The physics of soil steaming is described in great detail. The manual focuses on nursery soils and is of limited use for field steaming. The manual also describes the basics of how steam kills soil pests, and lists the critical temperatures needed to kill bacteria, nematodes, pathogens and weed seed.

Gay, P., P. Piccarolo, D. Ricauda Aimono, and C. Tortia. 2010. A high efficiency steam soil disinfestation system, part I: Physical background and steam supply optimization. Biosystems Engineering 107:74–85.

Traditionally steam has been applied by sheet steaming, which is slow and uses excessive fuel. With sheet steaming steam is injected into the space between a steaming tarp and the soil surface. Sheet steaming takes a long time because all steam that transfers deep into the soil, e.g., 24 inches deep, must cross the surface soil layer. Because of this the surface soil is excessively steamed in order to transfer enough steam to heat the soil to a depth of 24 inches. Gay et al. working in Italy found that injection of steam into soil is faster and more efficient than sheet steaming. They also found that the ideal moisture content for steaming of a sandy loam soil was 80% of field capacity, but for sand the ideal moisture was in the 60% range.

Barbeiri, P., A.C. Moonen, A. Peruzzi, M. Fontanelli, and M. Raffaelli. 2009. Weed suppression by soil steaming in combination with activating compounds. Weed Research 49:55–66.

Activating compounds can boost soil temperatures through a hydration reaction. The idea is to complement steam with a chemical agent such as CaO (quicklime) or KOH (potassium hydroxide) that prolongs the temperature at levels needed to kill soil pests, yet reduce the amount of steam needed to control soil pests. In this research steam was combined with CaO or KOH at 1,000 and 4,000 kg/ha. Steam plus either CaO or KOH resulted in warm soil temperatures for longer times, e.g., 3 hours, than steam alone. Increasing the rate of either CaO or KOH from 0 to 4,000 kg/ha plus steam resulted in improved weed control compared to steam alone. This suggests that CaO and KOH are complementary to steam and the combination results in improved weed control due to longer exposure to heat in the soil.

APPENDIX

SOLAR: RESEARCH REPORT

Description: Soil solarization is a pest management practice that uses plastic sheets to trap solar energy and kill soilborne organisms with heat.

What we've learned

- Solarization heat in the coastal strawberry production zone of California generally does not penetrate deep enough to kill soil pests, e.g., *Verticillium*, throughout the root zone as do fumigants.
- Solarization controls weed seeds (and probably pathogens) in the shallow soil surface layers even in coastal areas such as Salinas and Ventura.
- Biofumigants such as mustard meal are complementary to soil solarization and improve control of soil pests
- Solarization and conventional fumigants such as metam sodium are complementary and improve management of soil pests when used sequentially.

What we still need to know about solar

DISCOVERY

- Methods to deliver solar heat to deeper layers in the soil, i.e., enhanced solarization
- Can solarization be used to enhance anaerobic soil disinfestation (ASD)?
- Are there ways to combine biofumigants with solarization or enhanced solarization to manage soil pests?
- Test the feasibility of using double-layer plastic.
- Evaluate solarization film in combination with mustard seed meal.

EVALUATION & RESEARCH

- Develop a modular solar water heater that injects hot water into solarizing strawberry beds for the minimum amount of time required to kill soil pathogens.
- Determine if enhanced solarization and biofumigation are complementary in managing soil pests.
- Determine if enhanced solarization can be used to improve the consistency of ASD, e.g., weed control?
- Evaluate solarization combined with metam sodium or chloropicrin to determine if the treatments are complementary for control of soil pests.
- Evaluate the economics of solarization treatments

DEMONSTRATION & ADOPTION

- Demonstrate and train personnel to perform enhanced solarization.
- Demonstrate and train personnel to perform enhanced solarization/ASD.
- Demonstrate and train personnel to combine solarization with fumigants.

Research

Elmore, C.L., J.J. Stapleton, C.E. Bell, and J.E. DeVay. 1997. Soil solarization: a non-pesticidal method for controlling diseases, nematodes, and weeds. Oakland: Univ. of California Div. of Natural Resources. IPM Publication 21377.

This is the classic extension publication from the University of California, which describes how to do solarization under California conditions and for local crops. Topics are installation of the plastic mulch, ideal mulch colors (generally clear works best), soil moisture requirements, pests controlled, economics and limitations of solarization.

Saleh, H., W.I. Abu-Gharbieh, and L. Al-Banna. 1989. Augmentation of soil solarization effects by application of solar-heated water. Nematologia Mediterranea 17:127–129.

This paper describes the use of hot water to force solarization heat deeper into the soil to improve control of nematodes, i.e., enhanced solarization. These researchers installed drip tape under black plastic through which they injected hot water generated using a conventional solar hot water heater. In this study, conducted in the Jordan Valley during a very warm time of the year, soil temperatures in the combined hot water solarization treatment reached 56 to 60˚C at depths of 10 and 20 cm soil depth compared to 46˚C for conventional solarization. The researchers found that the solarization + hot water treatment resulted in better control of *Meloidogyne javanica* nematodes and *Fusarium oxysporum* than solarization alone.

Ploeg, A. and J.J. Stapleton. 2001. Glasshouse studies on the effects of time, temperature and amendment of soil with broccoli plant residues on the infestation of melon plants by *Meloidogyne incognita* and M. *javanica*. Nematology. 3:855–861.

This paper describes work on the complementarity of solarization and biofumigation with broccoli residues. The researchers found that heating soil 35–40˚C for 10 days in the presence of broccoli residues killed *Meloidogyne incognita* nematodes in the soil more completely than without broccoli residues.

Eshel, D., A. Gamliel, A. Grinstein, P. DiPrimo, and J. Katan. 2000. Combined soil treatments and sequence of application in improving control of soilborne pathogens. Phytopathology 90:751–757.

These Israeli researchers looked at combinations of low rates of methyl bromide (10 grams/m^2 = 89 lbs/A) or low rates of metam-sodium (10 ml/m^2= 10.7 GPA) in combination with short solarization (8 days) to control soil pathogens such as *Sclerotium rolfsii* and *Fusarium oxysporum*. They compared the sequence of solarization followed by fumigant to fumigant followed by short solarization. Generally short solarization followed by fumigant effectively killed soil pathogens.

Hartz, T.K., J.E. DeVay, and C.L. Elmore. 1993. Solarization is an effective soil disinfestation technique for strawberry production. HortScience 28:104–106.

This study was conducted in California strawberry at the UC South Coast Field Station near Irvine. Solarization was used in combination with metam-sodium at 77 liters/ha, resulting in control of *Phytophthora cactorum, Verticillium dahliae*, and weeds equivalent to methyl bromide: Pic (MBPic) 67:33 at 250 kg/ha. Strawberry fruit yields with solarization + metam sodium were similar to MBPic.

Members of the Strawberry Nonfumigant Working Group, August 2012

LEFT TO RIGHT: Joseph McIntyre, Dan Legard, Karen Klonsky, John Steggall, Carol Shennan, Bill Chism, Anne Katten, Brian Leahy, Pam Marrone, Steve Fennimore, Randy Segawa, Marshall Lee, Gary Obenauf, Matt Fossen, Nan Gorder, and Tim Griffin | Photo by Debra Lynn

(Missing: Rod Koda and Greg Browne. Bill Chism attended the first meeting, but wasn't able to participate for the duration)