Fumigant Use in California and an Assessment of Available Alternatives

Phase I Report on 1,3-D and Chloropicrin

PEER-REVIEWED REPORT

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Phase I Report on 1,3-D and Chloropicrin

Authors

Christopher W. Simmons, PhD
University of California, Davis

Janet C. Broome, PhD
University of California, Santa Cruz
Plant Health Consulting

Steering Committee Members

Gerald J. Holmes, PhD, Chair
Strawberry Center, California Polytechnic State University-San Luis Obispo

Alan S. Kolok, PhD, Co-Chair
University of Idaho

Christine L. Carroll, PhD
California State University, Chico

Julie Guthman, PhD
University of California, Santa Cruz

CCST Project Team & Leadership

Rhianna Hohbein, PhD
Project Manager

Ceasar Gutierrez
Project Assistant

Julianne McCall, PhD
CEO

Jason John, PhD
Deputy Director

Eric Chu, PhD
Director of Science Services

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About CCST

The California Council on Science and Technology is a nonpartisan, nonprofit organization established via the California State Legislature in 1988. CCST responds to the Governor, the Legislature, and other State entities who request independent assessment of public policy issues affecting the State of California relating to science and technology. CCST engages leading experts in science and technology to advise state policymakers—ensuring that California policy is strengthened and informed by scientific knowledge, research, and innovation.

Note

Layout by Mikel Shybut, PhD, CCST. Technical editing by Becky Oskin.

For questions or comments on this publication contact:

California Council on Science and Technology
1100 11th Street, Sacramento, CA 95814
ccst.us | ccst@ccst.us | 916-492-0996

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Study Process

CCST organized and directed the study leading to this report. Members of the CCST Steering Committee were appointed based on technical expertise and a balance of viewpoints. ***Appendix C*** provides information about CCST's Steering Committee membership. All experts who contributed to the study were evaluated for potential conflicts of interest. All study team members serve as individual experts, not as representatives of organizations or interest groups. Under the guidance of the Steering Committee, a team of experts (authors) assembled by CCST developed the findings based on original technical data analyses and a review of the relevant literature. ***Appendix D*** provides information about the authors. The Steering Committee met regularly to interact with the lead authors as the authors studied each of the issues identified in the scope of work. With regular interaction, the authors and the Steering Committee were able to collaborate to develop a series of findings, conclusions, and recommendations defined as follows:

Finding. Fact(s) the study team finds that can be documented or referenced and that have importance to the study.

Conclusion. A reasoned statement the study team makes based on findings.

Recommendation. A statement that suggests an action or consideration as a result of the report findings and conclusions.

The committee process ensures conclusions are based on findings (facts), and recommendations are based on findings and conclusions. Both the authors and the Steering Committee members proposed draft conclusions and recommendations. These were modified based on peer review and discussion within the Steering Committee, along with continued consultation with the authors. Final responsibility for the conclusions and recommendations in this study lies with the Steering Committee. All Steering Committee members have agreed with these conclusions and recommendations.

The conclusions and recommendations expressed in this publication are those of the Steering Committee and authors and do not necessarily reflect the views of the organizations or agencies that provided support for this project. They are provided as recommended considerations for the Department of Pesticide Regulation and others to evaluate in the larger context of their policy development process.

See ***Appendix G*** for a more thorough description of CCST's Study Process.

Executive Summary

The purpose of this study was to assess 1) the present state of fumigant use in California; 2) currently available alternatives for these fumigants and the extent of their use; 3) past and on-going research dedicated to fumigant alternatives; 4) viability of adopting these alternatives to effectively manage pests in California; 5) barriers to and incentives for wide-scale adoption of alternatives; and 6) areas where research may still be needed to answer some of these questions. This Phase 1 report addresses 1,3-dichloropropene (1,3-D) and chloropicrin which are used to treat agricultural soils for soilborne pests and pathogens prior to crop planting. The Phase 2 report will address four other pre-plant soil fumigants (dazomet, metam-sodium, metam-potassium, and methyl bromide); four post-harvest commodity fumigants (sulfuryl fluoride, phosphine, propylene oxide, and methyl bromide); and one structural fumigant (sulfuryl fluoride).

Fumigants are volatile chemical compounds used to control pests. Fumigants can be used as an insecticide, fungicide, disinfectant, nematicide, herbicide, or rodenticide. Fumigants are used in a variety of settings. They can be applied in homes, healthcare facilities, food facilities, and in agricultural settings to control vector-borne or animal-borne diseases and for crop growth and management.

While the specific chemicals used as fumigants have changed over the course of history, 1,3-D and chloropicrin have been relied on as effective soil fumigants for decades. 1,3-D is a byproduct in the production of epoxy by the Shell Oil Company. Its ability to control nematodes was discovered in 1943 and developed by the Pineapple Research Institute in Hawaii to control nematodes devastating the pineapple crop. Chloropicrin was discovered in 1848 and first patented for use as an insecticide in 1908. It was used as a warfare agent (tear gas) during World War I. In 1926, chloropicrin was first used as a fumigant in flour mills and since then it has been used as a soil and structural fumigant, either as an active ingredient or as a warning agent (tear gas) for other odorless fumigants. These two fumigants are often used together to control soilborne fungal pathogens, nematode pests, and weeds that are very destructive to crops. Acute and chronic exposure to fumigants has raised concerns for the welfare of those working in agriculture (including those applying the fumigants), and those living or working in communities in close proximity to fumigant use.

Summary of Key Findings

Over the last two decades, the phaseout of the ozone-depleting fumigant methyl bromide has driven ample research towards the exploration of other pre-plant soil fumigants, as well as alternatives to fumigation. For instance, more than $100 million has been spent within a single grant program to identify alternatives to methyl bromide, some of which was directed towards encouraging and optimizing the use of 1,3-D and chloropicrin. California growers rely on 1,3-D and chloropicrin for pre-plant fumigation. This production system enables high yields in a competitive, globally integrated food system. However, the human and environmental health impacts continue to be of concern, and there is a growing interest in the advancement of alternative methods of pathogen and pest control.

Fumigants and their alternatives are studied worldwide, with a significant portion of that work conducted in the U.S. and California. California's Pesticide Use Reporting system provides a robust dataset on fumigant use within the state. Similar data sources on pre-plant soil fumigant use anywhere else in the U.S. or the world were not found.

We identified a range of fumigant alternatives. All of these alternatives were previously evaluated in California, and this review of the literature did not reveal any new fumigant alternatives that were not previously investigated or considered for use in California. None of these individual fumigant alternatives would qualify as drop-in replacements for fumigation, as each offers unique benefits and is constrained by unique limitations.

The main barriers to adopting fumigant alternatives include the continued availability of effective fumigants, challenges related to the implementation, performance and economic feasibility of the alternatives, and an incomplete understanding of their environmental and unintended human health effects.

For example, soil treatment with steam provides equal effectiveness to fumigation but is currently not optimized for open field use at scale in California. The use of resistant varieties is a long-standing practice that continues to deliver genetic resistance for specific pathogens, with new sources of disease resistance coming online as breeding technology improves. Nevertheless, the development of resistant varieties that would satisfactorily manage a diversity of soilborne pathogens without fumigation remains unlikely, and weeds are not controlled by them. Most other alternatives, such as anaerobic soil disinfestation (ASD), are partially effective, have potential unintended environmental and human health impacts (although they are almost certainly significantly less harmful than the fumigants in question), and have found limited adoption. Given that each fumigant alternative may have only partial effectiveness, combining several fumigant alternatives (either simultaneously or in sequence) is likely to achieve the greatest effectiveness, versatility, and length of control. Indeed, research has increasingly validated combination approaches to fumigant alternatives, and additional targeted research could help identify combination methods for California's major fumigant-reliant crops.

The desirability of fumigation relative to the alternatives we discuss could potentially be resolved with a cost-benefit analysis. The challenge is that a direct cost-benefit analysis assumes that the health and environmental benefits of minimizing or eliminating fumigation can be quantified in the same way that the economic benefits of continuing fumigation can. In practice, these costs and benefits cannot be compared in a meaningful way.

Adverse human health impacts

Studies show that 1,3-D and chloropicrin are harmful to humans. While the health risks from short-term, high-level exposure (like brief contact with high concentrations) are well understood, the dangers of long-term, low-level exposure over months or years are less clear. People living near fields where these chemicals are used, such as in rural areas, face greater risks than those in urban areas far from such fields. The risks of exposure to these fumigants are greater for vulnerable groups like children, the elderly, and pregnant women. Additionally, cases of pesticide-related illness may often go unreported, particularly among farmworkers, due to language barriers, fear of immigration issues, and concerns about losing work or income.

Nursery plant propagation

The recommendations in this report apply to crop production and are not necessarily appropriate for nursery plant propagation. Given that planting stock is relocated within the state and across national and international borders, it is imperative that it be pest-free. Consequently, the tradeoffs between risks of exposure due to fumigation and the need for pest-free planting stock are different from crop production and should be considered.

Need for longitudinal studies

Studies seeking to assess the effects of fumigant alternatives may benefit from longer timescales (i.e., five years or more). This is not only true for the effects of alternatives relative to soilborne pathogens, but also for their impacts on human health and the environment.

Unintended consequences

While we made every attempt to describe foreseeable consequences resulting from changes to cropping systems, the potential for negative unintended economic, human health, and environmental consequences requires exercising caution when considering changes to a system as multifaceted and dynamic as crop production. Likewise, others may benefit from changes. It is challenging to balance the need of growers to manage crop pests successfully and to address the public health and environmental concerns of continued fumigation.

Assessment 1: The present state of 1,3-D and chloropicrin use in California.

Fumigant use statistics in California are robust, making it possible to know the crops, locations, timing, and use patterns for each fumigant. In California, strawberries and almonds are the crops where most of the pre-plant soil fumigation with these two chemicals occurs, with strawberries using 47.4% and almonds 10.3% of the total pounds of 1,3-D and chloropicrin applied in 2022. Indeed, fumigation was developed for use in California on strawberries in the late 1950s to control *Verticillium dahliae*, a soilborne pathogen that was destroying the crop at that time and continues to be a major reason (along with other pathogens) that fumigation is used in strawberries. The remaining fumigation occurs (in order of greatest to least pounds used) in sweet potatoes 4.9%, wine grapes 4.4%, carrots 3.8%, other grapes (table and raisin) 2.5%, walnuts 2.1%, raspberries 1.5%, cherries 1.1% and tangerines 1.0%. The location and timing of fumigant use is also closely aligned with the cropping patterns of these commodities. Thus, the top nine counties for fumigant use (ordered from high to low) are Monterey, Ventura, Fresno, Kern, Santa Barbara, Merced, Santa Cruz, Stanislaus, and Tulare Counties. September and October are the months of highest fumigant usage, together accounting for 37% of fumigant use in 2022. Most pre-plant soil fumigation is applied via deep, broadcast injections (30%), drip irrigation (30%), or shallow, broadcast injections that are tarped (23%). Totally impermeable films (TIF) have been used successfully to dramatically reduce the escape of fumigants but are an imperfect solution to the problem of escaping emissions because they can be breached due to faulty installation, wind, and animal tracks.

Assessment 2: Currently available alternatives for these fumigants and the extent of their use.

Alternatives to fumigating with 1,3-D and chloropicrin include other fumigants, non-fumigant chemical pesticides, anaerobic soil disinfestation (ASD) and biosolarization, solarization, biologically derived pesticides and biocontrol agents, cover cropping, crop rotations, resistant varieties and rootstocks, steam treatment, soilless cultivation, and sanitation. Each alternative practice varies by the crop-pest combinations, scale of use, effectiveness and duration, yield effects, associated costs, additional requirements for use, availability, ease, and reliability. All these alternatives are practiced to some degree in specific crops and locations. Across multiple crops, the non-chemical alternatives that are currently adopted to the greatest extent are resistant varieties and rootstocks, ASD and biosolarization, steam treatment, and soilless cultivation.

Assessment 3: Past and on-going research dedicated to fumigant alternatives.

The chemical milieu of fumigants used in California has been fluid throughout recent history. Research on alternatives to fumigation began in earnest when the fumigant methyl bromide was added to the list of substances that deplete the ozone layer in 1990. This effort ramped up again during methyl bromide's phaseout between 1999 and 2016. Across the range of fumigant alternatives, some have been studied for nearly a century, while others are relatively new. No drop-in replacements have emerged, and research has increasingly focused on examining combinations of fumigant alternatives. Achieving consistent results with combination approaches for most crop and pest pairings in California remains a challenge. Thus, despite 20 years of effort, California growers of some high value, intensively managed crops continue to rely on pre-plant soil fumigation with 1,3-D and chloropicrin, and other fumigants, and still use methyl bromide in some plant propagation systems. These systems produce high yields in a competitive, globally integrated food market. However, the human and environmental health impacts continue to be of concern, and there is a growing interest in the advancement of alternative methods of pathogen and pest control.

Assessment 4: Viability of adopting these alternatives to effectively manage pests in California.

Many fumigation alternatives have been adopted to various degrees based on their ease of use, effectiveness, and cost to growers. The fumigant alternatives with the highest demonstrated effectiveness across a range of crops include resistant varieties and rootstocks, ASD and biosolarization, steam treatment, and soilless cultivation. Disease-resistant varieties have been a mainstay of disease management long before fumigation was developed. Recent advances in breeding and genetics have improved this method of disease control and we expect continued improvements in the future. Anaerobic soil disinfestation is partially effective (it is location- and disease-dependent) and has found limited adoption in strawberries and almonds. Steam treatment is highly effective but currently lacks the speed, availability, and ease of use necessary for widescale adoption. In addition to its effectiveness, the adoption of each alternative is dependent on a variety of societal, environmental, and economic impacts. This includes the potential for reduced food production and subsequent increased prices to end consumers, potentially greater consumption per unit of land of other natural resources (e.g., water), greenhouse gas emissions, water pollution, and local air pollution due to specific practices.

Assessment 5: Barriers to and incentives for wide-scale adoption of alternatives.

At the most fundamental level, variable or insufficient pest control effectiveness for fumigant alternatives is the most significant barrier to adoption, especially in comparison to the known performance and familiarity of fumigation with 1,3-D and chloropicrin. Practices such as resistant varieties and rootstocks, solarization, biosolarization, anaerobic soil disinfestation, cover cropping, soilless cultivation, and steam treatment have promising data that speak to their ability to control or avoid major soil pests and pathogens, but they are still undergoing active research or engineering to increase their impact. Some alternatives—like ASD, biosolarization, solarization, cover crops, and crop rotation—require research to continue defining optimal conditions with respect to various soil textures, pest profiles, cropping systems, and other variables. Other alternatives such as steam or soilless cultivation require engineering solutions to optimize efficiency, effectiveness, and reduce costs. The flip side of this, however, is the continued allowability of fumigants. The history of regulatory action has shown that growers are more likely to experiment with and adopt alternatives when specific agricultural chemicals are disallowed or there are signals that they may be less available in the future. While this would increase uncertainty in agricultural systems reliant on fumigation, history has illustrated that fumigant use in California is responsive to socioeconomic and political forces to reduce fumigant use and that these are likely to increase. Moreover, growers face significant structural obstacles in the adoption of fumigant alternatives related to land costs, labor costs, accessibility of fumigant alternatives, the role of shippers and handlers, and embedded economic relationships. Addressing these obstacles likely requires direct economic support for transitioning away from fumigants.

There are various policy tools that could be employed to ease the potential economic impacts of transitioning to more complex alternatives to pre-plant fumigation with 1,3-D and chloropicrin. These fall into five broad categories that could be used to increase adoption of alternatives: 1) regulatory restrictions on chemical fumigants; 2) economic incentives such as subsidies and cost-sharing; 3) insurance targeted to support the use of pest management practices; 4) taxes imposed based on certain characteristics and used to encourage particular fumigant alternatives; and finally, 5) state procurement policies that encourage adoption of fumigant alternatives in producing commodity crops.

Additionally, the market can be brought to bear through organic certification, product labeling, and more recently developed sustainable and regenerative certification programs.

Such certifications typically exclude or limit the use of all fumigants and encourage the use of various alternatives.

Assessment 6: Areas where research may still be needed.

More research is needed to evaluate the combined effects of multiple alternative practices (e.g., ASD plus resistant varieties plus crop rotation plus sanitation) and comparing them to fumigation. For instance, steam treatment shows comparable effectiveness relative to 1,3-D and chloropicrin. Considerable engineering innovations would be required to scale up this technology. Resistant varieties and rootstocks are not yet available for most diseases. Next-generation breeding techniques to incorporate resistance to pathogens could eliminate or greatly reduce the need for fumigation. Fumigant mode of action against target pathogens, as well as human health impacts, deserve increased investigation. A more thorough understanding of the human mode of action would enable risk assessors to more accurately determine the probability of adverse health outcomes from different fumigant application rates and strategies. In addition, further study, including epidemiology and rodent model experiments, is needed to better understand the risks associated with exposure resulting from fumigant use. This is particularly true with respect to chronic, low concentration exposures and exposures that disproportionately affect vulnerable populations such as children, the elderly, and pregnant women.

Conclusions and Recommendations

The study team identified numerous **Findings** throughout the report. Below are consensus-based **Conclusions** (reasoned statements based on the Findings) and **Recommendations** (suggested considerations or courses of action as a result of Conclusions). Not all Findings have Conclusions, nor do all Conclusions have affiliated Recommendations.

Chapter 1: Pre-plant Soil Fumigants 1,3-D and Chloropicrin

2. **CONCLUSION:** For the time being, nursery applications should be given stronger consideration for continued use of 1,3-D and chloropicrin fumigants until there is more research and development of nursery-specific alternatives.. 36

5. **CONCLUSION:** TIFs significantly reduce fumigation emissions and associated acute risks to human health.. 42

8. **CONCLUSION:** Fumigant use is dynamic and is influenced by regulations, crops, geography, pathogens, and seasons, and growers need tools to manage these dynamics. 54

11. **CONCLUSION:** We need to better understand the causal relationships between 1,3-D exposure and acute and chronic health effects. 61

16. **CONCLUSION:** More research is needed on the synergistic and cumulative effects of different fumigants on human health. 65

17. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider studying the additive or synergistic effects of fumigant mixtures and other agrochemicals on human health. 65

20. **CONCLUSION:** More studies are needed using "exposure science" triangulating results from 1) toxicology using rodent models; 2) epidemiological studies of toxicants in the environment and their effects on human health; 3) environmental science; and 4) risk assessments; along with 5) social science studies using testimonials or other means of documenting the experience of exposure and illness to further understand the chronic and acute health effects of exposure.. 66

21. **RECOMMENDATION:** DPR should consider supporting the use of exposure science to better understand and mitigate potential exposures in vulnerable populations. 67

22. **RECOMMENDATION:** DPR should consider incorporating environmental justice work through various means (e.g., personnel, program focus) linked to their Environmental Monitoring branch so as to facilitate exposure science. 67

25. **CONCLUSION:** Greater knowledge about how 1,3-D impacts the functional roles of the soil microbiome and nematode communities would be informative for potential improvements in pathogen and nematode control efficacy and the development of methods to mitigate any possible negative effects such as impacts on soil nitrogen cycles. 69

28. **CONCLUSION:** More research on the possible indirect impacts of fumigation on greenhouse gas emissions is needed. Such research would be most valuable for California regulators if performed in California and using fumigation methods that are standard for chloropicrin in this state.. 70

32. **CONCLUSION:** TIF use during the pre-plant fumigation for other crops (e.g., almonds, grapes, carrots, and sweet potatoes) would decrease the emissions associated with 1,3-D and chloropicrin fumigation. However, increasing the use of TIF in crop settings that do not currently use tarps will increase plastic use and waste. 76

35. **CONCLUSION:** It is important to continue to watch for signs of resistance to fumigants developing in pathogen, nematode, weed, and arthropod pest populations. This would manifest as a loss of disease or weed control following use of the fumigants where previously control was achieved.. 78

Chapter 2: Fumigant Alternatives

This report explores 11 alternatives to fumigating with 1,3-D and chloropicrin.

1. Alternative fumigants
2. Non-fumigant pesticides
3. Anaerobic soil disinfestation and biosolarization
4. Solarization
5. Biologically derived pesticides and biocontrol agents
6. Cover cropping
7. Crop rotations
8. Resistant varieties and rootstock
9. Steam treatment
10. Soilless cultivation
11. Sanitation

45. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to define best practices for ASD and biosolarization. These practices should aim to maximize broad spectrum pest control effectiveness for California crops that currently rely on fumigation while also mitigating risks such as of nitrate leaching to groundwater or emission of greenhouse gases. DPR and/or other relevant California state agencies should consider supporting work to identify or develop supply chains for various organic matter streams that can be used in ASD or biosolarization and are cost-effective for growers. 124

47. **CONCLUSION:** Given its complete reliance on weather and climate conditions to achieve soil temperatures required for broad spectrum soil pest control, solarization will likely only be a possible fumigation alternative in cropping systems and regions that have a fallow period during several weeks of sustained hot, dry conditions. 128

49. **CONCLUSION:** Inactivation of fungal pathogens and phytoparasitic nematodes via biologically derived pesticides or biocontrol agents, and associated disease reduction and yield effects in treated crops, is variable and may be highly transient. The costs of using biologically derived pesticides and biocontrol agents at a scale for soil pest control are not well characterized. 134

50. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to determine the types of biologically derived pesticides and biocontrol agents, and their application practices, that maximize broad spectrum soil pest control with the aim of achieving parity with fumigation in California agriculture. If such conditions are identified, DPR and/or other relevant California state agencies should consider supporting analyses to determine the costs and net returns for growers. 134

52. **CONCLUSION:** Cover crops alone are unlikely to be an effective fumigation substitute. However, they can contribute to an integrated pest management strategy that uses multiple approaches to control soil pests. .139

54. **CONCLUSION:** The use of crop rotations requires growers to be skilled in cultivating multiple crops. For effective soil pest control, growers must select rotated crops that can disrupt the host cycle of pests in their fields while also being compatible with their local soil, climate, land availability, and market conditions. These factors create hurdles to adoption. In cases where soil is infested with pests or pathogens with broad host ranges, or if multiple pests and pathogens are present with differing disease mechanisms, crop rotations may have more limited effectiveness as a fumigation alternative. 143

56. **CONCLUSION:** Resistant varieties and rootstocks can be effective in controlling certain classes of soil pests, such as specific nematode and fungal pathogen species. They are less likely to be effective fumigation alternatives in fields with multiple pest stresses unless other complementary pest control strategies are used. .147

58. **CONCLUSION:** Steam treatment can deliver broad spectrum soil pest control, but the reliance on specialized equipment, limited knowledge of heating depth, and slow treatment times for a single applicator present barriers to adoption. 151

59. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting engineering and research efforts to characterize or enhance the depth of steam treatment along with work to improve steam treatment times for large fields. Additionally, given the fuel requirements to operate existing steam applicators, DPR and/or other relevant California state agencies should consider supporting life cycle assessments to understand the environmental impacts of using steam treatment in open field, greenhouse, and nursery settings and in response to different fuel types (e.g., natural gas, biogas, hydrogen). 151

61. **CONCLUSION:** Soilless cultivation systems represent a substantial departure from conventional agriculture in open fields, requiring infrastructure, nutrient and water management practices, and sanitation methods that are markedly different from those used in fields. 156

62. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting analyses to determine the feasibility and cost of transitioning various open field cropping systems to different hydroponic or solid substrate soilless systems, such as substrate bags in open fields or atop tables. 156

64. CONCLUSION: Greater study of potential mechanisms of the functional biodiversity on diversified farms and how it might relate to soil and plant health, in addition to reporting the costs and returns of diversified farming systems, could provide insights into how these farms operate without using fumigants. 157

75. CONCLUSION: Additional research is necessary to define the biosolarization and anaerobic soil disinfestation process conditions (e.g., amendment nutrient profiles, duration of tarp coverage) that avoid methane and nitrous oxide emissions. 163

76. CONCLUSION: A full health risk assessment is required for the complete array of volatile compounds commonly produced during biosolarization and anaerobic soil disinfestation. 163

78. CONCLUSION: Calculated exposure limits from DPR risk assessments for methyl isothiocyanate and allyl isothiocyanate do not indicate a clear reduction in exposure risk associated with adoption of these fumigants over 1,3-D and chloropicrin. However, a deeper analysis of the underlying data and methods used to determine acute, sub-chronic, and chronic exposure limits for each fumigant is needed to ensure valid comparisons of toxicity and exposure risk.. 166

81. CONCLUSION: There may be a need to supplement the more targeted fumigant alternative methods with additional weed control measures, such as with post-emergence herbicides or hand weeding. 169

83. CONCLUSION: Additional research is needed to quantify the full range of soil physical, chemical, and biological effects for the many possible soil amendments and field conditions that are relevant to anaerobic soil disinfestation and biosolarization. Conducting life cycle assessments to compare fumigant alternative use scenarios that increase or decrease greenhouse gas emissions (relative to fumigation) could help incentivize their adoption. 170

87. CONCLUSION: Based on the current state of knowledge, each cropping system and region in California may have one or more fumigant alternatives that provide partial or complete control of major pests for a span of months to years with less apparent risk to humans or the environment compared to 1,3-D or chloropicrin.. . . .174

88. RECOMMENDATION: DPR and/or other relevant California state agencies should consider supporting basic science research to further explore the pest inactivation mechanisms of fumigant alternatives, as well as field demonstration studies that directly compare feasibility, cost, and pest inactivation effectiveness between multiple fumigant alternatives and fumigation in a given cropping system and environmental context. Such work may involve experimentation or meta-analysis of existing published data. Additionally, DPR and/or other relevant California state agencies should consider supporting appropriate risk assessments for each fumigant alternative. 174

Chapter 3: Research on Fumigant Alternatives

90. CONCLUSION: Based on current data, ethanedinitrile (EDN) is inconsistent in its ability to control weeds, pathogens, and phytoparasitic nematodes while benefitting the health and productivity of crops. Additionally, there are poorly understood phenomena that affect transient inhibition and plantback times following EDN fumigation with higher application rates. There are no environmental or human health risk assessments for the use of EDN in California agriculture. 199

91. RECOMMENDATION: DPR and/or other relevant California state agencies should consider supporting research to determine the efficacy and safety of ethanedinitrile (EDN) use in the context of California agriculture. This could include field trials to study use in crops and regions that currently employ 1,3-D and chloropicrin fumigation in California. Additionally, the work should include measurement of EDN escape and risk of exposure and disease for agricultural workers, adjacent communities, and non-target organisms. .199

93. CONCLUSION: Additional targeted research would be useful to determine the most effective combination methods for major fumigant-reliant crops. 208

98. CONCLUSION: Combination approaches that integrate multiple fumigant alternatives, whether simultaneously or in series, are likely to offer the greatest versatility and duration for broad-spectrum soil pest control. 215

Chapter 4: Addressing Barriers and Increasing Adoption of Fumigant Alternatives

Introduction and Background to the Study

Fumigants are volatile chemical compounds used to control pests. Fumigants are used as insecticides, fungicides, disinfectants, nematicides, herbicides, and rodenticides. They are applied in a range of settings including homes, healthcare facilities, and food facilities. They are applied to benefit crop production and to control vector-borne diseases of plants and animals.

Soil fumigants were developed in response to ongoing concerns about soilborne pathogens that posed risks to crop yields. In the late 1950s, the broad-spectrum fumigant methyl bromide was developed as a pre-plant soil treatment and first used to control soilborne diseases in California strawberry production (Koch 1956). It was then found to be even more effective when combined with chloropicrin (Wilhelm et al.,1961). This fumigant combination was adopted widely and throughout the California strawberry industry to control the main disease, Verticillium wilt, which had caused heavy losses. Owing to its ease of application and broad spectrum of activity, many growers in the United States and abroad came to rely on methyl bromide for the production of several high-value crops including eggplant, pepper, tomato, watermelon, carrot, and strawberry (Gullino et al., 2003; Rosskopf and Di Gioia 2023; Rosskopf et al., 2005), as well as fruit and nut tree crops, grapes, ornamentals, sweet potatoes,* turf, and cut flowers (Brennan 2008; Rosskopf et al., 2016; Zasada et al., 2010). Fumigation allowed many crops to be grown intensively without any rotation with other crops. The strawberry industry, among others, became highly dependent on pre-plant fumigation with these two fumigants (Olver and Zilberman, 2022; Guthman 2019; Duniway 2002).

However, in the 1980s, methyl bromide was identified as a significant contributor to **ozone**** depletion, prompting international concerns (Yang et al.,1980). The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (United National Environment Program 1992) aimed to phase out ozone-depleting substances, with increasingly stringent methyl bromide production reduction targets set between 1993 and 2005. While Critical Use Exemptions (CUEs) were available, applicants that wished to obtain them had to demonstrate that there were no technically and economically feasible alternatives available and that all steps had been taken to reduce methyl bromide use to the extent possible, including pursuing the development of methyl bromide alternatives and substitutes (Rosskopf et al., 2005). Over

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* While some sources advocate for “sweetpotato” as a single word, we have opted to use the two-word spelling in this report to align with common usage.

** Bolded terms can be found in the glossary.

this timeframe, alternative fumigants like 1,3-dichloropropene (1,3-D) and chloropicrin saw increased usage.

Since their commercialization, scientific and public concern about fumigants' impacts on human health and the environment has grown. This, combined with the phaseout of methyl bromide, has spurred a proliferation of research into alternative pest management methods. There are continued signals that fumigants will be seeing even more regulatory scrutiny going forward.

Phase 1 of the study commissioned by the California Department of Pesticide Regulation (DPR) will focus on the two most commonly applied pre-plant soil fumigants used in California: 1,3-D and chloropicrin. This report will address the current state of fumigant use in California including effectiveness of these chemicals; their effects on human health, environmental impacts, and ways to mitigate these consequences; currently available alternatives for these fumigants; past and ongoing research into fumigant alternatives; the viability of adopting these alternatives to manage pests in California; barriers to wide-scale adoption of the alternatives; potential ways to increase adoption of these alternatives; and areas where additional research may still be needed. The Phase 2 report will address four other pre-plant soil fumigants (dazomet, metam-sodium, metam-potassium, and methyl bromide); four post-harvest commodity fumigants (sulfuryl fluoride, phosphine, propylene oxide, and methyl bromide); and one structural fumigant (sulfuryl fluoride).

This report builds on DPR's Non-fumigant Strawberry Production Working Group Action Plan (2013) as well as other DPR reports related to fumigant regulation and use, and most recently is, in part, a complement to DPR's, "Accelerating Sustainable Pest Management: A Roadmap for California" (2023). Sustainable Pest Management (SPM) is defined in the DPR report as a "holistic, whole-system approach" applicable to both agricultural and other managed ecosystems, including urban and rural communities. SPM builds upon **integrated pest management** (IPM) by incorporating a broader focus on the three pillars of sustainability: human health and social equity, environmental protection, and economic vitality. The Roadmap sets an initial target for 2025, calling on the state to create plans, funding mechanisms, and programs aimed at prioritizing the reduction of high-risk pesticides and supporting the transition to safer pest management practices. By 2050, the goal is to eliminate the use of Priority Pesticides and to have SPM adopted as the standard pest management system in California.

Chapter 1: Pre-plant Soil Fumigants 1,3-D and Chloropicrin

Section 1.1: Chapter overview

This chapter provides an overview of the use, impacts, and management of 1,3-dichloropropene and chloropicrin, focusing on their role in agricultural systems and their broader implications. Over the next 7 sections, we provide 1) an introduction of the fumigants; 2) the pests that these fumigants are used to manage; 3) application methods for these fumigants; 4) commodities and crops where the fumigants are used; 5) emission reduction measures used with these fumigants; 6) an analysis of pesticide use trends in California; 7) human health, environmental, and ecological concerns; 8) the tradeoffs of using these fumigants; and 9) the use of these two fumigants within other states and countries.

Chapter 1 contains 23 Findings, 10 Conclusions, and 3 Recommendations.[*]

Section 1.2: Introduction to the fumigants

1,3-Dichloropropene

1,3-dichloropropene (1,3-D, $C_3H_4C_{l2}$; hereafter, 1,3-D) is a chlorinated **volatile organic compound** (VOC).[**] At room temperature, 1,3-D is a colorless liquid with a sweet smell and a **flash point** of 95°F (35°C). A mixture of dichloropropene and dichloropropane, 1,3-D was first generated as a byproduct of the production of allyl chloride to make epoxy by the Shell Oil Company. The nematicidal activity (capability of inactivating or killing nematodes) of this mixture was then discovered by Walter Carter in Hawaii in 1943 (Carter, 1943; Chellemi, 2014). 1,3-D was introduced more broadly as a commercial fumigant in 1955 and was first registered for use in California in 1970. Its mode of action involves multiple mechanisms that are generally referred to as "miscellaneous nonspecific multisite inhibitors" that affect the enzymatic, nervous, and respiratory systems of nematodes (Rich et al., 2004; IRAC, 2021). 1,3-D has more recently been shown to also provide some control of plant pathogens, as well as certain arthropods (invertebrates such as the garden centipede and wireworms), especially when combined with chloropicrin. This expanded use has been driven by the phaseout of the broad-spectrum fumigant methyl bromide, the emergence of

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[*] **Finding**. Fact(s) the study team finds that can be documented or referenced and that have importance to the study. **Conclusion**. A reasoned statement the study team makes based on findings. **Recommendation**. A statement that suggests an action or consideration as a result of the report findings and conclusions.

[**] Bolded terms can be found in the glossary.

new pathogens like *Macrophomina phaseolina* (which causes charcoal rot in strawberries), and recent research (Baggio et al., 2022). Recently published work on controlling the fungal pathogen *Neopestalotiopsis* sp. in strawberries in Florida also found 1,3-D effective (Alonso et al., 2024). Klose et al. (2007) found 1,3-D to be most effective against the pathogen *Pythium ultimum* and least effective against *Verticillium dahliae*, and intermediate in control of *Fusarium oxysporum* and *Phytophthora cactorum*. Koike et al. (2013) found 1,3-D and chloropicrin to be moderately effective against both *Macrophomina phaseolina* and *Fusarium oxysporum* f. sp. *fragariae* in the warmer summer plant strawberry production season in Ventura County.

1,3-D is applied to agricultural soils prior to planting fruit and nut trees, strawberries, grapes, carrots, and other food and non-food crops. 1,3-D is injected into the soil as a liquid using various shanks or other devices, or it can be applied as an emulsion through drip irrigation lines. The volatility of 1,3-D increases the probability of off-field drift and human exposure through inhalation. Under certain environmental conditions, 1,3-D can also contribute to ozone-related air pollution. The California Department of Pesticide Regulation (DPR) has been managing the use of 1,3-D to help protect human health and the environment since 1990 (Segawa and Luo, 2022).

1,3-D is a **restricted use pesticide** as per federal (40 C.F.R. Section 152) and state regulations (section 6400(e) of the California Code of Regulations, Title 3). Restricted use pesticides are designated as such given their "potential to cause unreasonable adverse effects to the environment and injury to applicators or bystanders" (U.S. EPA, 2024a). Restricted use pesticides are only available to certified applicators (or someone under the direct supervision of a certified applicator); they are not available for purchase by the general public. The U.S. Environmental Protection Agency (EPA) determines whether the use of a product should be restricted; the criteria are specified in Part 152 of Title 40. In California, purchase and use of 1,3-D for agricultural production are allowed only when accompanied by a restricted materials permit from the local county agricultural commissioner (CAC). Before issuing a permit, the CAC must evaluate the permit application to determine whether the intended use may cause a substantial adverse environmental impact based on local conditions at the application site. Depending on the results of this review, the CAC may deny the permit or impose permit conditions including the use of specific measures to mitigate off-site drift and thereby limit possible environmental impacts, human exposure, and human health effects. As part of the permit for any restricted material, certified applicators must provide a notice of intent to the CAC before applying the fumigant. The notice of intent includes application-specific information, such as the number of acres being treated and date application will be initiated (Segawa and Luo, 2022).

The U.S. EPA has designated 1,3-D as a **hazardous air pollutant** since 1990 under the federal Clean Air Act. Air pollutants are designated as hazardous if they are “known or suspected to cause cancer or other serious health effects” or if they pose environmental threats (U.S. EPA, 2023). The state of California maintains a similar list of **toxic air contaminants** that “may cause or contribute to an increase in mortality or an increase in serious illness” (California Health and Safety Code § 39655). As per section 39657(b) of the California Health and Safety Code, any substance that has been listed federally as a hazardous air pollutant is considered to be a toxic air contaminant in the state of California. Thus, 1,3-D is also listed as a toxic air contaminant in section 6860(b) of the California Code of Regulations, Title 3 (hereafter CCR, Title 3). Due to the designation of 1,3-D as a toxic air contaminant, DPR must determine the “need for and appropriate degree of control measures.”

1,3-D is a **VOC** that can contribute to the formation of **ozone**, a component of smog and a major air pollutant in California. The federal Clean Air Act requires states to develop State Implementation Plans (SIP) outlining how they will mitigate air pollution to meet ambient air quality standards. California’s SIP is not a single document, but rather is a collection of plans, programs, rules, and regulations (California Air Resources Board, 2024). Currently, section 6448.2 of CCR, Title 3 addresses California’s SIP requirements for 1,3-D soil fumigations. California’s SIP addresses five regions in California that exceed the federal ozone standard (i.e., nonattainment areas or NAAs) during the May–October peak ozone season: the San Joaquin Valley NAA, Sacramento Metro NAA, South Coast NAA, Southeast Desert NAA, and Ventura NAA (Segawa and Luo, 2022).

Since 1989, 1,3-D has been listed by California as a chemical carcinogen (OEHHA, 2023). Human health risks associated with 1,3-D (including carcinogenicity) resulted in restricted use beginning in the mid-1990s (U.S. EPA, 2008a; OEHHA, 2023). More recently, in response to a risk characterization document regarding inhalation exposure (DPR, 2015a) and recent monitoring of 1,3-D emissions (DPR, 2019a, b), DPR initiated the process of mitigating both **acute** and **chronic** exposure. The resulting regulations restrict the use of 1,3-D to mitigate the potential **72-hour acute risk** and **70-year lifetime cancer risk** to non-occupational bystanders (DPR, 2024a). The mitigation measures also further reduce the emissions of 1,3-D as a VOC and allow the use of 1,3-D only to produce agricultural commodities.

The 2024 regulations address acute exposure by 1) adding a new application method type, 24 in (~61 cm) deep injection; 2) substantially limiting shallow applications for both polyethylene tarped and untarped applications; 3) reducing the maximum allowed block size for most untarped application methods; 4) increasing the required soil moisture to 50% of the field’s capacity; and 5) adjusting buffer zones and setback requirements. Even with these changes, the extent of the reduction depends to a large degree on application rate (i.e., the volume of compound per unit time or volume of compound per geographic unit (acre, hectare)) and setback distance. These new regulations also require an annual report from DPR that evaluates the relationship between 1,3-D use and air monitoring data. The annual report also requires the inclusion of new information such as fumigation application method in existing pesticide use records and reports. These changes are intended to address chronic exposure. However, if chronic exposure continues to be a problem after the acute mitigations, 1,3-D use limits within specific areas—i.e., the township caps—will be triggered. The proposed use limits will include an adjustment to the previously established township caps. While the new caps are higher, they are designed to be protective of chronic exposure when paired with the mitigations for acute exposure (Segawa and Luo, 2022). More on the environmental, ecological, and human health impacts of 1,3-D is provided in ***Section 1.8***.

Chloropicrin

Chloropicrin (trichloronitromethane, $Cl_3C\text{-}NO_2$, also known as nitrochloroform) was discovered in 1848 by John Stenhouse, a Scottish chemist, when he reacted sodium hypochlorite with picric acid. It was first patented for use as an insecticide in 1908 and was used as a gas warfare agent from 1914–1918 during World War I. In 1926, chloropicrin was first used as a fumigant in flour mills (DPR, 2009). Since then, it has been used as a soil and structural fumigant, either as an active ingredient or as a warning agent for other odorless fumigants.

Chloropicrin is a volatile oily liquid. It is also a **lacrimator** (i.e., tear gas) due to its sharp penetrating odor, which causes tearing. Because of its low odor threshold and capacity to cause sensory irritation even at very low concentrations, chloropicrin was often used as a warning agent for methyl bromide, a colorless and odorless broad-spectrum soil fumigant. Chloropicrin is itself a broad-spectrum fumigant with insecticidal, fungicidal, nematicidal, and herbicidal properties. It has been used as such more frequently following the phase-out of methyl bromide and is almost always combined with 1,3-D, where it provides control for several soilborne pathogens of strawberry, raspberry, vegetables, and other high-value specialty crops. Chloropicrin provides pre-plant control or suppression of many diverse plant pathogens, including *Rhizoctonia solani* (causing damping-off and various root and crown rot in over 200 plant species); *Setophoma terrestris* (predominantly affecting allium crops like onion and garlic); *Pyrenochaeta* spp. (root rots in over 20 crops); *Colletotrichum coccodes* (black dot in potato and diseases in other crops); *Monosporascus cannonballus* (vine decline in melons); and many others (Guillino et al., 2002; Slusarski and Spotti, 2016; Stanghellini et al., 2003). Fumigation with chloropicrin has also targeted certain **oomycete** pathogens (also known as water molds), including species in the *Phytophthora* and *Pythium* genera. These pathogens—which cause root and crown rot on a wide range of crops—grow, reproduce, and move in and with water.

The mode of action of chloropicrin is not well understood but may be related to its reaction with biological thiols (Sparks et al., 1997). Thiols are organic compounds essential for maintaining cellular function in organisms. Chloropicrin is also known to inhibit the enzymes pyruvate and succinate dehydrogenase (Sparks et al., 2000). The inhibition of these enzymes has been correlated to the lethality of various halonitromethanes, quinones, fungicides, and other thiol-reactive chemicals.

DPR placed chloropicrin into reevaluation in 2001 because air monitoring data revealed that concentrations of chloropicrin near treated greenhouses exceeded established occupational exposure limits (Cortez, 2001). Further, **genotoxicity** and developmental toxicity studies indicated that low doses of chloropicrin could cause adverse effects, prompting DPR to designate chloropicrin as a high priority for a thorough risk assessment as part of its re-evaluation (Lewis, 2012). As of July 2024, chloropicrin is still under re-evaluation by DPR which is requiring the **registrant** to conduct and submit data from five new toxicological studies on the carcinogenic potential of the active ingredient (Lewis, 2012; DPR, 2024b).

Additional regulatory changes were developed to mitigate acute exposures in agricultural fields (DPR, 2024b). In 2015, new restrictions were introduced including requisite buffer zones (minimum of 25–100 ft (~8–30 m), depending on the tarp used); approved tarps and accompanying tarp cutting regulations; time of day restrictions on applications; notification of neighbors; on-site posting; emergency preparedness and response measures; training for certified applicators supervising applications; creation of Fumigant Management Plans; and a requirement of filing of a notice of intent extended from 24 hours to 48 hours in advance of the application. Overall, the 2015 restrictions are more conservative than those implemented at the federal level in 2012 (DPR, 2015b).

Like 1,3-D, chloropicrin is currently listed as a restricted material in the California Code of Regulations, Title 3 (section 6400(e)), requiring a certified applicator. Chloropicrin is also a VOC that contributes to ozone and is listed by California as a toxic air contaminant (DPR, 2024c).

Section 1.3: Pests that these fumigants are used to manage

Broadly speaking, 1,3-D is commonly used to control soil-borne pests such as **nematodes**, arthropods (insects and mites), and soilborne pathogens in a variety of California crops. It was originally developed and continues to be used to control nematodes, but more recently it has been shown to be effective in controlling soilborne pathogens, particularly in strawberries and in combination with chloropicrin.

Chloropicrin is most effective in controlling soilborne pathogens, including fungal, bacterial, and **oomycete** microorganisms and, to a lesser extent, nematodes, weeds, and arthropod pests. More details about these different pest types are below.

Nematodes

Nematodes are microscopic, unsegmented roundworms that live in the water films between soil particles (***Figure 1.1***). Free-living nematodes (e.g., bacterial and fungal feeders) can occupy any ecological niche that has an available source of organic carbon. Like other organisms found in soil, nematodes help improve soil health by decomposing organic matter, mineralizing nutrients, and breaking down toxicants (Bongers and Ferris, 1999). In contrast, plant-parasitic nematodes attack plant roots and limit crop growth, quality, and yield. Omnivorous and predatory nematodes may prey on other species. Some nematodes parasitize insects (i.e., entomopathogenic nematodes) and can play an important role in regulating pests and other insect populations.

Figure 1.1. Microscopic view of root-knot nematodes (*Meloidogyne* spp.) attached to a tomato plant root. Photo: Jonathan D. Eisenback, Virginia Polytechnic Institute and State University, Bugwood.org.

Nematodes do not typically kill plants, but rather are plant stressors. They can deform plant tissues (root-knot nematodes) or destroy tissues while feeding (e.g., root lesion nematodes). They may act alone or in conjunction with other pathogens and stress factors in crops to reduce growth and yield. Above-ground plant symptoms of nematodes include stunted growth and plants which lack vigor. If not treated, nematodes reduce yields by an average of 5–20%, although in some fields they can reduce yields by up to 80% (Khan, 2023; Chitambar et al., 2018), significantly impacting a grower's returns. Nematodes can most severely impact the quality of root vegetables (e.g., carrots, potatoes) (***Figure 1.2***).

Nematodes tend to be distributed in patches in a field (Quist et al., 2019). Nematodes invade and feed on plant tissues, causing mechanical damage to cells, potentially leading to cell death and necrosis. This damage interferes with critical functions, including the uptake and transport of water and nutrients from roots, as well as the distribution of products from photosynthesis (like sugar) from leaves to the rest of the plant (Westerdahl et al., 1998) (***Figure 1.3***). In addition to the direct damage they inflict, the openings and physiological changes wrought by the invasion and feeding of plant-parasitic nematodes may also facilitate or aggravate infections with other soil-borne microbes. Nematodes may also carry and transmit viruses from one plant to another. Nematode related injury increases the susceptibility of plants to environmental stressors, such as lack of water or high temperatures.

Figure 1.2. Sweet potato root showing damage by root-knot nematode infection (*Meloidogyne* spp.). Symptoms include galls and deformities on the surface, which result in cracking as the roots enlarge, reducing marketability and yield. Photo: Gerald Holmes.

The species and population sizes of plant-parasitic nematodes that become established in a field are influenced by a variety of factors, including the species of nematodes present in the agricultural soil at time of planting. This will be influenced by past cropping history, soil preparation prior to planting, farming methods (e.g., diversified or monoculture), and the nematode host-status of cover crops and native vegetation. Newly seeded and transplanted plants are more susceptible to nematode infections than established plants. Nematodes can also be introduced to fields by contaminated nursery stock, farm equipment, and irrigation water (Statewide Integrated Pest Management Program, 2024). The relative susceptibility of selected rootstock will influence whether various nematode species present in soils or introduced via contamination prove problematic for the crop. However, even resistant rootstock cultivars may suffer some damage if planted in nematode infested soils.

Plant parasitic nematodes can be characterized by their life cycle and how they interact with plant hosts. By definition, at least part of the life cycle of a migratory endoparasitic nematode is spent inside host roots, while ectoparasitic nematodes spend their entire lifecycle in the surrounding soil.

The most well-known and impactful endoparasitic nematodes globally, and within California, are the root-knot nematodes in the *Meloidogyne* genus (Chitambar et al., 2018). These species can be found in the soil or as a sedentary **endoparasite** (an immobile life stage inside the plant tissue) in roots. The second-stage juveniles enter a root, take up a permanent feeding site, and then develop into immobile, swollen adult females within the root. At least five species of root-knot nematodes impact crops in California: northern root-knot nematode (*Meloidogyne hapla*), Javanese root-knot (*M. javanica*), southern root-knot (*M. incognita*), peanut root-knot (*M. arenaria*), and Columbia root-knot (*M. chitwoodi*). These species have wide and variable host ranges, thrive under different temperatures, and varying degrees of pathogenicity. Citrus nematodes (*Tylenchulus semipenetrans*) also cause yield losses of citrus in California of 10–30% (Chitambar et al., 2018). Citrus nematodes also affect grapes.

Figure 1.3. (**A**) Side-by-side comparison of a healthy tomato plant (left) and a tomato plant infected by the southern root-knot nematode (*Meloidogyne incognita*, right). The infected plant exhibits stunted growth and wilting, indicative of root system damage caused by nematode-induced galls. (**B**) Close-up of tomato plant root systems: a healthy root system (left) with uniform structure and fine roots intact, contrasted with a root system infected by the southern root-knot nematode (*Meloidogyne incognita*, right), showing large, irregular galls that disrupt normal root function and nutrient uptake. Photos: Gerald Holmes.

Lesion nematodes (*Pratylenchus vulnus* and *P. penetrans)* are problematic for many vines, tree fruits, and tree nut crops in California and have a wide host range. They move through and cause mechanical damage to the root as they feed and reproduce. This damage leads to blackened roots and fewer feeder roots. This in turn compromises root integrity and allows secondary invasions by fungi and bacteria. Above-ground symptoms include lack of vigor, dieback, **chlorotic** and small leaves, and reduced yield. In California, this nematode is the primary cause of tree decline and replant problems in nut tree orchards, especially walnuts (Chitambar et al., 2018). On plums, yield losses range from 6–16%, depending on the rootstock. Lesion nematodes are widely distributed in California vineyards and seriously affect grape yields (Chitambar et al., 2018).

The ectoparasitic nematodes with the greatest impact on California's crops include Dagger *(Xiphinema americanum; Xiphinema index)*, ring (*Mesocriconema xenoplax; Criconemella)*, needle *(Longidorus elongatus),* and stubby root nematode (*Paratrichodorus minor)* (Westerdahl et al., 1998). These nematodes feed on—but do not penetrate—the roots and lay eggs singly in the soil. They go through four molts, and all juvenile stages are believed to feed on roots. Several important viruses—including tomato ringspot, tobacco ringspot, and cherry rasp leaf virus—are transmitted by *Xiphinema* species, and the cleanliness and protection of nursery stock is important to control their spread (Chitambar et al., 2018).

1,3-D is the most effective fumigant currently available to control a wide range of nematodes in many different crops. It is often used together with chloropicrin which helps broaden the spectrum of pests controlled. Systematic field sampling for each important nematode pest is part of an integrated control program, along with the use of crop and species-specific nematode action thresholds. Most of this work has been done for nematicides like 1,3-D, and additional research will be needed to confirm population thresholds and treatment effectiveness for the alternatives discussed later in this report.

Pathogens

Soils are home to possibly the highest level of microbial diversity of any environment on Earth. Each gram of soil has been reported to be occupied by approximately 10 billion microorganisms and thousands of different microbial species (Parks, 2024; Gastauer et al., 2019). Plant pathogenic microorganisms are specialized members of the microbial community that obtain nutrients and occasionally shelter from plants. If these pathogens are left uncontrolled, they can cause significant loss of yield and crop quality. The pathogens often produce resting structures that enable continued long-term survival in the soil, even in the absence of the main host. Pathogens can also reside on cover crops, on native vegetation surrounding crops, in the planting stock propagation fields, and on the planting stock. Many fungal pathogens infect plant root tips as the roots grow towards the fungus. Root tips leak nutrients which stimulate the pathogen to germinate and grow towards the host. Pathogens responsible for vascular wilt diseases invade the vascular system of the plant. Once there, they can move systemically into the plant, causing localized restrictions in water movement resulting in water stress and ultimately plant death. Other pathogens cause roots to rot, either fine roots and/or tap roots, either of which results in poor plant uptake of water and nutrients, plant stress, and potentially plant death. Fungi are the main pathogen targets of pre-plant fumigation with chloropicrin. Economically significant plant pathogenic fungi in California include various host-specific forms (forma specialis) of *Fusarium oxysporum* (which causes the disease known as Fusarium wilt), *Macrophomina phaseolina* (which causes charcoal rot) (***Figure 1.4***), *Verticillium dahliae* (which causes Verticillium wilt), and the Oak root fungus (*Armillaria mellea*) (which causes a crown and root rot). Several of the preceding soilborne pathogens cause disease in strawberries; average yield losses of 20–50% have been reported and at times up to 100% or complete loss (Wilhelm and Paulus, 1980; Shaw and Larsen, 1999; Duniway, 2002; Koike, 2013; Baggio et al., 2022) (***Figure 1.5***).

Figure 1.4. Rows of strawberry plants affected by charcoal rot, caused by the soilborne fungus *Macrophomina phaseolina*. The disease leads to crown and root rot, wilting, and plant death, resulting in strawberry yield losses. Photo: Jenny Broome.

Fumigation can also be targeted at certain oomycete pathogens (also known as water molds), including species in the *Phytophthora* and *Pythium* genera. These pathogens—which cause root and crown rot on a wide range of crops—grow, reproduce, and move in and with water. Oomycetes include the pathogen that caused the Irish Potato Famine in the late 1840s.

There are fewer bacteria that are a target of pre-plant fumigation, and the effectiveness of fumigants in killing bacteria directly is not well documented. That being said, chloropicrin has shown effectiveness against some bacterial diseases of crops, including *Streptomyces scabiei* (common scab on potato) and *Ralstonia solanacearum* (bacterial wilts in dozens of crops) (e.g., Hutchinson, 2005; Jones et al.,1998). Other bacteria that can be targeted directly or indirectly with fumigation include *Agrobacterium tumifaciens* (also known as

Rhizobium tumefaciens) and *Pseudomonas syringae. A. tumifaciens* causes a **gall** on the crown or roots of various crops, while *P. syringae* causes a bacterial **canker**. However, *P. syringae* is mainly problematic if ring nematodes are in the soil causing tree stress. This stress enables the surface-dwelling bacteria to infect the roots and crowns of certain stone fruit trees. Although the bacterial cankers of *P. syringae* prompt treatment, the real target of the fumigation is the nematodes. In addition to the well-documented plant pathogens causing disease in California crops described above, there are plant disease complexes, like Prunus replant disease, where the causal agents are still under investigation. These disease complexes appear to involve a combination of nematodes, fungal and oomycete pathogens, and soil applied pre-plant fumigants are known to control the problem (Browne et al., 2013). Many almond replant sites have Disease-based Prunus Replant Disorder, which is a microbial complex that does not include nematode pests. Chloropicrin is an effective fumigant for control of this complex: pre-plant fumigation with chloropicrin has been shown to increase almond yields by 40% or more in the first few years of production compared to untreated soils (Browne et al., 2013).

Figure 1.5. Strawberry field with high incidence of Fusarium wilt caused by the plant pathogenic fungus *Fusarium oxysporum* f. spp. *fragariae (race 1)*. The disease results in stunted growth, wilting, and browning of plant vascular tissues, often leading to plant death and yield loss. Photo: Jenny Broome.

Like nematodes, the plant pathogens that become established in a field will be determined by a variety of factors, including the kinds of pathogens present in the agricultural soil at time of planting. This will be influenced by past cropping history, farming methods (e.g., diversified or monoculture), and the pathogen host-status of cover crops and native and surrounding vegetation. Pathogens can also be introduced to fields by contaminated nursery stock, farm equipment, people, animals, and irrigation water. Different soil types (i.e., percent sand, clay, or loam) are amenable to different soil-borne pathogens, while different rootstocks will have differing susceptibilities to plant pathogens.

Weeds

Weeds compete with crops for light, water, and nutrients and can reduce yields. If left uncontrolled, weeds can become increasingly impactful over time due to expanding seed banks (reservoir of viable seeds present in the soil). Weeds can also be a source of pathogens and arthropod pests for crops. Weed seeds can be controlled by pre-plant fumigants, light-blocking tarps, and herbicides, as well as other alternative approaches discussed later in this report. In general, soil fumigants will kill both germinating seedlings and quiescent seeds (i.e., inactive or dormant) by interfering with seed respiration. Properly irrigated soil (neither too wet nor too dry) is a more effective medium for fumigation because 1) wet seeds respire at a higher rate than dry seeds and 2) fumigants can better penetrate a seed coat swollen with water (Fennimore, 2012). Saturated soil will leave insufficient pore space for the distribution of fumigants. While 1,3-D and chloropicrin are less effective than methyl bromide for weed control, combinations of 1,3-D and chloropicrin together with post-emergence herbicides have been found to be comparable to methyl bromide treatments in Florida tomatoes (Santos et al., 2005). 1,3-D combined with chloropicrin is better than chloropicrin alone (Fennimore et al., 2003). Each fumigant controls weeds better than an untreated field (Samtani et al., 2010). For weed control for strawberries, as well as for pathogen control, University of California (UC) Integrated Pest Management (IPM) recommends 1,3-D and chloropicrin drip application, which should be followed up sequentially 5–7 days later with metam sodium or metam potassium (UC IPM, 2018). Additionally, herbicides can be used either pre- or post-crop planting and combined with weed-suppressive plastic tarps to increase weed control. Qiao et al. (2010) found good to moderate weed and pathogen control and recommends 1,3-D in combination with other fumigant alternatives.

Arthropod pests

Soil-dwelling arthropod pests are not as important overall to control as nematodes, pathogens, or weeds, but there are a few arthropod target pests included on the fumigant labels, such as symphylans (*Scutigerella immaculata)* and wireworms. Full-grown symphylans (also known as garden centipedes) are slender white centipedes with 15 body segments and between 11 to 12 pairs of legs; they can grow to 0.33 in (~8.4 mm) long (Bell and Waters, 2021). Adults may live several years. The adult females lay eggs in the soil that hatch into small versions of adult symphylans. They move long distances in the soil but cannot tunnel through soil and so rely on existing soil pores. The primary food of symphylans is decaying organic matter, but they can also feed on root hairs. Symphylans may damage sprouting seeds, seedlings before or after emergence, or older plants (UC IPM, 2024).

Wireworms are the soil-dwelling larvae of click beetles (Elateridae). Wireworms that can damage crops, mainly potatoes and sweet potatoes, include the Dryland wireworm (*Ctenicera pruinina),* Pacific coast wireworm (*Limonius canus),* corn wireworm (*Melanotus communis*), and Sugarbeet wireworm (*Limonius californicus)*. Adult wireworms are slender, reddish brown to black click beetles that are 0.25–0.5 in (6–13 mm) long. As suggested by their name, wireworm larvae are wirelike and they have slender, cylindrical bodies that are yellowish to brown in color. They are about 0.75 in (19 mm) long when full grown. Common wireworm species require three to four years to complete their life cycle. Click beetles do not damage potatoes and sweet potatoes, but the wireworm larvae may damage seeds and root systems early in stand establishment, resulting in poor stands. However, the most tell-tale sign of wireworm infestations are holes in potatoes and sweet potatoes left by feeding wireworms (UC IPM, 2024) (***Figure 1.6***). The UC IPM program does not recommend fumigants to control wireworms; however, these pests are included on the labels for both 1,3-D and chloropicrin (UC IPM, 2024).

Figure 1.6. Sweet potato root showing visible wireworm damage, with characteristic holes and tunneling caused by *Melanotus communis* larvae. A wireworm is visible near the damaged area. Photo: Gerald Holmes.

Section 1.4: Pesticide application methods and uses

Application of these fumigant chemicals to the soil to reach and control a range of pests is a challenging task as the material must reach the pathogens at all existing depths all while exposed to chemical, biological, and physical processes active in soils (Gullino et al., 2022). Some pathogens have aerial phases and resistant soilborne resting structures, which increase the control challenges. Fumigant application methods are provided on the compound's label. They can be applied by shank injections from tractor-drawn applicators at various depths into the soil profile—either **broadcast** (meaning across the entire field) (***Figure 1.7***) or in a strip—or fumigants can be applied via **chemigation** (meaning applied through drip lines laid on top of or buried into the soil). Fumigants can be applied with or without the use of various kinds of tarps, mulches, and films that are either made of polyethylene or that have added specialized layers of film known as virtually or totally impermeable films (VIF or TIF, respectively). Untarped soils can be overhead irrigated and compacted to better contain the fumigant and reduce emissions.

Figure 1.7. Tractor injecting fumigants into the soil using the broadcast method, followed by immediate coverage of the field with clear plastic tarps. Photo: Gerald Holmes.

There are 12 different application methods outlined in regulatory updates for chloropicrin released in 2015: TIF broadcast shank injection, TIF bed injection, TIF strip deep injection, TIF drip, non-TIF broadcast shank injection, non-TIF bed injection, non-TIF strip injection, non-TIF drip, untarped broadcast or strip shallow injection, untarped broadcast or strip deep injection, untarped bed injection, and untarped drip. As of January 1, 2024, there are 24 different application methods for 1,3-D (DPR, 2024d).

Totally impermeable films (TIF) were introduced around 2007 and by definition always contain a barrier polymer—ethylene vinyl alcohol (EVOH)—in either five- to seven-layer products. Five-layer products have one layer of EVOH resin sandwiched between two internal “tie” layers and two external polyethylene layers (the tie layer serves to bind the EVOH to the polyethylene layers). Seven-layer products have extra layers of polyethylene. EVOH resin is a random copolymer of ethylene and vinyl alcohol (-CH2–CH2) n–(CH2–CHOH)m-) that serves as a fumigant vapor barrier. EVOH is much less permeable to gases than the nylon polymer used in VIF and better contains fumigants than either VIF or polyethylene tarps alone. TIFs allow fumigant use rates to be reduced by 20–30% while maintaining effectiveness (Fennimore and Ajwa, 2012). Because the film retains fumigants so effectively, TIF tarp cutting periods (i.e., when tarps can be removed post-fumigation as per the U.S. EPA and DPR) were extended, as were plant-back periods. This change was implemented to reduce the release of fumigants following tarp cutting, allowing more time for in-soil degradation and thereby mitigating exposures to human applicators and bystanders. Postponed plant-back periods also serve to reduce the **phytotoxicity** to plants post fumigation (Qin et al., 2011; Gao et al., 2013).

1,3-D and chloropicrin are primarily applied to fields prior to planting in two different ways: 1) through deep or shallow depth shank injection into the soil (with or without tarps applied immediately afterwards to increase effectiveness and contain the products); or 2) through drip irrigation lines placed on beds with tarps (possible because these fumigants are liquids at ambient temperatures, unlike methyl bromide).

Section 1.5: Commodities and crops where the fumigants are used

California grows over 400 crops across 54 counties. Due to the expense and highly regulated nature of fumigant use, only the higher value crops and those most impacted by soilborne pests and pathogens receive pre-plant soil fumigation. Some crops, such as strawberry, have multiple soilborne pathogens and nematode species that cause significant yield losses (Shaw and Larsen, 1999). These crops have been fumigated since the chemicals were introduced to California, and their largescale production is highly reliant on their use (e.g., see Olver and Zilberman, 2022). Other crops, like almonds, are highly impacted by nematodes in the Central Valley. ***Table 1.1*** shows the 12 crops and fumigant uses that account for the greatest amount of 1,3-D and chloropicrin applied in California in 2022 (in terms of total pounds applied). These 12 crops and fumigant uses are described in more detail below. These data are derived from the 2022 Pesticide Use Report made available by DPR.

Table 1.1. Acres treated and pounds of active ingredient for 1,3-Dichloropropene and chloropicrin applied in 2022 in California. Listed are the 12 crops and major uses that accounted for the greatest amount of 1,3-D and chloropicrin reported in the state. Together, these account for 90% of the total pounds applied of both fumigants.

Crop or Use ("Site_Name")	Acres Treated in 2022	Pounds Applied in 2022	Percent of Total Pounds Applied (%)
Strawberry (All Or Unspec)	34,683	8,788,706	47.44
Almond	8,299	1,908,593	10.30
Soil Application, Preplant-Outdoor (Seedbeds, Etc.)	7,824	1,665,648	8.99
Sweet Potato	8,328	900,215	4.86
Grapes, Wine	2,562	818,477	4.42
Carrots, General	6,874	697,069	3.76
Uncultivated Agricultural Areas (All Or Unspec)	1,887	546,243	2.95
Grapes	1,690	465,897	2.51
Walnut (English Walnut, Persian Walnut)	2,205	392,153	2.12
Raspberry (All Or Unspec)	740	269,718	1.46
Cherry	919	194,693	1.05
Tangerine (Mandarin, Satsuma, Murcott, Etc.)	557	181,638	0.98
Total	**76,568**	**18,526,000**	**90.84**

Strawberry

California grows about 90% of U.S. strawberries by volume (NASS, 2024a). Strawberries were California's sixth highest-valued commodity in 2022 at $2.68 billion (CDFA, 2023a). In 2023, California growers harvested 42,700 acres of strawberries in three main districts: Watsonville/Salinas, Santa Maria, and Oxnard (NASS, 2024b). In California, strawberries are grown as an annual crop and thus replanted each year. Fields are pre-plant fumigated in late summer to early fall, and then the majority of growers plant in the fall. However, about 25% of the crop is planted in the summer in the Santa Maria and Oxnard districts. Summer planting is preceded by pre-plant fumigation in the late spring.

Strawberry plant propagation nurseries are located in the high elevation northern counties of California and into Oregon. There are also low elevation nurseries in the Central Valley (Holmes, 2024). The broad-spectrum soil fumigant methyl bromide—though banned by the Montreal Protocol along with other ozone depleting substances in the 1990s—is still used by strawberry nurseries (in combination with chloropicrin) as it is allowed through Quarantine and Pre-Shipment (QPS) phytosanitary regulations. The Clean Air Act and the U.S. EPA authorize methyl bromide use under qualifying QPS uses (such as official USDA Pest Quarantines) and various state/county/local programs (such as CDFA's Nematode-Free Nursery stock regulations). In contrast to nurseries, fruit production fields are not eligible for QPS and are instead primarily fumigated with 1,3-D, chloropicrin, and a few other fumigants.

Almonds

California produces 100% of the United States' commercial supply of almonds and 80% of the world's supply. Almonds were California's fourth highest-value commodity in 2022 at $3.52 billion (CDFA, 2023a). In 2022, California had 1.6 million acres of almonds (NASS, 2024a), the vast majority of which were grown in the Sacramento and San Joaquin Valleys. Almonds are generally replanted on land previously used for orchard production (Duncan et al., 2011, 2024; Niederholzer et al., 2024). Almond fields are pre-plant fumigated in either the spring or fall, and then new almond trees are generally planted in winter to early spring. 1,3-D is the primary fumigation used for almonds, although some chloropicrin is used. Almond trees start to produce a crop in year 3 with increasing yields until year 7. On average, almond trees will produce for 25–30 years.

Pre-plant outdoor soil application (seed beds, etc.) including nursery plant propagation fields

According to DPR staff scientists, the site code "Soil Application, Pre-Plant Outdoor (Seedbeds, etc.)" indicates fumigations for which a specific crop is not listed, usually in circumstances where the future crop is not known at the time of fumigation. It also applies if and when multiple crops will be grown on the site, or if it is the fumigation of nursery soil. Because this code could be used for many possible scenarios, interpretation of this fumigant use pattern is complicated and likely includes many different commodities as well as possibly greenhouse and nursery applications. Because of the important role fumigation plays in assuring clean nursery stock (and because other crops to which this title likely applies will be discussed elsewhere), this section will provide an overview of fumigant use for nursery plant propagation, specifically.

Due to the dry, temperate Mediterranean climate of California and the extensive production of high-value agricultural commodities, there is a considerable amount of plant propagation and multiplication in the state including outdoor nursery seed beds; clonal propagation; tree fruit and nut nursery fields; vine nursery fields; and strawberry and raspberry nursery fields. According to the nursery program at the California Department of Food and Agriculture (CDFA), as of 2024, there are an estimated 59,220 acres of licensed nursery stock being produced in California (B. Lanini, 9/18/24, pers. comm.). This estimate is composed mostly of "common stock," but also includes acres under the CDFA Registration and Certification (R&C) nursery programs. Common stock refers to stock outside of an R&C program for farm planting and must also be certified as commercially clean for nematodes. R&C programs exist only for specific commodities and are funded by an assessment fee to manage both planting stock genetic integrity and cleanliness. The citrus program is mandatory, but all other crop programs are voluntary. This includes avocado, deciduous fruit and nut trees, seed garlic, grapevines, pome fruit trees, and strawberry nursery stock.

The R&C programs are based on a clean stock system of required sanitation, handling, and testing methods to assure cleanliness of the planting stock. This program—combined with the CDFA Nematode Certification Program for nursery stock which is outlined in CCR sections 3055-3055.6 and CCR 3640—makes it mandatory for California nursery stock for farm planting to be commercially clean of nematodes. All R&C stock is tested and certified.

There are 786 acres of R&C strawberry nurseries; a small percentage of the R&C acres are in screen houses and the rest are in fields. In 2022, there were over 4,020 acres of strawberry nursery fields in California (Holmes, 2024), with roughly 25% included in a CDFA R&C program, and 75% was common stock. There are 6.5 acres of R&C nurseries growing deciduous fruit and nut trees. There are 221 R&C nursery acres of open field grapevines and 2,012,185 square feet of greenhouses growing grapevines (B. Lanini, CFDA, 9/18/2024, pers. comm.).

In 1995, UC Davis and the Foundation Plant Services (FPS) program took over the clean stock foundation program for sweet potatoes to address issues with diseases caused by viruses. Using **tissue culture meristem shoot tip propagation**, actively growing shoot tips are cultivated in a sterile environment to eliminate viruses. These virus-free plants are grown into large mother plants in a greenhouse, from which FPS produces about 60,000 rooted cuttings annually for growers.

Researchers have contended that the use of fumigants in nursery plant propagation is the most important fumigant use pattern to maintain due to the significant negative consequences of contamination (Holmes, 2024; Guthman, 2019). There are state, national, and international regulatory restrictions that require nursery plants and rootstock to be fumigated and/or tested and shown to be free of regulated pests prior to shipment to avoid accidental introductions of soilborne pests and pathogens on plants (CDFA, 2009; APHIS, 2024; IPPC, 2024). Plants may host pathogens internally or contain seeds whose surfaces are contaminated; this is a risk for clonally propagated nursery stock, whether it is dormant bare-root plants grown in fields or containerized nursery stock. As with strawberry nurseries mentioned above, other nurseries are also eligible for QPSs and may continue to use methyl bromide alone or in combination with other fumigants. (Please note that methyl bromide will be discussed in greater detail in the Phase II report).

1. **FINDING:** Because of the particularities of the nursery industry and the need for clean planting material and biosecure exports, the tradeoffs of fumigant use in the nursery industry are significantly different than commercial crop production.

2. **CONCLUSION:** For the time being, nursery applications should be given stronger consideration for continued use of 1,3-D and chloropicrin fumigants until there is more research and development of nursery-specific alternatives.

Sweet potatoes

In 2023, there were approximately 19,000 acres of sweet potatoes harvested in California, primarily in Merced and Stanislaus Counties (NASS, 2024b). Sweet potato fields are pre-plant fumigated with 1,3-D in late fall and early spring and transplanting of sweet potato slips/starts begins from late April to late May. Harvest usually begins in mid-July. Only marginal amounts of chloropicrin are used for sweet potatoes.

Grapes (wine, table, raisin)

Grapes were California's second highest valued commodity (after dairy) at $5.54 billion in 2022 (CDFA, 2023a). In 2023, 820,000 acres of grapes were grown in California**.** This includes 570,000 acres of wine grapes (91% of U.S. total); 120,000 acres of table grapes (100% of U.S. total); and 130,000 acres of raisin grapes (100% of U.S. total) (CDFA, 2023b). Wine grapes are grown across 49 of California's 58 counties. Raisin grapes are grown exclusively in the San Joaquin Valley, with 70% grown just in Fresno County. Most table grapes are grown in the southern Central Valley. Grapes are typically planted in early spring with a pre-plant soil fumigation applied either in the early spring or the previous fall.

Carrots

In 2023, California harvested 54,500 acres of carrots (NASS, 2024b), with approximately one-quarter of that grown in the Imperial Valley. California produces over 85% of all carrots grown in the U.S. Carrots have become an increasingly important commodity in California, rising to be California's 10th most valuable commodity in 2022 at $1.11 billion (CDFA, 2023a). Carrots are a cool season crop and are grown year-round in four main regions. In the southern San Joaquin Valley and the Cuyama Valley (Kern and Santa Barbara Counties), carrots are planted in two periods: 1) from December to March for harvest from May to July; and 2) from July to September for harvest from November to February. In the southern desert (Imperial and Riverside Counties), they are planted from August to February for harvest from December to June. In the high desert (Los Angeles County), they are planted from April to July for harvest from August to December. Finally, on the central coast

(Monterey County), they are planted from December to August for harvest from April to January (Nunez et al., 2008). Fumigation is done prior to planting, either in early spring or late summer into the fall.

Uncultivated agriculture

The site name "Uncultivated Agricultural Areas (All or Unspec)" is generally believed to indicate the fumigation of fields that were fallowed for some specific time period, or possibly drainage ditches or rights of way near or running through agricultural fields. There is not a strict definition, however, so interpretation of this use pattern is complicated.

Walnuts

California grew 400,000 acres of walnuts in 2022, accounting for 100% of the U.S. crop and 38% of the world's crop (CDFA, 2023a). Walnuts are grown throughout California's Central Valley. New walnut trees are planted in the winter to early spring with pre-plant fumigation the preceding fall. On average, walnuts will need to be replanted every 35 years. Walnut fields are primarily fumigated with 1,3-D, although some chloropicrin is used, especially if walnut trees are planted in sequence.

Raspberries

In 2023, California's growers produced 71 million pounds of raspberries from across 5,300 acres (NASS, 2024b), composing just over half (51.4%) of the total pounds of raspberries produced in the U.S. (NASS, 2024a). Raspberry fields are fumigated with a mix of chloropicrin and 1,3-D. Most pre-plant fumigation occurs between July and October. Raspberries are grown in Ventura, Santa Cruz, Santa Barbara, and Monterey Counties. They are typically planted in early winter in the Watsonville/Salinas area, and late spring into early summer in the Santa Maria and Oxnard growing areas. Growers can get two crops a year from their raspberry plantings: a primocane crop six months after planting and a floricane crop the following season ("primocane" refers to first-year shoots that grow from a plant's root system while "floricane" refers to shoots that grow in the second year). Growers then may remove the canes (i.e., the main stem or shoot that grows from raspberry's root system) and replant within two to three years.

Cherries

In 2023, there were 37,000 acres of cherries planted in California, which produced 107,500 tons of cherries at a value of $282 million (NASS, 2024b). Approximately 60% of the California cherry crop is sold in the U.S., while the other 40% is exported. After a cherry orchard is planted, it takes about six years until it produces its first major crop and then the trees can produce fruit for up to 30 years (Long and Kaiser, 2010), with the most productive years being from 10 to 25 years (Bethell, 1988).

Tangerines

Both “mandarin” and “tangerine” are often used interchangeably to refer to this citrus crop, although “tangerine” was originally used for a particular type of mandarin, the “Dancy,” which was imported from Tangiers and had an orange-red rind color. Later, in the U.S., “tangerine” was used for the whole mandarin group, but in fact “mandarin” is an older term and used globally. While citrus has been grown in California for hundreds of years, tangerines have recently increased in popularity. In 2023, California growers produced 940,000 tons of tangerines (NASS, 2024a) on 67,000 acres with a value of over $753 million (NASS, 2024b). California grows 95% of the U.S. tangerine crop, with most of it grown in the San Joaquin Valley (in Tulare, Kern, Fresno, and Madera Counties). Despite their lower acreage compared to oranges in California, tangerines receive more pre-plant fumigation, likely due to their high value and the more recent plantings. In general, citrus trees can produce for up to 50 years. For tangerines, and citrus in general, pre-plant fumigation is used to control the widespread invasive species the citrus nematode that causes citrus slow decline (UC IPM, 2024), and to a much lesser extent the more regionally concentrated sheath nematode, as well as for control of Phytophthora root rot.

Section 1.6: Emission reduction measures used with these fumigants

Emissions from fumigation can occur during the actual application, immediately after the application as the fumigant dissipates into the soil’s air spaces, and/or following the cutting and then removal of the tarp, if one is used. Yates et al. (2015) conducted a large open field experiment in 2007 near Buttonwillow, measuring volatilization and cumulative emission rates for 1,3-D and chloropicrin, and found the daily peak volatilization rates ranged from 12 to 30 μg m−2 s−1 for 1,3-D and from 0.7 to 2.6 μg m−2 s−1 for chloropicrin. Depending on the method used for quantification, total emissions of 1,3-D and chloropicrin, respectively, ranged from 16 to 35% and from 0.3 to 1.3% of the applied fumigant. Using total emissions calculated from one of several models available for comparison, the results of this study fall within the range of values reported in the literature for 1,3-D for similar application methodology (25−66%) (Chellemi et al., 2013; Gao et al., 2008). The results for chloropicrin were much different from emission values reported in the literature (i.e., 30−60%), which was attributed to the unusually high soil reactivity at the field site.

Emission reduction and mitigation measures for fumigants include proper field preparation prior to fumigation; fumigating at reduced rates; buffer zones around the fumigated area; use of specialized tarps or soil compaction and sealing methods; injection depths of the fumigant; size of the field being treated at any one time; soil temperatures during fumigant injection; and soil moisture content during injection. These practices can be combined for greater emission reductions. If impermeable tarps are used, then the time they must remain post-injection is also important for emission reduction.

Field preparation for fumigation should be done as if preparing a field to be used as a seedbed. This means the soil should be cleared of past crop material, subsoiled in more than one direction to break up any hard pan present, and then worked to a "seedbed-like texture," i.e., free from large clods and with minimum crop debris. Pathogens can survive fumigation within large pieces of debris, and debris can also provide channels through which fumigant gases can prematurely escape from the soil. Soil moisture should be conducive to an easily-worked soil, typically 50–70% of field capacity. Soil temperature at the depth to be fumigated should be greater than 50°F (10°C) for best effectiveness and adsorption.

After broadcast fumigation, the soil surface can be compacted with a roller/packer to impede the loss of fumigant emissions, allowing more time for in-soil degradation. Tarps or films can be used to contain fumigants for added effectiveness and to reduce emissions. Polyethylene films are the simplest type of film, and more recently, low-permeability films, such VIF and TIF, have been developed. TIFs have been shown to effectively control emissions and improve fumigation effectiveness in annual and perennial crops. This is because TIFs retain higher fumigant concentrations and create a more uniform distribution of fumigant in the soil profile compared to standard polyethylene tarps (Qin et al., 2011). Compared to polyethylene tarps, TIFs reduced cumulative emissions over a two-week period by more than 90% (Gao et al., 2013). TIFs increased fumigation efficiency and reduced emissions for strawberries grown on the coast and for inland perennial crops in California (Qin et al., 2011; Gao et al., 2013).

Tarps are identified on the U.S. EPA (U.S. EPA, 2024b) website as qualifying for different buffer zone credits, starting with 20% reduction in buffer zones for polyethylene tarps, 40% for VIF tarps, and 60% for TIFs. DPR offers no buffer zone reduction credits; instead, they allow only the 60%-credit TIFs to have smaller buffer zones and provide a buffer zone table with the distance reductions built in. DPR has recognized that humidity greatly affects a film's permeability, and nylon films become much more permeable to gases under high relative humidity conditions. TIFs are used for approximately 85 - 90% of tarped chloropicrin use in California.

Regulations also dictate the length of time before tarps can be perforated (i.e., punctured to release trapped gases) and then removed. Currently, TIF tarps cannot be perforated until at least nine days (216 hours) have elapsed following the application of chloropicrin. A minimum of 10 days is required for 1,3-D. In addition, the tarp cannot be removed until a minimum of 24 hours after perforation for both chloropicrin and 1,3-D. Tarps may be perforated or removed earlier "only if label-specified adverse weather conditions have compromised the integrity of the tarp" (DPR, 2017). TIF technology does not eliminate emissions and, if not performed correctly, can result in greater worker or bystander exposure at tarp cutting. Exposure at tarp cutting can be minimized if regulations are followed. The fumigant buffer zones (i.e., the area surrounding the fumigated area) are an additional method to mitigate human exposure to fumigants via increasing the distance between the chemical application and possible offsite movement that could expose field workers and bystanders to the chemicals. Buffer zones are described on the fumigant product label in compliance with federal and California regulations and are based on application rate, field size, application equipment, and application methods. Requisite buffer zones differ depending on other emission-reduction measures implemented (such as high-barrier tarps), site conditions, and geographic restrictions. For example, requisite buffer zones differ for inland compared to coastal counties. Inland counties generally require larger buffer zones due to prevailing weather conditions that increase the risks of drift exposure. The buffer zone distance is based on the broadcast-equivalent application rate for the active ingredient (i.e., pounds of active ingredient per acre).

As of January 2024, California regulations (specifically, sections 6448, 6448.2, 6624, and 6626 of CCR, Title 3) require that air concentrations of 1,3-D must not exceed a 72-hour time-weighted average of 55 ppb to mitigate acute risk for non-occupational bystanders. Above this target, DPR is required to conduct an additional evaluation of risk. DPR believes that the mitigation measures implemented to limit acute exposures to 55 ppb or less will also mitigate the 70-year chronic risk for non-occupational bystanders. Prior to the new regulations, Segawa and Luo (2022) found that the highest historical use of 1,3-D may have caused annual average air concentrations to exceed the regulatory target of 0.56 ppb. These exceedances were associated with applications for tree and grape crops that fumigated at an injection depth of 18 in (~46 cm); therefore, the 2024 regulations now require a 24-in (~61 cm) injection for these crops. DPR estimates that these new regulations will collectively keep annual average air concentrations at or below 0.35 ppb (DPR, 2024e). However, this would still exceed the **No Significant Risk Level (NSRL)** of 3.7 micrograms per day (equal to an annual average concentration of 0.04 ppb) established by the Office of Environmental Health Hazard Assessment through the Proposition 65 process (OEHHA, 2024).

While tarps increase fumigant efficiency, reduce fumigant emissions, and mitigate potential human exposure, the tarps themselves present other environmental challenges, including the greenhouse gas emissions and air pollution associated with their production, the degradation of these materials leading to the release of microplastics in the environment, and a large quantity of plastic that requires disposal. For example, plastic tarps and fumigation films generate an estimated 3,971 tons of plastic waste every year in Monterey County alone (Krone, 2020). Disposal of plastic tarps is challenging. While many plastic tarps can technically be recycled, there are few recycling facilities willing to accept these materials. The tarps themselves must be first cleaned of soil, organic matter, and pesticides before they can be recycled. Overall, these challenges mean that recycling is neither accessible nor economical for many growers, and most plastic tarps end up in landfills (Madrid et al., 2022). However, trends may be changing. Though at the time of writing, no statewide estimates of tarp recycling existed, in 2023 an estimated 900 acres of strawberry plastic tarps were recycled via a company, Flipping Iron Inc., based in Bakersfield, and in 2024 they estimate 4,000–5,000 acres of plastic will be recycled (J. Muñoz Meija, pers. comm., 2024). Until fairly recently tarps in Florida were burned, which released considerable amounts of toxic materials into the air.

In some cases, the tarps used during bed fumigation can be left in place for the duration of the growing season, taking the place of other plastic tarps that would typically be used to retain soil moisture, limit weeds, and protect fruit quality. For example, plastic tarps are used in beds for all California strawberry production regardless of fumigant use. Additional plastic tarps are only used if the field is broadcast fumigated prior to forming beds. Fumigating with TIFs on beds and using drip lines to apply the fumigant via chemigation is more expensive, but the TIF can then be used for the entire strawberry production season to protect fruit from soil contamination and control weeds. The TIF is removed a year after initial fumigation. Conversely, broadcast fumigation with TIF involves injecting the fumigants into the soil, placing 10 ft (3 m) panels that are glued together, and leaving the panels for 10 days. After this period, the tarps are cut and removed from the field. Beds are then created, and the fields are covered with plastic tarps again for the production season.

Since broadcast TIF is only deployed for nine to 10 days, it has far less potential to generate microplastics than bed films while being used in the field. Bed films are used by many conventional and organic growers and are used for bed **anaerobic soil disinfestation** (ASD). Bed films are subjected to many months of environmental exposure and possible structural degradation throughout the crop production cycle. Recent research into biodegradable plastic tarps have shown a reduction in the generation of microplastics with their use (Yu et al., 2021), however they cannot be used for fumigation. Regarding microplastics, broadcast fumigation (and broadcast ASD or **biosolarization**) with TIF, followed by in-season biodegradable row covers, appears to be the lowest potential generator of microplastics (aside from no tarp use at all). At this time, organic growers cannot use biodegradable films, but there are efforts to change this.

3. **FINDING:** Over the past 20 years, DPR, the U.S. EPA, and the fumigant company registrants have studied and then implemented a range of changes to fumigant application methods to attempt to contain the chemicals, reduce emissions, and mitigate the human health and environmental impacts of 1,3-D and chloropicrin.

4. **FINDING:** The development and use of totally impermeable films (TIFs) has increased fumigant effectiveness, reduced use rates, and mitigated emissions. However, the resultant plastic waste continues to be of concern.

5. **CONCLUSION:** TIFs significantly reduce fumigation emissions and associated acute risks to human health.

Section 1.7: Analysis of pesticide use trends for chloropicrin and 1,3-D

California instituted full pesticide use reporting in 1990. County Agricultural Commissioners (CACs) are the local regulatory lead for pesticide use enforcement which includes pesticide use reporting; all growers, pest control applicators, and agricultural chemical service providers must work with CACs to report their pesticide use. As specified by California Code of Regulations Title 3 (Food and Agriculture) section 6448, CACs must submit a Notice of Intent (NOI) 48-hours prior to a planned pesticide application of a restricted use material like pre-plant soil fumigants. Then, within 30 days of applying the pesticide, all pesticides must be reported down to a township, range, and section geospatial tag of one square mile. These data are then consolidated at DPR, checked for errors, and released via an annual pesticide use report (PUR). The PUR is made available online and supports the analysis of pesticide use trends in the state. PUR data are useful for enforcement; air and water quality environmental monitoring; endangered species protection; public health; worker health and safety; and research on pesticide use, regulations, and generating research priorities (DPR, 2017). Rules for California restricted use materials (which require an NOI) differ from those for federally restricted materials, which may not.

We obtained PUR data for chloropicrin and 1,3-D from 1990 to 2022—the most recent year from which error-checked data were available. These data included every application of any product that contained either of these two active ingredients, including the pounds of active ingredient applied, the pounds of total product applied, acres treated, the target crops (or "sites"), spatial tags of the applications, dates of application, and the fumigation methods (where available). DPR scientists provided high level summaries of 1,3-D and chloropicrin use over time and by crop. The statistical package R (R Core Team, 2024) was then used to extract and graph the data for trend analyses. Pesticide use can be evaluated in terms of pounds of pesticide active ingredient, pounds of product applied, acres treated, the number of applications, or some combination of these variables. Because fumigants are used at relatively high rates compared to other pesticides to facilitate their movement through soil, fumigants have constituted a significant amount of the total pesticides used by pound in California as can be seen in the most recent annual pesticide use report, where 1,3-D and chloropicrin are in the top five active ingredients applied by pounds in 2022 (NASS, 2024a).

1,3-D and chloropicrin use (in terms of pounds of active ingredient applied) has been increasing in California since 1990 (***Figure 1.8***; ***Figure 1.9***). During this timeframe crop acreage has increased as well. For example, strawberry acreage almost doubled from 22,000 acres in 1990 to 41,570 acres in 2022; almond acreage increased threefold from 431,000 acres in 1990 to 1.3 million acres in 2022; whereas grape acreage (wine, table, and raisin) increased less dramatically, from 700,000 acres in 1990 to 888,000 acres in 2022. Additionally, there have been shifts in production to higher-value crops over this timeframe.

The broad-spectrum fumigant methyl bromide was discovered in the 1950s and found to be highly effective at controlling a wide range of pests. It proved especially useful for controlling strawberry pests and pathogens when combined with chloropicrin, and the strawberry industry built its production system around pre-plant fumigation to control weeds, nematodes, and the soilborne disease Verticillium wilt (Holmes et al., 2020; Guthman, 2019). However, by the early 1990s methyl bromide was found to deplete the Earth's ozone layer. As per the international agreement, the Montreal Protocol of ozone-depleting substances, federal and state regulators in the U.S. instituted a gradual phase out of anthropogenic methyl bromide (***Figure 1.8***).

The Montreal Protocol allows for **critical use exemptions (CUE)** for agricultural products for which there are no technically or economically available alternatives. The U.S. EPA applied for a CUE for continued methyl bromide use, and between 2005 and 2016, CUEs were granted by the Parties of the Montreal Protocol for qualifying commodities. However, these CUEs expired for all methyl bromide used for fruit production in December 2016 (***Figure 1.8***). Growers of strawberry and other commodities switched from methyl bromide to a combination of chloropicrin and 1,3-D, and the use of these two fumigants increased over the course of the methyl bromide phase out. 1,3-D use peaked in 2016, whereafter its use began to decline (***Figure 1.9***).

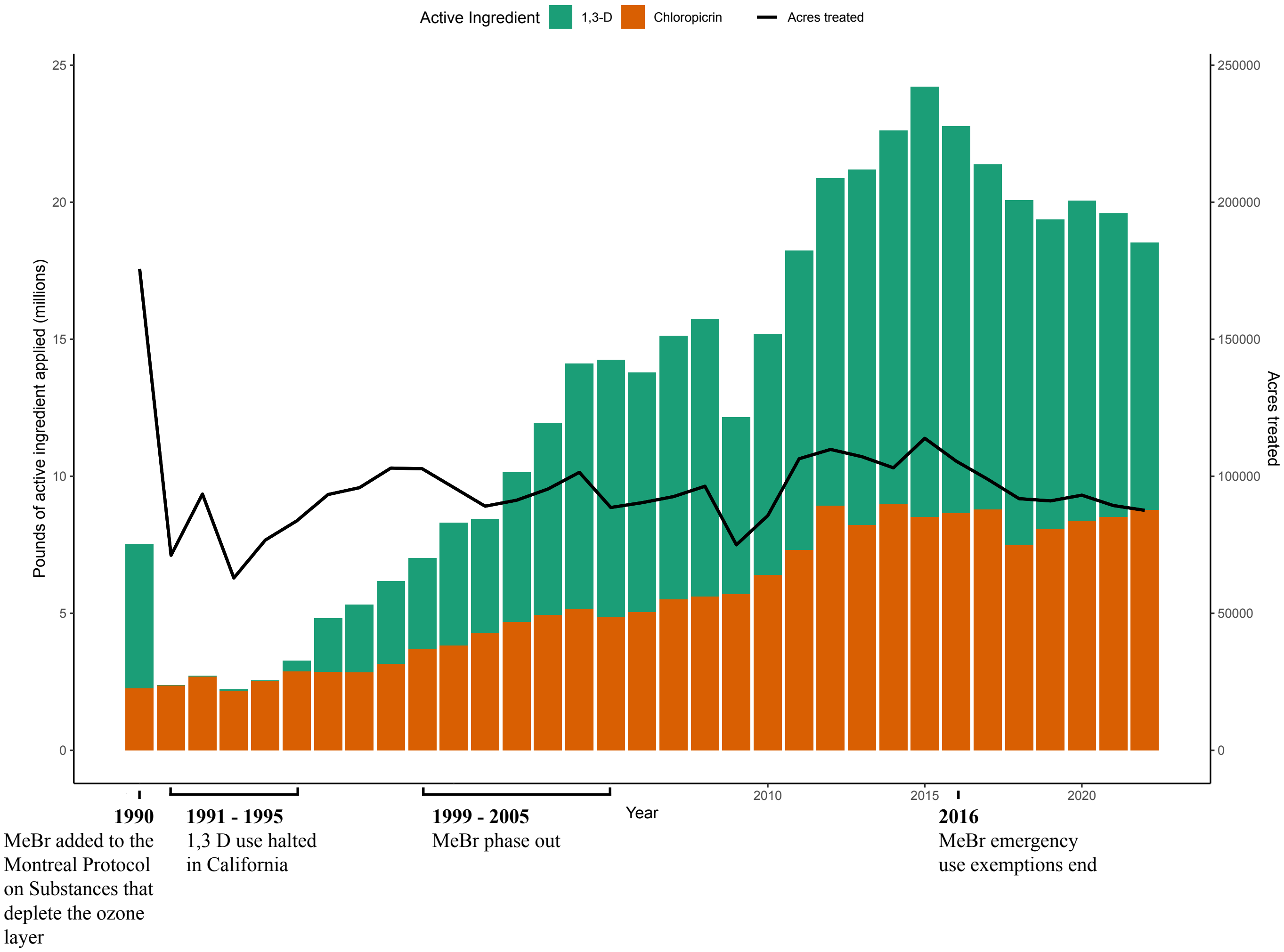

Figure 1.8. Total acres treated and pounds of active ingredient applied of chloropicrin and 1, 3-D in California from 1990 to 2022. Important years when regulatory changes occurred are noted and may account for some of the trends (Montreal Protocol and 1,3-D restrictions due to air monitoring results). Data were derived from the DPR PUR database provided in June 2024.

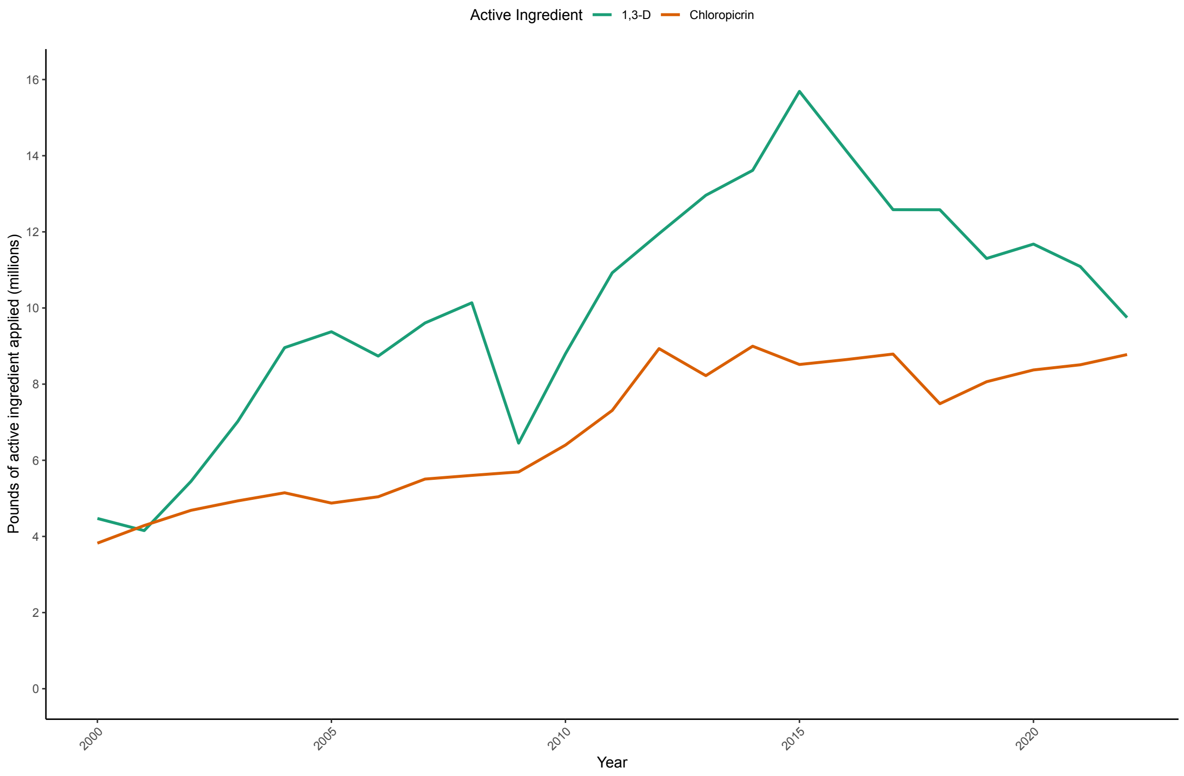

Figure 1.9. Pounds of active ingredient applied in California from 2000 to 2022.

1,3-D use has been more variable than that of chloropicrin (***Figure 1.8***; ***Figure 1.9***). For example, during the early 1990s, DPR found 1,3-D air concentrations exceeded federal and California safety thresholds. Its use was canceled until 1995 when a suitable set of mitigation practices were developed and put into regulation, including lower application rates; township caps followed soon thereafter (***Figure 1.9***). According to the main California distributor of 1,3-D, some recent reductions in its use are related, in part, to lack of product availability (Stanghellini, 7/23/2024, pers. comm.). 1,3-D is a byproduct of epoxy production, and when there are slowdowns in the housing market, there is less epoxy demand, and thus less 1,3-D available. For example, the 2007 housing market crash precipitated a downturn in construction and an associated decrease in 1,3-D availability between 2008–2012 (see ***Figure 1.8*** and ***Figure 1.9***) (Fields and Hodkinson, 2017). 1,3-D availability then stabilized and use increased, likely due to increasing strawberry and almond acres (described in ***Section 1.5***) as well as the phaseout of methyl bromide. More recently, 1,3-D again has limited availability, and its use has been decreasing through 2022 (Stanghellini, 7/23/2024, pers. comm.) (***Figure 1.8***; ***Figure 1.9***). As of January 2024, DPR regulations have increased the distances of mandatory setbacks to occupied structures for 1,3-D to 100 ft (~30 m) or more depending on season, location, tarp, and crop (DPR, 2024d). This may lead to future reductions in 1,3-D use in the state, particularly at the agricultural urban interface where setback requirements of more than 100 ft (~30 m) from occupied structures may reduce available land that can be fumigated.

Strawberry crops over the past 12 years have received the most pounds of these two fumigants and the amount has increased during this timeframe as has the number of acres planted to strawberry, going from 22,000 acres in 1990 to 41,570 acres in 2022 (***Figure 1.10***). Researchers have suggested that the replacement of broadcast methyl bromide applications with chemigation applications of 1,3-D and chloropicrin may have led to an increase in two new diseases of strawberry—Fusarium wilt and *Macrophomina* charcoal rot—which were first detected in California from 2003 to 2005 and 2006 to 2009, respectively (Koike, 2008; Koike et al., 2009). However, more recent research suggests that cryptic (i.e., asymptomatic) infections of strawberry plants coming from nurseries may have also been responsible for the introduction and increase of *Macrophomina* charcoal rot (Pennerman et al., 2024). Recent California Strawberry Commission acreage data has also suggested that yields per acre have decreased for the past four years. However, demand for strawberry has remained high, and so a greater acreage of strawberry has been planted (California Strawberry Commission, 2024). This trend of increasing strawberry acreage is reflected in the increase in 1,3-D and chloropicrin use from 2020 (***Figure 1.10***).

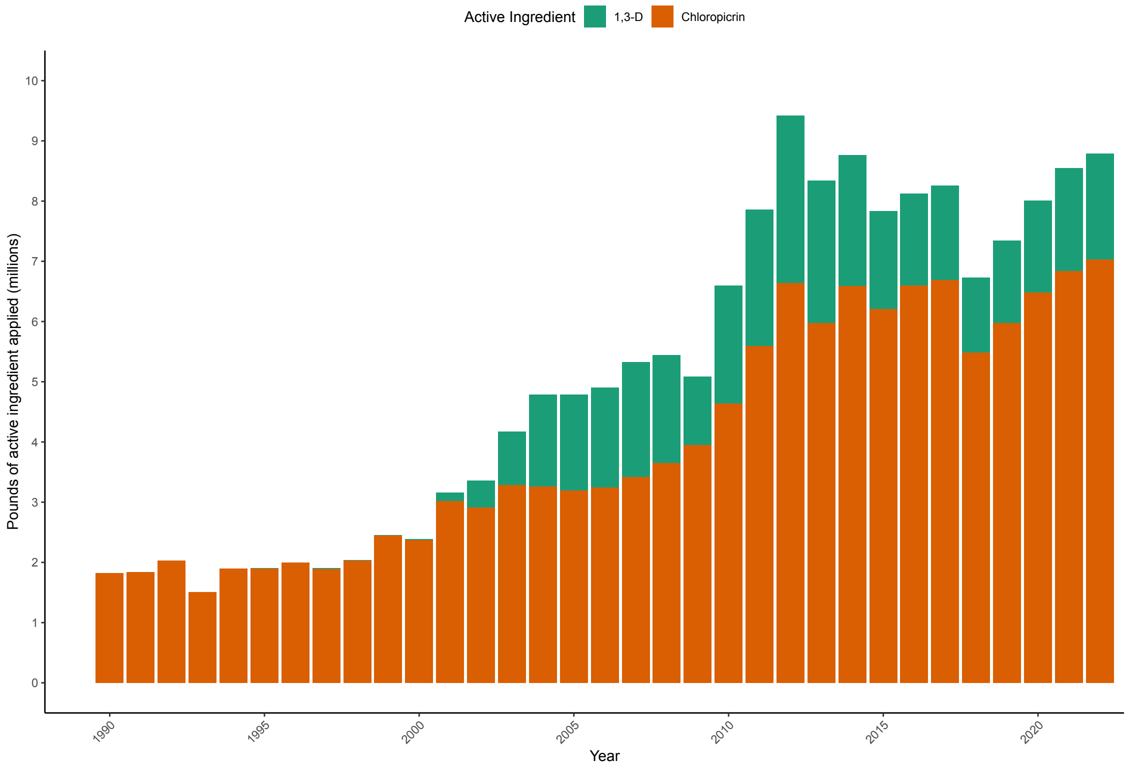

Figure 1.10. Pounds of 1,3-D and chloropicrin applied to strawberry from 1990 to 2022.

Almond orchards rank second only to strawberries in the combined use of 1,3-D and chloropicrin in California. Up to one-third of California's almond and stone fruit acreage is infested with potentially debilitating plant parasitic nematodes, and an even larger portion is affected by Prunus replant disease (PRD)—a poorly understood soil borne disease complex that suppresses early growth and reduces cumulative yield in replanted almond and peach orchards (Browne et al., 2013). Almond orchards are primarily fumigated with 1,3-D to target root-knot, root lesion, and ring nematodes. Additionally, dagger nematode—which can transmit the Tomato ringspot virus and causes yellow bud mosaic disease on almond trees—is also a concern. To a lesser extent, fumigation is also used against Prunus replant disease. Total use of 1,3-D and chloropicrin in almond orchards increased significantly (133%) between 2014 and 2015, likely due to the shift from methyl bromide to 1,3-D. However, this increase can also be explained, in part, by an increase in almond plantings (and hence non-bearing acres), which grew from 170,000 to 240,000 acres over the same time period. More recently, the use of these two fumigants has declined in 2021 and 2022, which is also when non-bearing acres experienced a 15% decline (***Figure 1.11***) (NASS, 2024a). This recent drop may be due to both the previously noted limited supply of 1,3-D, as well as recent drought and associated reductions in new plantings of almond acres. Almond acreage has increased steadily from 510,000 acres in 2000 to 1.3 million acres in 2022, a 2.5-fold increase, but recent non-bearing acres have decreased as noted.

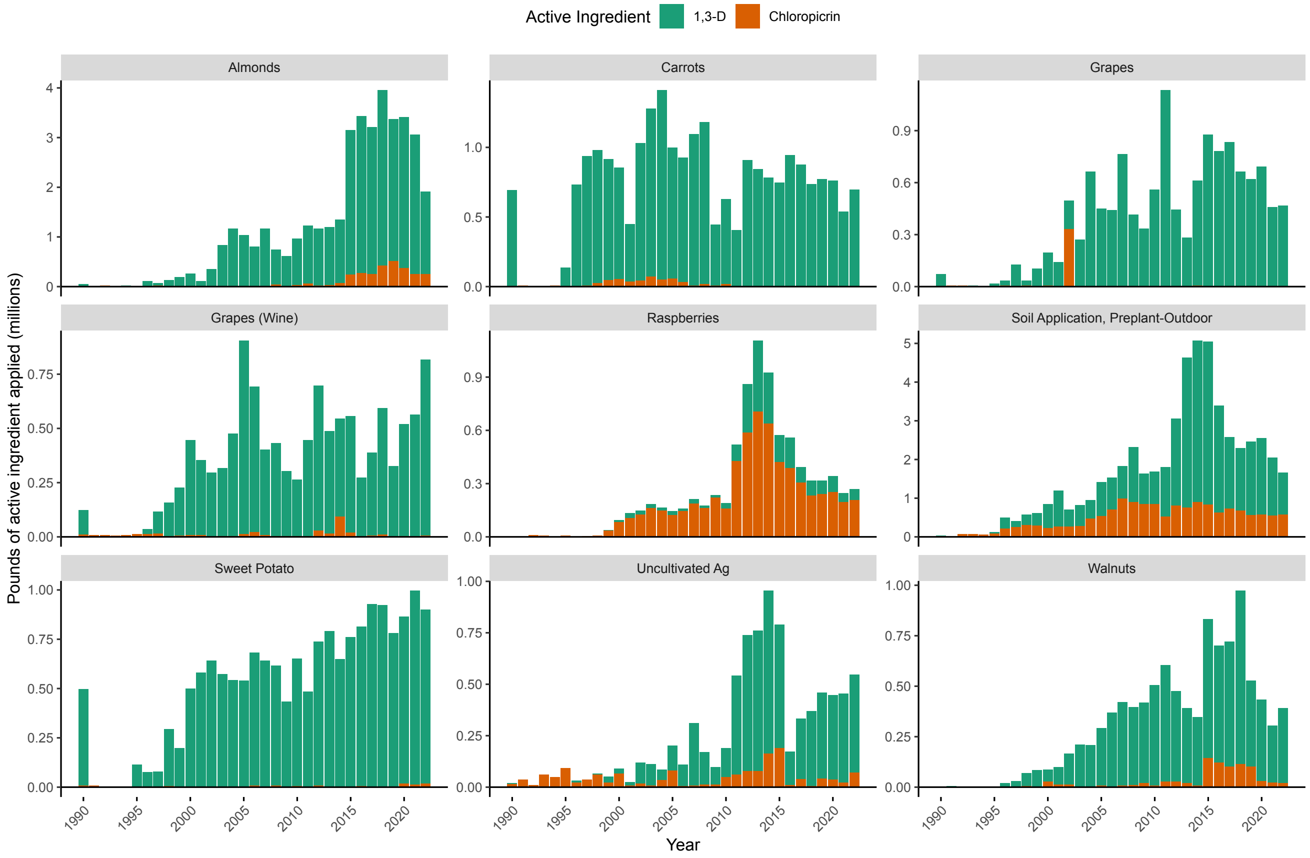

Figure 1.11. Pounds of 1,3-D and chloropicrin applied to the next nine crops receiving the most pounds of these two active ingredients from 1990 to 2022.

A pesticide use category called "Soil application, pre-plant outdoor (seedbeds, etc.)" accounts for the third highest pounds applied and follows the same trend as almonds with a peak of 1,3-D use in 2015 and then a reduction. This pesticide use category includes numerous different crops to be planted post-treatment, and it is a harder use pattern to interpret because it depends on how the CAC, growers, and applicators and consultants interpret that site category (NASS, 2024a).

Sweet potato land is the fourth largest recipient of these fumigants, followed by wine grapes, carrots, and other grapes (table, raisin) (***Figure 1.11***). Grape acreage (wine, table, and raisin) increased less dramatically than strawberry or almonds, from 700,000 acres in 1990 to 888,000 acres in 2022. Walnut fumigation trends show a pronounced increase following the transition from methyl bromide to 1,3-D through 2015. Recent declines in walnut fumigation can be explained by poor walnut prices over the past five years leading to reduced planting: non-bearing acres declined 22% from 2019 to 2021 (70,000 acres to 55,000 acres) and grower return declined during that same time frame from $1,890 to $1,200 per ton, a reduction of 37% (NASS, 2024a).

Additionally, there have been shifts in production from lower value crops (like cotton and wheat) to higher value crops, especially tree crops like almonds and pistachios (NASS, 2024a). These shifts are the result of many different factors including changes in prices, market demand, and water availability.

Within California, geographical pesticide use patterns for these two fumigants are apparent. For example, strawberry growers are primarily located in coastal counties like Monterey, Santa Barbara, Ventura, Santa Cruz (***Figure 1.12***), and in those counties, more 1,3-D and chloropicrin was applied for strawberries compared to any other crop. And, as is typical for the fumigation of strawberry fields, mixtures were composed of more chloropicrin than 1,3-D (***Figure 1.12***). By contrast, growers in the Central Valley counties of Fresno, Kern, Merced, Stanislaus, and Tulare use much more 1,3-D than chloropicrin. Coastal county strawberry growers are targeting soilborne pathogens and weeds (and nematodes to a much lesser degree). Meanwhile, nematodes thrive in the warm sandy soils in the interior valleys of California, impacting plant health and productivity for grapes, tree nuts, tree fruits, and vegetable crops.

Figure 1.12. Total pounds of chloropicrin and 1,3-D applied from 2000 to 2022 across the nine California counties with the highest cumulative application of these two fumigants.

Seasonal fumigation patterns are driven by a variety of factors including 1) the environmental parameters known to improve fumigation effectiveness for target pests (e.g., soil temperature, air temperature, and soil moisture); 2) crop growth requirements (e.g., season length, optimal temperature, soil moisture); and 3) the need to minimize potential offsite drift and exposure for workers and bystanders.

Due to California's Mediterranean climate, the warm, dry months of August, September, and October see the heaviest fumigant use (prior to the onset of the rainy winter season) (***Figure 1.13***). Fumigant applications begin again once the rain has stopped, often as early as February. This fumigation period continues over several months before planting must take place, a timeframe that is dictated by the minimum growing period required for each specific crop. The length of the growing season varies by region, so there is an interaction between county, crop, and fumigation timing.

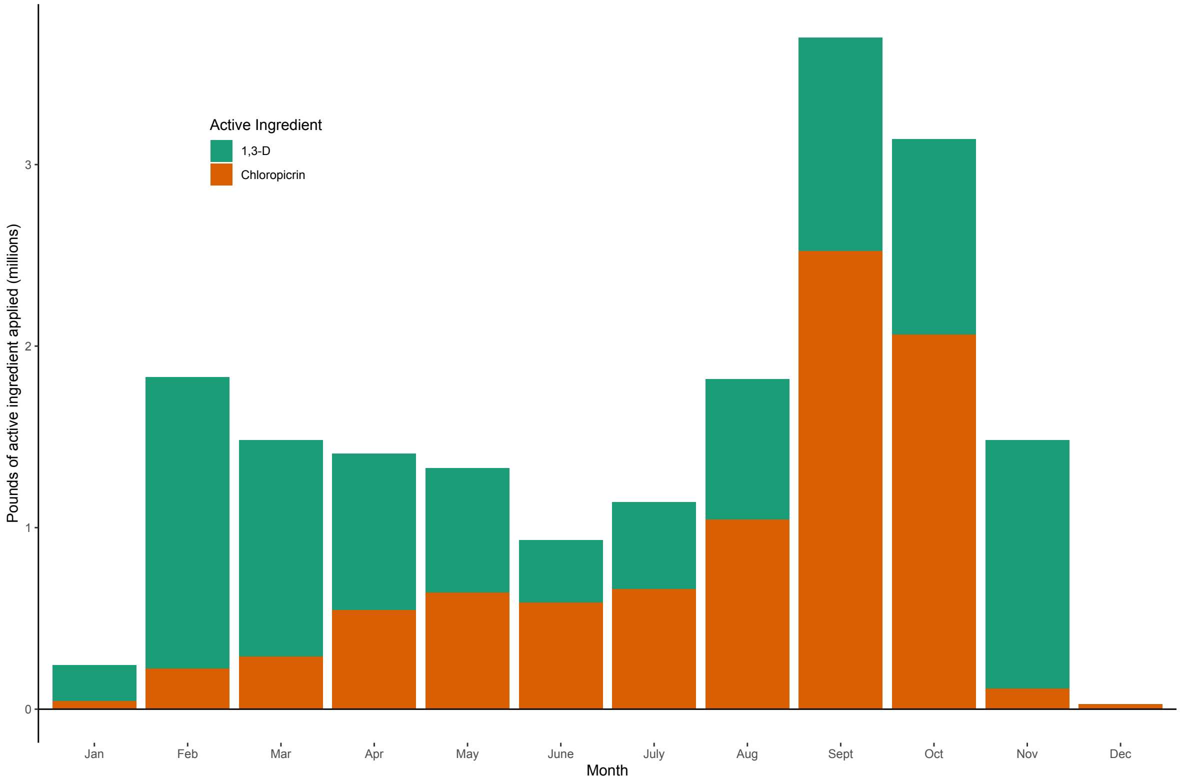

Figure 1.13. Seasonal use patterns for 2022, represented by the total pounds of chloropicrin and 1,3-D applied each month.

Most strawberry pre-plant fumigation applications occur in the late summer into early fall prior to fall planting, although some growers apply pre-plant fumigant earlier in the year prior to summer planting (***Figure 1.14***). Similarly, land destined for almonds is pre-plant fumigated in February and November (***Figure 1.15***). The category called "Soil application, pre-plant outdoor (seedbeds, etc.)" likely includes numerous different crops to be planted post-treatment. It is therefore a harder use pattern to interpret, and will depend on how the CAC, grower, and consultant community interpret that site category. Sweet potato land has a similar fall and early spring annual application, as is the case for carrots, wine grapes and other grapes (table, raisin) (***Figure 1.15***).

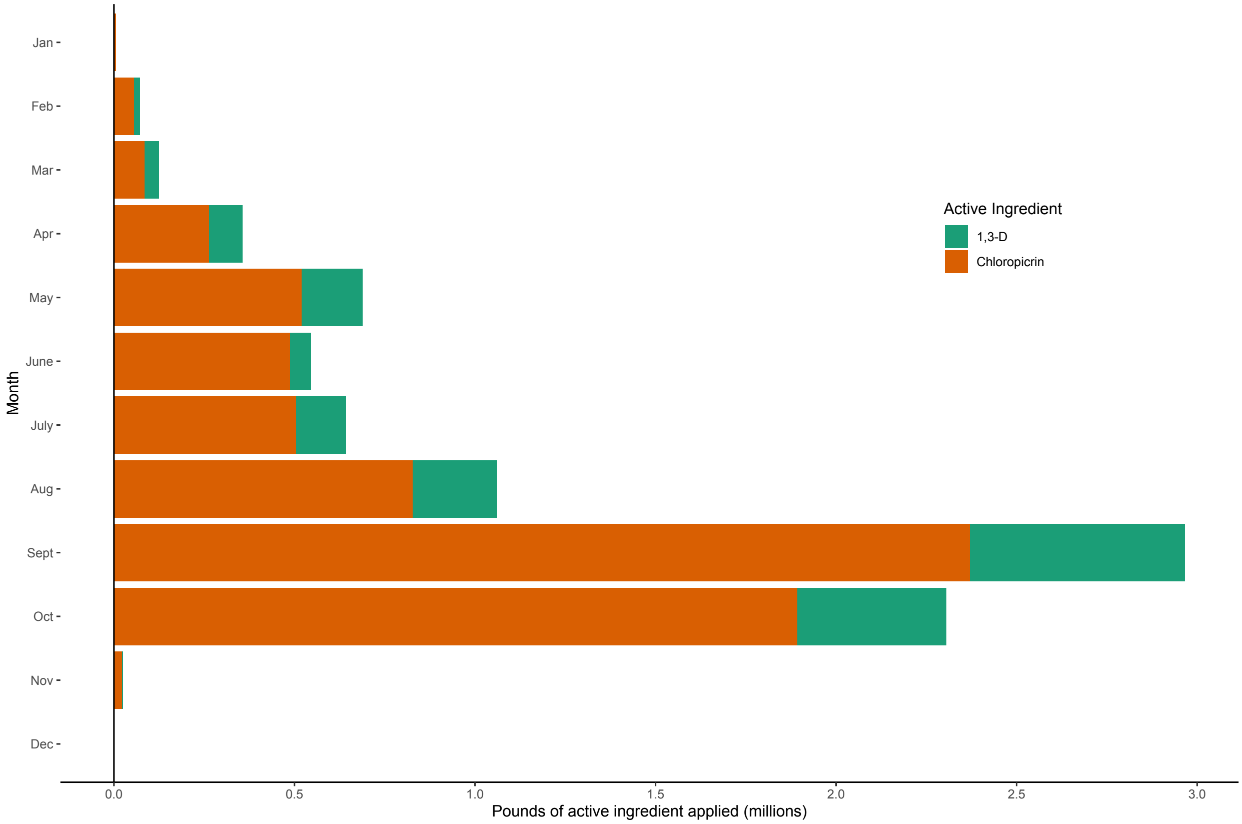

Figure 1.14. Pounds of 1,3-D and chloropicrin applied each month for strawberries in 2022.

Figure 1.15. Seasonal use patterns in 2022 for the nine crops with the highest 1,3-D and chloropicrin use (excluding strawberries), shown as monthly totals of active ingredient applied.

As of 2024, there are 12 different application methods allowed for chloropicrin and 24 different application methods for 1,3-D. Almost all pre-plant soil fumigation applications of strawberry fields included TIF tarps in 2022. Approximately 61% of 1,3-D and chloropicrin used for the pre-plant treatment of strawberries is applied as a chemigation treatment through drip lines, and 39% of the two fumigants are applied as a broadcast, tarped, shanked-in fumigation (***Figure 1.16***). Deep broadcast and strip applications of fumigants work better to target nematodes and soilborne pathogens affecting deeper rooted perennial tree and vine crops (like almonds, grapes, and walnuts). For sweet potatoes, carrots, and other annual, shallow-rooted vegetable crops, the fumigations are not tarped and are instead done through shallow broadcast or bed applications (***Figure 1.17***). The differences in application methods used by crop is related to the different costs of the treatments, the prices growers receive for their crops, the amount of time a crop is being grown in a particular field (perennial vs. annuals) and thus the importance and value of the investment in using a pre-plant soil treatment. Perennial orchards may grow for 20–30 years, whereas annual vegetable crops are planted and harvested all in one year. The choice in fumigant application method is also related to the depth of roots of a particular crop, and the related issue of where pathogens and pests are likely to be in the soil profile, the type and the depth of cultivation and plant residue which can harbor pests, and differences in methods of field preparation by crop (UC IPM; Freeman, 2019).

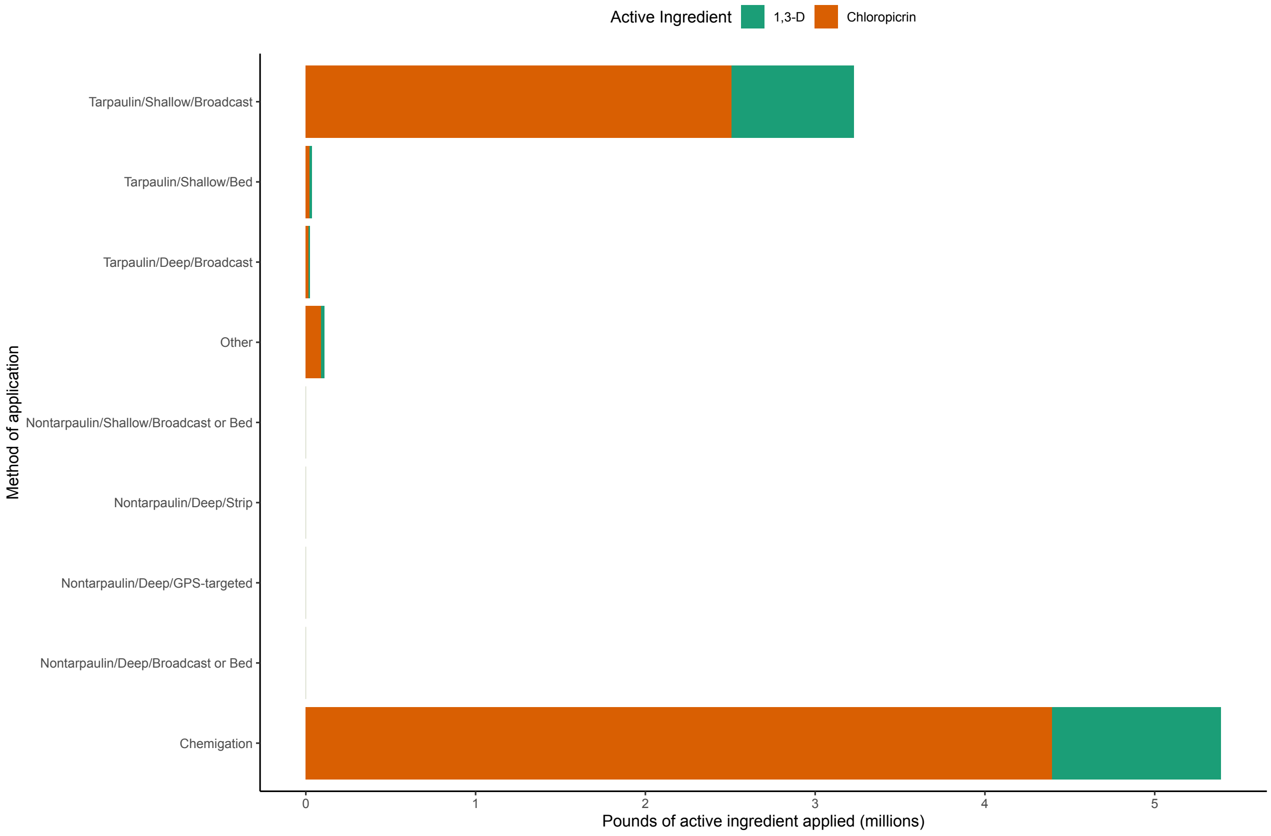

Figure 1.16. Chloropicrin and 1,3-D application methods used pre-plant for strawberry in 2022.

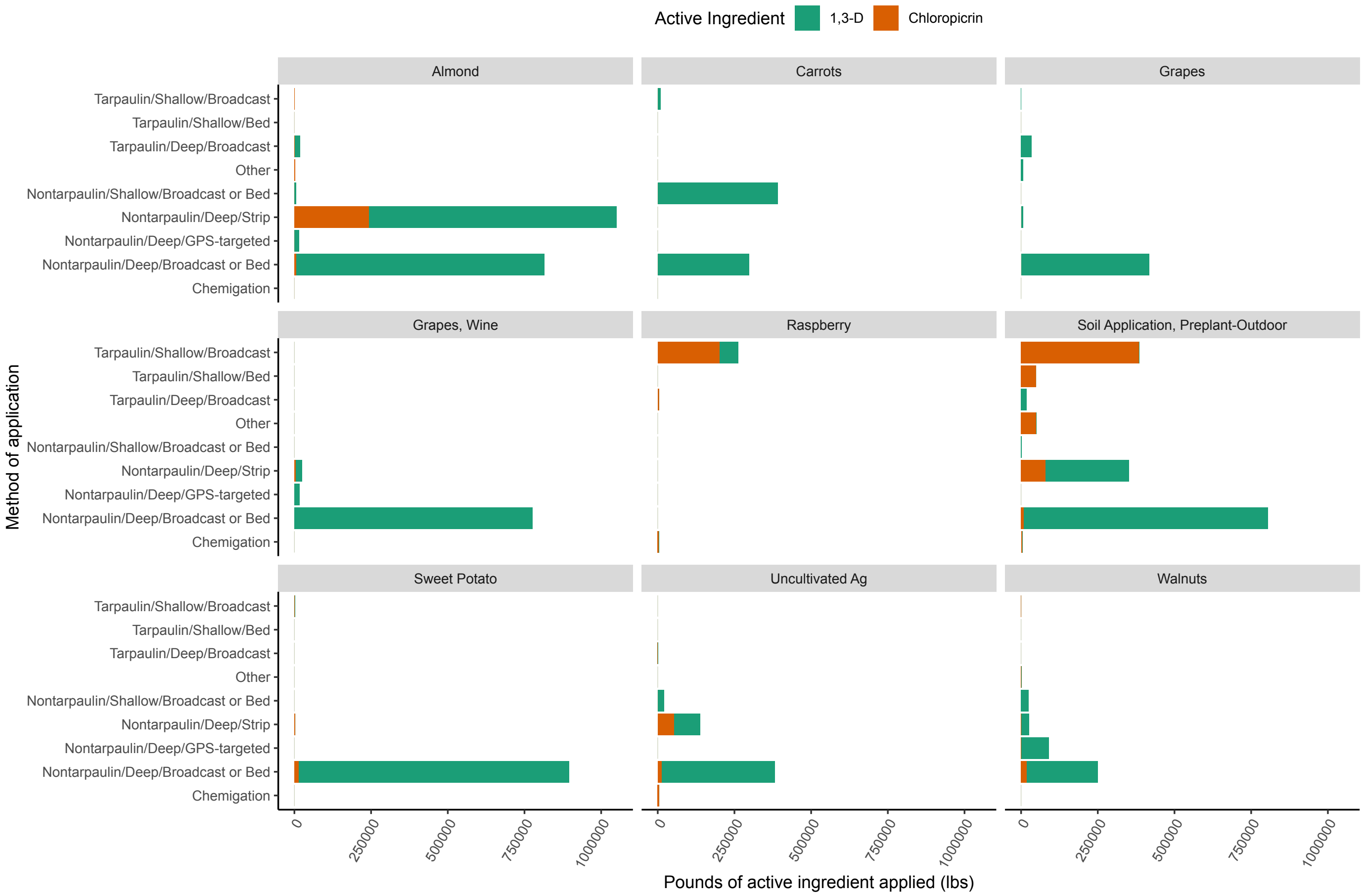

Figure 1.17. Application methods for chloropicrin and 1,3-D used pre-plant in 2022 for the nine crops with the highest use of these fumigants (excluding strawberries), shown as total pounds of active ingredient applied.

> 6. **FINDING:** To date, California's key specialty crops, especially strawberries, have significantly relied on pre-plant fumigants to control soil-borne pathogens, nematodes, weeds, and arthropod pests.

> 7. **FINDING:** The use of chloropicrin and 1,3-D has increased since 1990. The increasing use of chloropicrin is due to expanded crop acreage, the phaseout of methyl bromide, and the discovery of new strawberry pathogens in California. 1,3-D use has varied more over time due to its limited supply as a by-product of the housing construction market, increases in almond acreage, and regulatory changes.

> 8. **CONCLUSION:** Fumigant use is dynamic and is influenced by regulations, crops, geography, pathogens, and seasons, and growers need tools to manage these dynamics.

Section 1.8: Human health, environmental, and ecological concerns, and their basis

Human health concerns: Overview

The use and release of toxicants into the environment as part of farming carries risk and requires that potential hazards associated with these toxicants be identified by the regulatory community via the analysis of chemical, biological, and physical data. Their use also requires research-based best management practices to inform how these chemicals could be applied more safely to protect human health and most efficiently to protect crop production. And, finally, it requires regulatory programs to try to ensure their safe use to protect human health and the environment. The regulatory community uses risk assessment tools in their determination of risk and in their attempt to guide the safe use of pesticides like fumigants. These risk assessment tools combine hazard information, direct environmental monitoring, simulation modeling, and studies of human exposure and actual pesticide use patterns reported in California to determine and predict potential risk of human exposure. Regulators can also use this information to attempt to minimize or mitigate potential adverse consequences. Some farming systems do not use as many pesticides as others. Avoidance or minimization of pesticide use, as is done with organic farming systems, is one way to minimize risks related to fumigant use; however, growers that do so risk lower yields and decreased revenue if not offset by a price premium.

Human health risk assessments involve generating data on the toxicity of active ingredients with dermal, oral, and inhalation studies using mice, rats, rabbits, and other model organisms in controlled laboratory studies. These data can then be combined with information on exposure pathways and use patterns to predict how human health might be affected by the use of these chemicals. Data from accidental exposures and resulting health outcomes can also be used for health risk assessments. Ultimately, these data will be combined with statistical models that predict the potential human health consequences of various scenarios given explicit sets of assumptions. The National Institute of Occupational Health and Safety leverages these various datasets to develop recommended exposure limits. As discussed in ***Chapter 2***, these metrics can be compared to those from other fumigant and non-fumigant pesticides to gauge relative toxicity.

Regulatory risk assessments are based on using acute and chronic toxicity data generated with animals, as well as accidents resulting in human exposure and any related documented health outcomes, and then these hazards are combined with exposure as assessed through direct monitoring of workers and respirator air sampling for occupational exposure and/or air monitoring stations near fumigant applications for bystander exposure, and the use of complex risk models and fumigant use data to model risk and ultimately make decisions about regulations and how best to mitigate this risk.

The high volatility of fumigants allows for their dispersal and effectiveness in soil, but may also lead to high atmospheric emissions. Because of their volatility, nonoccupational bystander exposure to fumigants occurs through inhalation because of off-site movement from a treated field into ambient air. Inhalation exposure is a function of the fumigant emissions from the treated soil to air, the distance between the emissions and non-occupational bystanders, and the weather conditions when the emissions occur.

Determination of toxicological endpoints is based on animal toxicity testing with oral, dermal, and gavage exposures at a range of doses and observations on how the animals respond. Mice, rats and rabbits are the most commonly used animals for toxicology studies. Then various characterizations of the chemical toxicity are taken such as Lethal Dose where 50% of the study organism is killed (LD50), or NOEL or No Observable Effect Levels are determined and then various assumptions are used to increase the safety margin by adding multiples of 10- or 100-fold. Finally, chronic toxicity exposure assumes that workers are exposed five days a week, eight hours a day, for 40 years while nonoccupational bystanders are assumed to be exposed seven days a week, 24 hours a day, over a 70-year lifetime. Toxicity effects derived from these animal studies must be considered in light of the dose, duration of exposure, and route of exposure to be meaningful for determining exposure impacts to humans. We have included this information when it was available, but it was sometimes lacking.

The collected data, modeling, and assumptions made are meant to allow the use of these fumigants while also protecting both human health and the environment. However, certain subpopulations are typically more exposed to these risks than others, for example farm workers and those living in rural agricultural communities (Harrison, 2011). While regulatory standards assume some level of acceptable exposure, these risks fall disproportionately on workers and nearby communities as compared to urban consumers who benefit from the increased supply of healthy fresh produce produced using pre-plant soil fumigants.

Human health concerns: 1,3-D

Acute toxicity

Animal toxicology studies have shown that 1,3-D can cause acute effects such as lung and liver hemorrhaging and neurotoxic effects. 1,3-D has also been associated with acute inhalation exposure in nine firemen following a tank truck spill and cleanup in California in 1973 that caused mucous membrane irritation, chest pain, and breathing difficulties (Markovitz and Crosby, 1984). In rats acutely exposed to 1,3-D by inhalation, effects on the lung have included **emphysema** and **edema**. Neurotoxic effects—such as hunched posture, lethargy, and decreased respiratory rate—have also been seen in orally exposed rats. These and other acute animal tests in rats, mice, and rabbits have demonstrated 1,3-D to have moderate acute toxicity from inhalation, moderate to high acute toxicity from oral exposure, and high acute toxicity from dermal exposure (ATSDR, 1992; U.S. DHHS, 1993). 1,3-D vapors are reported to be readily absorbed in the body; it is then rapidly excreted in the urine so that the major metabolic pathway for 1,3-D leads to its detoxification and excretion in rats and humans within a fairly short timeframe after acute exposure (Waechter and Kastl, 1988; Schneider et al., 1998).

Threshold limit values (TLVs) are guidelines for exposure developed by the American Conference of Governmental Industrial Hygienists (ACGIH) and are a key component in determining the **permissible exposure limits (PELs)** for chemicals such as 1,3-D. PELs are enforceable legal standards of exposure established by the federal Occupational Safety and Health Administration (OSHA). PELs also include the chemical's toxicity and particle size. A PEL is usually given as a time-weighted average (TWA), although some are short-term exposure limits (STEL) or ceiling limits. A TWA is the average exposure over a specified period, usually eight hours. This means that for limited periods a worker may be exposed to concentration "excursions" (i.e., brief temporary exposures) higher than the PEL, as long as the TWA is not exceeded, and any applicable excursion limit is not exceeded. The TLV-TWA for 1,3-D is 1 ppm, whereas for comparison the TLV-TWA for formaldehyde it is 0.1 ppm (100 ppb).

Chronic toxicity

1,3-D is listed in California as a toxic air contaminant (TAC) (called hazardous air pollutants or air toxics by the U.S. EPA). These airborne chemicals are thought to cause or are suspected of causing cancer, birth defects, and/or other serious harms that could result in increased mortality, serious illness, or which may otherwise pose a present or potential hazard to human health. The federal Clean Air Act establishes regulations to limit the emissions of designated hazardous air pollutants.

In chronic studies using animals, 1,3-D produces histopathological effects (i.e., tissue abnormalities observable under a microscope such as lesions or changes to tissue structure or cellular composition) at the "portal of entry" meaning the tissue where the toxicant entered the body, or in organs involved in its excretion or elimination. Specifically, inhalation exposure produces histopathological changes in the nasal tissues of mice and rats and urinary bladder hyperplasia (increased cell growth) in mice (Lomax et al., 1989). Mild hyperplasia of the forestomach was observed in rats that ingested 1,3-D with their feed (Stott et al., 1995). No toxicologically significant effects were noted in reproductive or developmental toxicity studies with rats and rabbits (Breslin et al., 1989; Hanley et al., 1988).

Evidence for the carcinogenic potential of 1,3-D in humans is mixed and made more difficult due to a lack of clarity around the mode of action of the chemical. California designates 1,3-D as a known carcinogen under Proposition 65. The Department of Health and Human Services (DHHS) has determined that 1,3-D may reasonably be anticipated to be a carcinogen (NTP, 2021). The International Agency for Research on Cancer (IARC) has determined that 1,3-D is "possibly carcinogenic" to humans. The U.S. EPA—which recently completed a cancer assessment in 2020—reclassified 1,3-D as "suggestive evidence of carcinogenicity" (U.S. EPA, 2020). Historically, 1,3-D was classified in the U.S. as "likely to be carcinogenic to humans" via oral and inhalation exposure routes based upon the results of rodent cancer bioassays conducted in the 1980s. The new, downgraded determination was derived from a cancer weight of evidence (WOE) analysis based on updated **toxicokinetics**, genotoxicity, and carcinogenicity data for 1,3-D that was peer reviewed by a panel of experts. Contemporary studies led the authors of the WOE analysis to conclude that the currently manufactured form of 1,3-D—without the original stabilizer epichlorohydrin—is not mutagenic and not carcinogenic below certain doses, pointing to a threshold-based approach for cancer risk assessment (Hays et al., 2020).

The decision by the U.S. EPA to downgrade 1,3-D from "likely to be carcinogenic" to "suggestive evidence of carcinogenicity" has been critiqued by both DPR (CalEPA, 2020a,b) and OEHHA (OEHHA, 2021) and criticized by numerous nonprofit organizations who argue that the review was incomplete, biased, and that the findings contradict those of other organizations and agencies that designate 1,3-D as carcinogenetic. These complaints led to an inquiry by the Office of Inspector General, which found that the cancer assessment process lacked transparency and that the U.S. EPA did not follow standard operating procedures nor adhere to guidelines for independent peer review (Davidson et al., 2022).

An examination of 1,3-D exposure in southern California from 2005 to 2011 identified a significant relationship between 1,3-D use and asthma-related emergency room visits such that a 0.01 ppb increase in 1,3-D exposure was associated with a 13.5% increase in emergency room visits (Gharibi et al., 2020). A national study of 1,3-D use and pancreatic cancer mortality rates found no significant relationship when all data were considered (McGwin Jr. and Griffin, 2022). However, for states with the longest history of reported 1,3-D use (at least 20 years), the greatest use rates for 1,3-D (average of ≥8 kg (17.63 pounds) 1,3-D applied per square mile) were significantly correlated with pancreatic cancer mortality; specifically, there was an 11% increase in mortality compared to states with the lowest reported 1,3-D use (using a five-year lagged model) (McGwin Jr. and Griffin, 2022).

In 2015, DPR's comprehensive risk characterization document identified potential acute and cancer human health risks from 1,3-D inhalation exposure (Marks, 2016). In 2016, DPR determined that its management strategy for mitigating cancer risks to non-occupational bystanders needed to be updated (Marks, 2016). As a result, DPR updated the maximum annual use limit in each township, eliminated 1,3-D applications for December, and implemented other use restrictions through restricted material permit conditions and a memorandum of understanding with the registrant to control total emissions of 1,3-D to address cancer risk (exposure over 70 years) to non-occupational bystanders. However, more recent air monitoring and data analyses also indicated that additional mitigation measures were needed to address short term acute exposures to non-occupational bystanders, including infants and children, from 1,3-D use (Henderson, 2021).

DPR's 2016 (cancer) and 2021 (acute) risk management directives specify regulatory target concentrations of less than 0.56 ppb for a 70-year lifetime average to mitigate cancer risk to non-occupational bystanders (Marks, 2016), and no more than a 72-hour average of 55 ppb to mitigate acute risk to nonoccupational bystanders (Henderson, 2021). OEHHA has identified a No Significant Risk Level (NSRL) of 3.7 µg per day (equal to an annual average concentration of 0.04 ppb) (OEHHA, 2024).

DPR's environmental monitoring branch, as well as the California Air Resources Board (CARB), conduct a range of air monitoring studies each year and have for many years. DPR conducts two types of monitoring: long-term ambient monitoring in selected communities (to measure concentrations over several weeks or months) and application-site monitoring in the immediate vicinity of specific pesticide applications (to measure concentrations over several hours or days).

Ambient monitoring typically involves one 24-hour ambient air sample collected each week on a randomly assigned day of the week at locations under study between 7 a.m. to 3 p.m. DPR's air monitoring network currently consists of stations in Oxnard (Ventura County), Shafter (Kern County), Santa Maria (Santa Barbara County), and Watsonville (Santa Cruz County, bordering Monterey County). A collocated sample is also collected and used as a quality control monitoring station. All samples are collected using the same sampling procedures and analyzed by the CDFA's Center for Analytical Chemistry (CDFA CAC) Laboratory. In May 2022, the CDFA CAC revised their laboratory methods, setting new method detection limits (MDL) for each 1,3-D isomer and establishing "Trace" as a reportable result (DPR, 2024f).

Average concentrations of 1,3-D are then calculated from this 24-hour air monitoring for acute, sub-chronic, chronic, and lifetime periods. DPR uses a 24 hour sample to compare to the established 72-hour acute exposure level. A rolling average of 90 days (13 consecutive weeks) is used to calculate a sub-chronic exposure. The one-year average concentration is used to determine the chronic exposure. The lifetime exposure of 1,3-D has a regulatory target of 0.56 ppb. This value is derived from toxicology studies and is based on a set of assumptions for one person's cancer risk over a 70-year average of inhalation exposure (assuming inhalation exposure occurs 24 hours a day and 365 days per year) (DPR, 2016). In the absence of 70 years' worth of 1,3-D monitoring data, DPR uses the average concentrations from the start of a study to calculate lifetime exposure. To determine the risk associated for each exposure period, DPR uses a Hazard Quotient (HQ). The HQ is calculated as a ratio of the measured 1,3-D concentrations to a **screening level** or a regulatory target. An HQ of greater than one indicates exceedance of the screening level and requires DPR to act to further evaluate the data and assess possible mitigation measures (Delgado, 2024).

The most recent draft DPR Air Monitoring Report for Oxnard, Santa Maria, Shafter, and Watsonville found that of the 204 air samples taken for 1,3-D measurement, 21.4% contained trace or quantifiable levels of 1,3-D (Delgado, 2024). The greatest 24-hour concentration of 1,3-D was observed in Shafter (5.1 ppb), which was 9.2% of the regulatory target (55 ppb) that would cause DPR to perform a more rigorous evaluation of exposure. Shafter was also the site of the greatest observed sub-chronic exposure (based on 13-week sampling periods)–0.42 ppb–which was 13.5% of the health screening level (3 ppb). Similarly, the chronic 1,3-D exposure in Shafter was the highest measured at 0.15 ppb (7.7% of the health screening level of 2 ppb). The draft Air Monitoring Report also provides the cancer risk (expressed as the probability of an additional cancer case per 100,000 individuals over a 70-year period) for each monitoring location. Estimated cancer risk ranged from 1.5 excess cancer cases per million people in Watsonville to 7.7 excess cases per million in Shafter.

For eight years, DPR has also conducted weekly air sampling for 1,3-D in the communities of Delhi and Parlier. In 2023, Delhi's 1,3-D ambient air concentrations were below currently established thresholds of 1,3-D for acute, sub chronic, chronic, and lifetime exposures. In Parlier, concentrations of 1,3-D were below acute, sub-chronic, and chronic exposures. However, lifetime exposures were above currently established thresholds in Parlier.

Health risks to humans from inhalation exposure to 1,3-D were assessed by combining toxicity studies conducted with laboratory animals with exposure projections for humans under both non-occupational and occupational conditions. Since short-term, seasonal, annual, and lifetime exposures were expected, corresponding risk values for each of these scenarios were calculated. For non-oncogenic effects in adults, **margins of exposure (MOEs)** of 30 or greater were considered sufficient to protect human health. For non-oncogenic effects in children, MOEs of 100 or greater were considered sufficient to protect human health (DPR 2015). In toxicology, the **MOE** of a substance is the ratio of its NOAEL (no-observed adverse effect level) to its theoretical, predicted, or estimated dose or concentration of human intake. It is used in risk assessment to determine the dangerousness of substances that are both genotoxic and carcinogenic.

> 9. **FINDING:** Many studies have established that 1,3-D has both acute and chronic human health impacts.

> 10. **FINDING:** The U.S. EPA and California state agencies, including DPR and OEHHA, have reached conflicting determinations about the relative carcinogenicity of 1,3-D, which illustrates both that carcinogenicity remains difficult to establish and that variability among agencies with respect to their discerning criteria is a concern.

> 11. **CONCLUSION:** We need to better understand the causal relationships between 1,3-D exposure and acute and chronic health effects.

Human health concerns: Chloropicrin

Acute toxicity

Chloropicrin is corrosive, known for being toxic to exposed mucous membranes, the respiratory tract, and the eyes. After mild exposure to chloropicrin vapors, patients often experience the following symptoms: labored breathing, cough, chest pain, reddening of the skin, tearing, runny nose, headache, and irritation (Zuckerman, 2017; Barry et al., 2010). These symptoms occur rapidly after inhalation and eye exposure, but they have also been found to be transient and reversible (NIOSH, 2011; Pesonen and Vähäkangas, 2020). Severe acute exposure to chloropicrin vapors can cause "significant injuries to the upper and lower respiratory tract," including pulmonary **edema** (fluid buildup in the lungs) and death (National Library of Medicine, 2024; Pesonen and Vähäkangas, 2020). There is no antidote for chloropicrin (NIOSH, 2011). Because of the corrosive action of the chemical, after it has been ingested, symptoms of stomach irritation such as nausea and vomiting can occur and persist for weeks (Zuckerman, 2017). Acute eye exposure to high concentrations of chloropicrin can cause severe ocular damage, including corneal edema and vision impairment or blindness; no treatments currently exist for reversing ocular damage caused by chloropicrin exposure (Okoyeocha and Tewari-Singh, 2024). Skin contact can produce chemical burns (Henderson et al., 2015).

DPR has determined that the appropriate regulatory target level to restrict acute exposure to chloropicrin is 73 ppb or 0.073 ppm averaged over an eight-hour period based on human studies by Cain (2004), U.S. EPA's risk assessment, and DPR's Risk Characterization

Document. The American Conference of Governmental Industrial Hygienists has assigned chloropicrin a TLV-TWA of 0.1 ppm (or 100 ppb).

Chronic toxicity

Due to the chemical properties of chloropicrin which make it very permeable to the mucous membranes, especially the membranes around the eyes, its eye effects are much more of a concern than its nasal effects. Therefore, eye irritation is the appropriate focus of mitigation measures (Reardon, 2010; Cain 2004). DPR believes by addressing these effects during acute exposures, it will also address seasonal and chronic effects from inhalation exposures.

Chloropicrin has been listed as a toxic air contaminant by the state of California since 2011; the U.S. EPA does not classify it as a hazardous air pollutant. Chloropicrin is not considered by the U.S. EPA to be a carcinogen via inhalation exposure. However, chloropicrin has been found to be carcinogenic in rats and mice, and in 2012 both OEHHA and DPR believed that there was sufficient data to "conclude that chloropicrin is in all likelihood a genotoxic carcinogen" (Fan, 2012). DPR took a weight-of-evidence approach to determine carcinogenicity using animal data which showed some tumor formation only in female mice and inconsistent in-vitro and in-vivo genotoxicity tests. These studies were used to calculate cancer potency factors based on a small set of animal data using multiple uncertainty factors to extrapolate to humans. DPR placed chloropicrin into reevaluation in 2001 based on air monitoring data (Cortez, 2001), as well genotoxicity and developmental toxicity studies submitted under the Birth Defect Prevention Act (Senate Bill 950) (Lewis, 2012). It is still under re-evaluation by DPR for carcinogenicity. DPR has required the registrant to conduct and submit data from five new toxicological studies to attempt to determine its carcinogenic potential (Lewis, 2012; DPR, 2024b).

In DPR's most recent air monitoring report, chloropicrin was found in trace or quantifiable amounts in 27.7% of 206 samples taken (Delgado et al., 2024). Santa Maria showed the highest 24-hour acute level of chloropicrin (1.2 ppb, 1.7% of the health screening level) while Oxnard exhibited the greatest sub-chronic and chronic concentrations. Notably, the observed sub-chronic level (an average of 0.33 ppb across 13 weeks) was 95.4% of the screening level. As a result, DPR is conducting a more detailed evaluation of pesticide use data, historical weather patterns, intensive modeling, and more intensive monitoring to better understand potential sources and exposures in this area.

> 12. **FINDING:** Many studies have established that chloropicrin has both acute and chronic health impacts.

Human health concerns: Potential exposure to occupational workers and non-occupational bystanders

DPR has several worker health and safety programs that monitor worker activities and potential for exposure to ensure workplace safety. Their studies target work tasks, application methods, and scenarios, and involves collecting samples for research to improve future regulations. DPR also has programs to develop farm worker safety outreach and education, and conduct evaluations of the best engineering, administrative, and personal protective practices. For example, the DPR worker health and safety branch is currently conducting studies of all fumigants and potential occupational exposure through two-hour air sampling of the breathing zone air of workers in fields during fumigation and including drivers, co-pilots, applicators, shovelers, soil sealers, and irrigators and is comparing their results to accepted exposure limits. The PEL of 0.1 ppm is being used for chloropicrin, the TLV of 1.0 ppm is being used for 1,3-D, and for MITC, both metam sodium and metam potassium, 0.220 ppm is being used (DPR, 2022a).

> 13. **FINDING:** DPR is conducting studies that will examine a range of different individual workers' exposure to different fumigants.

DPR's Pesticide Illness Surveillance Program (PISP) includes a historical database with information from physicians' reports and field investigations of any pesticide related health impacting incidents. These investigations, conducted by the county agricultural commissioners, document circumstances of the exposures. In 2019, the most recently available PISP report summarizes 1,198 cases, and identified 409 (34%) stemming from 87 episodes associated with agricultural use pesticides. Exposures from pesticide moving off-site contributed to 256 (63%) of the 409 agricultural cases. Fumigants were involved in 50 cases (12%) (DPR, 2023a).A query of the PISP database from 1992 to 2019 for 1,3-D- and/or chloropicrin-related pesticide injuries reported from agricultural products shows a range of cases (i.e., people reporting exposure) and incidents (pesticide exposure events) (DPR, 2024j). The reports ranged from a high of 353 cases from seven incidents in 2005, to as low as only one case and incident in both 1996 and 2004. In 2001, there were 19 cases associated with the highest number of incidents, eight, in any one year. Over the 27 years of surveillance there were on average 47 cases and four incidents each year of pesticide illness. There is documented underreporting of pesticide illnesses occurring due to farm worker language barriers, potential concerns about immigration status, loss of work and income (Harrison, 2011).

> 14. **FINDING:** There is underreporting of pesticide illness occurring due to the prevalence of vulnerable populations in farming communities.

Lee et al. (2011) used DPR's PISP data to evaluate incidences of acute illness from off-target pesticide drift exposure from 1998–2006 and determined the incidence was relatively low and most cases presented with low-severity illness. However, the rate of poisoning from pesticide drift was 69 times higher for residents in five agriculture-intensive California counties compared with other counties, and the rate of occupationally exposed cases was 145 times greater in agricultural workers than in nonagricultural workers. Oriel et al. (2009) conducted a focused review of chloropicrin-related PISP cases and concluded that fumigant label directions and local permit conditions were not always adequate to prevent off-site exposure or resultant irritation or other symptoms. This finding triggered DPR to make changes to its regulated use. Starting in 2010, significant changes were also made to fumigant labels.

Since 2014, local, county, state, and federal agencies have taken several actions against one of the largest certified fumigant applicators related to pesticide exposure incidents and pesticide use violations. These regulatory actions include licensing actions, fines, and most recently a two-year probationary licensing action (to date, no other fumigant applicators in California have had regulatory actions and fines levied against them for pesticide use violations). U.S. EPA fined the company $44,275 for pesticide exposure complaints of bystanders in Fresno County related to a November 2016 non-tarped application of chloropicrin in an almond orchard where the soil surface compacting was not done, the Fumigant Management Plan was missing required information, and the post application summary was not accurate (U.S. EPA, 2021). In addition, the County Agricultural Commissioners (CACs) took licensing action against the company based on 40 incidents since 2014, including four that were rated as having a "priority" status, which means serious illness/injury occurred and/or five or more people were involved. The company paid $125,000 to the CACs in Butte, Fresno, and Santa Cruz Counties in settlement for that action (DPR, 2023b). DPR also instigated a licensing action against the company, citing nine recent episodes that occurred. For instance, in October 2020, 20 residential bystanders and three Salinas firemen experienced pesticide exposure due to a Trical misapplication; in October 2019, 39 field workers were exposed to both fumigants with 32 symptomatic and three seeking medical attention; and in October 2018, due to a misapplication of both fumigants by the company, 13 residential bystanders experienced symptoms of pesticide exposure (DPR, 2022b). In addition, in November 2022, the company paid $400,000 in penalties from a civil judgement in Monterey County for a series of pesticide incidents (DPR, 2023b). In September 2023, DPR put the company's license to operate on a two-year probation based on nine incidents and 61 pesticide use violations (DPR, 2023b). The probationary period requires the company to provide additional early notification near sensitive sites, use of TIF for certain applications, enhanced post fumigation monitoring, create and hire three new compliance coordinator positions, and create a stewardship program.

Human health concerns: Challenges related to toxicology, including inequalities of exposure and cumulative and interactive health impacts of pesticides

Toxicology is the scientific study of how chemicals can cause harm to living organisms. It examines the effects of toxicants (harmful substances) on human health and the environment. Toxicology is a complex science, at times trying to use animal models to understand and protect human health. These animal studies have some important limitations. For example, they cannot adequately assess pain, exhaustion, and other meaningful health stressors; cognitive and neurobehavioral impacts are also difficult to capture and may not translate well to human outcomes; laboratory animals live much shorter lives than humans and thus do not develop the full range of exposure-induced diseases that humans do; and animal studies often use high doses to detect effects which may not reflect human exposures, particularly at non-occupational levels. These efforts are further complicated by the fact that individual people may respond differently to toxicants.

Toxicants are often studied and regulated individually, but recent research has shown that they can interact when combined, leading to more significant effects. Cumulative risk considers exposure to multiple toxicants simultaneously, which can be especially relevant for communities facing multiple sources of pollution. For example, Joseph and Kolok (2022) analyzed the relationships of pediatric cancer rates to an environmental burden index (EBI) that represented an aggregate measure of several potentially carcinogenic metals and pesticides including fumigants metam, 1,3-D, and chloropicrin. They found a statistically significant correlation (P-value <0.05) between EBI levels and pediatric cancer rates.

> 15. **FINDING:** Little is known about the synergistic and cumulative effects of different fumigants on human health.

> 16. **CONCLUSION:** More research is needed on the synergistic and cumulative effects of different fumigants on human health.

> 17. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider studying the additive or synergistic effects of fumigant mixtures and other agrochemicals on human health.

Environmental justice focuses on the disproportionate impact of toxicants on disadvantaged communities, highlighting the need for fair and equitable protections. Environmental health disparities occur when communities exposed to poor environmental quality and social inequities experience more illness and disease. These disparities highlight the need for policies that consider both environmental risks and social factors (NIEHS, 2022). Research into questions of environmental justice and mixture toxicity is ongoing; however, regulators have had trouble moving forward (Sprinkle and Payne-Sturges, 2021). Constraints, both external (statutory and judicial) and internal (methodological concerns), hindered progress in this area. Recently, the U.S. federal environmental health establishment has started to develop coherent strategies to address mixture toxicity, cumulative risk, and environmental justice. For example, researchers should meet with community members and stakeholders to learn more about the community, involve them in the research process, collectively determine the environmental exposure issues of highest concern for the community, and develop sustainable interventions and implementation strategies to address them (van Horne et al., 2022; Harrison, 2011; Lievanos et al., 2011).

Scientists work to predict harm and protect public health based on rigorous scientific evidence (NIEHS, 2023). New research approaches and frameworks like **exposure science** may offer novel and more impactful ways to engage affected communities. Exposure science is a multidisciplinary field that brings together researchers from various interdisciplinary areas that include risk assessment, epidemiology, public health, toxicology, environmental chemistry, public policy, and engineering (van Horne et al., 2022). Since randomized controlled trials are a moral and practical impossibility for establishing direct causation of toxic exposure on human subjects, these epidemiological and animal studies are routinely triangulated with testimonial studies (e.g., Brennan et al., 2015; Saxton, 2015) to further document human health risks and exposure. Triangulation, referring to the use of multiple methods or data sources, is commonly used in qualitative research to enhance the validity and credibility of findings (Patton, 1999).

> 18. **FINDING:** Rural farming communities where fumigants are used are more exposed to the harmful impacts of these fumigants.

> 19. **FINDING:** A small number of studies based in epidemiology and qualitative social science research have shown that some subpopulations—such as pregnant women, children, and elderly—are more vulnerable to adverse health effects from fumigant exposure.

> 20. **CONCLUSION:** More studies are needed using “exposure science” triangulating results from 1) toxicology using rodent models; 2) epidemiological studies of toxicants in the environment and their effects on human health; 3) environmental science; and 4) risk assessments; along with 5) social science studies using testimonials or other means of documenting the experience of exposure and illness to further understand the chronic and acute health effects of exposure.

> 21. **RECOMMENDATION:** DPR should consider supporting the use of exposure science to better understand and mitigate potential exposures in vulnerable populations.

> 22. **RECOMMENDATION:** DPR should consider incorporating environmental justice work through various means (e.g., personnel, program focus) linked to their Environmental Monitoring branch so as to facilitate exposure science.

Environmental and ecological concerns: 1,3-D

1,3-D is broken down in air, usually within several days with a half-life of seven to 50 hours in ambient air (U.S. EPA, 2016). Some of the 1,3-D in soil and water will evaporate into the air and the rest will be broken down. In 1990, the detection of high 1,3-D concentrations in ambient air samples at multiple sites in California led to a suspension of 1,3-D as a soil fumigant. The suspension remained in effect until 1995, when DPR developed and tested mitigation measures to reduce emissions.

1,3-D is a **VOC** and its emissions can contribute to the formation of ground level ozone. Ozone is a major air pollutant in California and a component of smog. Smog can form when sunlight reacts with specific chemicals in the atmosphere. However, during the winter months, other reaction pathways may lead to smog containing a lower proportion of ozone. Nitrogen oxides (NOx)—which come from car exhaust, coal power plants, and factory emissions—play a crucial role and combine with at least one **VOC** such as emissions of the fumigant 1,3-D. When sunlight hits these chemicals, they form airborne particles and ground-level ozone, which collectively make up smog and affect air quality and visibility. Ground-level ozone is harmful to human health, especially for people with respiratory illnesses like asthma.

Currently, Title 3 of the CCR section 6448.2 addresses the VOC requirements for 1,3-D field soil fumigations. The VOC requirements are mandated by the pesticide element of the ozone SIP for the federal Clean Air Act, as well as subsequent amendments to the SIP that expanded requirements including DPR's VOC regulations. The pesticide SIP element pertains to five regions in California that exceed the federal ozone standard (nonattainment areas (NAA)) during the May–October peak ozone season: the San Joaquin Valley NAA, Sacramento Metro NAA, South Coast NAA, Southeast Desert NAA, and Ventura NAA (Segawa and Luo, 2022). 1,3-D use in these districts had been regulated through geographically based township caps; however, DPR's 2024 regulations will now address 1,3-D contributions to smog through new mitigation measures, some of which target these nonattainment areas.

Ground water contamination with 1,3-D has been reported in the Northeastern U.S., but within California, 1,3-D is not listed as a ground water contaminant. The regional difference is believed to be due to the soils and climate in California which impact how quickly the chemical both volatilizes and breaks down.

Greenhouse gas (GHG) emissions are important environmentally impacting pollutants. In the U.S., agriculture overall accounts for about 11% of total sources of GHG, with cropland soil management accounting for 50% of all agricultural sources (5.5% total) (Economics Research Service, 2022). The GHG nitrous oxide is 275 times more potent than carbon dioxide, and nitrous oxide emissions occur during tillage, landplaning, irrigation, chemical fertilizer application, compost incorporation and assimilation, and during soil fumigation as well as during anaerobic soil disinfestation (USDA ERS). Prescott et al. (2023) examined VOC production as well as GHG production under TIF tarps to assess potential modes of action of the ASD treatment. They did not measure emissions beyond the tarps, but it is interesting to note that under the tarp, production of GHG (methane, nitrous oxide, and carbon dioxide) from active anaerobic ASD treatments (both flat and bed) was higher than what they measured under TIF from fumigation with 1,3-D and chloropicrin in California strawberry fields.

Agricultural soils are responsible for more than half of the total nitrous oxide emissions in California (CARB 2022). Soil fumigation can lead to long-term disruptions to the microbiome in agricultural soils, including microbiota that are directly involved with the nitrogen cycle (Fang et al., 2019). Changes to this soil community can affect the balance of nitrous oxide between soils and the atmosphere.

> 23. **FINDING:** It is not clear that the contributions of fumigation with 1,3-D are a significant source of greenhouse gases from agriculture.

Fumigants are applied to control soilborne pests, however, understanding the impacts of repeated and long-term effects of fumigants on overall soil health and resident microorganisms are of critical importance not only for evaluating their environmental safety, but also because soil microbial and nematode communities have a central role in soil quality and nutrient cycling, plant growth, and crop production. Recent developments of molecular biology tools to assess real time soil microbiome changes will offer new insights into this area going forward. Any disturbance to the soil from pre-plant fumigant use, steam soil pasteurization, or anaerobic soil disinfestation/biosolarization has been shown to result in changes to the soil microbiome, although often these changes are relatively short-lived. As nematodes are the principal target of 1,3-D, more research is needed on what this fumigant does to the many beneficial nematodes present in soils, some of which assist with nutrient cycling as well as assist with controlling pest nematodes and pathogens. There are a wide range of beneficial nematodes in soils including plant associates that feed on fine roots and root hairs without causing damage to the plant; **labile** carbon (i.e., readily decomposable carbon) that is exuded during their feeding sustains a microbiome that benefits the plant. Free-living nematodes do not rely on plants for food. Bacterial feeders (known as bacterivores) are small, common nematodes that consume bacteria. Fungal feeders use a delicate spear (or stylet) to pierce fungal hyphae and spores. Predatory nematodes are larger in size, have teeth, and consume other soil nematodes. Omnivorous nematodes feed on nematodes, fungi, bacteria, and more (Stirling, 2023). Free-living nematodes, especially bacterivores, play a crucial role in nutrient cycling. They contribute to mineralization, converting organic nutrients into inorganic forms that plants can absorb. By consuming bacteria, they help maintain adequate nutrient levels for plant health. In one study of nematodes in peanuts, 1,3-D was found to have non-target effects on free-living nematodes, particularly fungivores. It decreased soil abundances of the fungivore genera *Filenchus* and *Aphelenchus* but did not affect any other nematode genera including bacterivores, omnivores, herbivores, and predatory nematodes (Grabau et al., 2020).

1,3-D was found by Menge et al. (1983) to cause no harm to arbuscular mycorrhizae in grapes. Zeng et al. (2019) studied effects of 1,3-D fumigation on soil bacterial diversity, observing increases in some bacterial diversity indices but not in others, along with a reduction in some fungal families (including one which parasitizes nematodes and arthropods). Liu et al. (2015) found that 1,3-D initially affected bacterial diversity, but the populations recovered quickly, and soils treated with 1,3-D had higher bacterial diversity over time than unfumigated soil. Fang et al. (2019) found fumigation with 1,3-D initially decreased various bacterial populations but by 59 days post fumigation some nitrogen-fixing, nitrification and denitrification bacteria populations had recovered to pre-fumigation numbers, with stronger inhibitory effects in the clay soil over the sandy soil.

> 24. **FINDING:** Few studies have investigated how repeated fumigations with 1,3-D impact the soil microbiome and nematode communities over time.

> 25. **CONCLUSION:** Greater knowledge about how 1,3-D impacts the functional roles of the soil microbiome and nematode communities would be informative for potential improvements in pathogen and nematode control efficacy and the development of methods to mitigate any possible negative effects such as impacts on soil nitrogen cycles.

Environmental and ecological concerns: Chloropicrin

Chloropicrin is classified as a **VOC** under California law. It is a reactive compound that promotes ground-level ozone if present with other reactive organic compounds in the atmosphere, which can result in smog. Ground-level ozone is harmful to human health, especially for people with respiratory illnesses like asthma.

Fumigation with chloropicrin can have an indirect effect on greenhouse gas emissions from agricultural soils due to the impacts it can have on the soil microbiota (including nitrogen cycling groups). Research has demonstrated that chloropicrin fumigation can lead to significantly elevated nitrous oxide emissions from soils (up to 25 times higher than baseline) (Spokas and Wang, 2003; Fang et al., 2018; Fang et al., 2022). These effects can last for more than six weeks following treatment (Spokas et al., 2005; Fang et al., 2022). However, these results have been inconsistent across studies and may depend on many interacting factors that will be complex to disentangle, including the microorganisms present (Li et al., 2022), soil oxygen content (Spokas et al., 2006; Fang et al., 2022), soil acidity (Fang et al., 2018, Spokas et al., 2005; Yan et al., 2017), and soil texture (Li et al., 2017). In some cases, the increase in nitrous oxide emissions may be generated by increased populations of microorganisms known to be beneficial for crop production. Spokas and Wang (2003) found that soil treated with chloropicrin produced more nitrous oxide than untreated soil, but soil treated with methyl isothiocyanate (MITC) did not. In this study, a tarp was not used, and they treated soil at shallower depths than is done in California (Spokas and Wang, 2003). To date, no research on this subject has been performed within California.

> 26. **FINDING:** Soil fumigation with chloropicrin may indirectly lead to increased greenhouse gas emissions via impacts to microorganisms involved in nitrogen cycling.

> 27. **FINDING:** Insufficient research exists to determine the significance to which fumigation with chloropicrin impacts greenhouse gas emissions in California.

> 28. **CONCLUSION:** More research on the possible indirect impacts of fumigation on greenhouse gas emissions is needed. Such research would be most valuable for California regulators if performed in California and using fumigation methods that are standard for chloropicrin in this state.

Evaluating the impacts that fumigants have on overall soil health and resident microorganisms is important not only to understand the environmental impacts but also because soil microbial communities influence soil quality and nutrient cycling, and this in turn impacts plant growth and productivity. Some pathogens in addition to parasitizing plants are also **saprophytes** (i.e., they consume dead or decaying organic matter) and can rapidly re-colonize recently fumigated soils. Some research has reported that in addition to direct killing of target pathogens or nematodes, soil fumigation can shift the microbial community, which sometimes can lead to increasing the number of beneficial microorganisms in the soil. For example, Castellano-Hinojosa et al. (2024) found that Tri-Clor (Pic100) and Pic-Clor 60 controlled *Fusarium*, but it also appeared to result in a major increase of native *Trichoderma* and *Bacillus* species. Species of both genera are commercially produced biological control organisms that can control pathogens through nutrient or space/niche competition, antibiotic production, and/or direct parasitism, or a combination of all three. Fluorescent pseudomonads (another known group of beneficial bacteria) were found to increase post-fumigation with chloropicrin (Duniway et al., 1998), and Rasmann et al. (2009) found that tomatoes grown on 1,3-D and chloropicrin-treated fields had greater arbuscular mycorrhizae colonization of the roots than did the organic production system run in parallel in a five-year study (mycorrhizal fungi benefit crops by enhancing nutrient and water uptake). Additionally, increases in *Bacillus* spp. in the soil after treatment with chloropicrin resulted in greater potassium use efficiency and enhanced tomato growth (Sun et al., 2023). The authors feel that their study may help explain the “Pic kick” or crop yield enhancement that has been associated with chloropicrin for years in the absence of any major pathogen being present and controlled (Sun et al., 2023). This yield enhancing effect has cascading benefits including land use reduction and use of less water, fertilizer, post-plant pesticides, diesel, gasoline, and labor.

Li et al. (2022) determined that nitrous oxide emissions in a Pic-Clor 60 fumigated soil in Florida tomatoes was similar or lower than the ASD treatment, likely due to a different microbial community in the two soils. Both soils emissions were highest on the day of planting when the TIF tarps were punched into for enabling crop planting.

Chloropicrin is on the DPR list of pesticides that could potentially contaminate groundwater. Chloropicrin is a water-soluble compound with low soil adsorption, similar to other chemicals that have been found in groundwater (U.S. EPA, 2008b). During heavy rainfall, it has the potential to leach into groundwater or enter surface water. However, its high vapor pressure and significant Henry’s Law constant suggest that volatilization is the primary mechanism by which it dissipates into the environment. Chloropicrin is often applied under tarps, which helps reduce the likelihood of it moving into water sources. Between 1986 and 2003, no chloropicrin was detected in 1,719 well water samples collected across 34 California counties (DPR, 2022c). However, more recently it has been detected in one to two wells sampled out of 144 to 625 total wells sampled in 2017, 2018, 2019, and 2021, but was not detected in any wells in 2016 or 2020 (DPR, 2022c).

Chloropicrin can spontaneously generate when free chlorine or chlorine-containing molecules become introduced to water sources, such as wells, that also have trace concentrations of a variety of nitrogen-containing organic compounds, particularly nitrite

(Duguet et al., 1988). Chloropicrin can also spontaneously form in water by the reaction of free chlorine with humic acids, amino acids, and nitrophenols, and the presence of nitrates increases the amounts formed (World Health Organization, 1996). In addition, disinfectants used in water treatment such as chlorine, chloramines, and ozone, can react with dissolved natural organic matter and nitrite to form a range of disinfection by-products (DBPs), including chloropicrin (Kirkham Cole et al., 2007). It is plausible that detections of chloropicrin in well and groundwater could be a function of the leaching potential of agricultural compounds and the near ubiquitous presence of chlorine in soils.

> 29. **FINDING:** There is a dearth of information regarding the modes of action for these fumigants against both humans and target pests.

Comparison of human health and environmental/ecological concerns for fumigants

In addition to the acute toxicity studies using animals and laboratory cell cultures, and the chronic toxicity studies on carcinogenic, mutagenic, and other possible effects, there have been some real-world epidemiological public health studies of toxicant exposure over time to non-occupational bystanders, and in particular to children in communities where fumigants are used. To address potential confounding factors, these studies typically include covariates such as socioeconomic status, maternal health, and residential proximity to other pollution sources (Goodman et al., 2020). Results from epidemiological research on 1,3-D and chloropicrin exposure have varied based on the demographics, exposure types, and health effects studied. Various studies have been undertaken by the University of California Berkeley School of Public Health through a longitudinal study called the Center for Health Assessment of Mothers and Children of Salinas (CHAMACOS). CHAMACOS began in 1999 and has followed 800 children and pregnant mothers over more than 20 years, collecting and analyzing 300,000 biological samples and recording residential address to assess pesticide exposure. Gemmill et al. (2013) used these data to examine the relationship between residential proximity to higher fumigant use and prenatal development; they observed an association between higher methyl bromide use during the second trimester of pregnancy and lower birthweight and restricted fetal growth. Gunier et al. (2018) examined total use of fumigants (including 1,3-D, chloropicrin, methyl bromide, and metam sodium) around the home during pregnancy and early childhood (birth to age seven); they did not observe adverse associations of total fumigant use with lung function or respiratory symptoms (like asthma) in children. A slight but significant positive effect on lung function was detected for prenatal proximity to chloropicrin use (Gunier et al., 2018). They felt further research was needed in larger and more diverse populations with a greater range of agricultural fumigant use to further explore the relationship with respiratory function and health. The CHAMACOS study also found a negative correlation between proximity to fumigant use and children's intelligence: there was a decrease of approximately 2.5 points in Full-Scale intelligence quotient at seven years of age for each 10-fold increase in methyl bromide or chloropicrin use within 8 km (~5 mi) of the child's residences from birth to seven years of age (Gunier et al., 2017).

> 30. **FINDING:** The CHAMACOS study has found that residential proximity to fumigant use during pregnancy is associated with lower birth weight and reduced IQ at age seven. However, additional studies looking at a larger and more diverse population with a greater range of agricultural fumigant use are needed to further explore the relationship of fumigant use and children's health.

Methyl bromide has been phased out through the Montreal Protocol due to the harm it causes to the stratospheric ozone layer. It is still used in California and elsewhere in the U.S. under a QPS exemption for some nursery propagation fields. Toxicity in human and animals is from inhalation of methyl bromide gas, which causes respiratory, developmental, cardiovascular, and reproductive toxicities in animals. It has been shown to be genotoxic but has not been classified as a human carcinogen.

The main methyl isothiocynate generators used as fumigants in California include Dazomet, metam sodium, and potassium N-methyldithiocarbamate (metam potassium) which all release methyl isothiocyanate (MITC) gas upon application. Metam sodium, metam potassium, and MITC are acutely toxic to mammals, birds, aquatic invertebrates and fish (U.S. EPA, 2008c; DPR, 2004). Adverse developmental, oncogenic and genotoxic effects of metam sodium in laboratory animals have been observed. Along with its degradation product methyl isothiocyanate (MITC), metam sodium is a "restricted use" pesticide" due to its potential danger to farm workers, the general public, animals, crops or the environment. Both metam sodium and MITC are Toxic Air Contaminants under the AB 1807 Toxic Air Contaminants Act (Tanner, 1983). MITC is highly irritating to eyes, lungs and skin, and may cause a chemically induced asthma-like condition called reactive airways dysfunction syndrome. Other degradation products of metam sodium include methyl isocyanate, hydrogen sulfide, carbon disulfide, carbonyl sulfide, and methylamine. Toxic effects may result from exposure to any of these compounds, either alone or as mixtures such as in concert with metam sodium and MITC (DPR).

Table 1.2 provides an overview of the main fumigant active ingredients used in California and includes their status regarding a range of human and environmental health indices. Chloropicrin and metam sodium have the highest number of cases in DPR's Pesticide Illness Surveillance Program (PISP), likely due to the long history of their use in California and major incidents like the Dunsmuir metam sodium spill in 1991. DPR's Risk

Management Directives lay out for each active ingredient their acute toxicity and chronic toxicity endpoints which reflect animal model toxicity data with additional factors included which shows relative toxicity of the materials. Methyl bromide is the most acutely toxic, with 1,3-D also acutely toxic as well as chronically toxic, and chloropicrin's chronic toxicity is still being evaluated.

Joseph et al. (2022) used U.S. Geological Survey Pesticide National Synthesis Project data and cancer incidence among adults and children from the National Cancer Institute State Cancer Profiles to investigate geospatial relationships in eleven Western states. They found fumigants were correlated with cancer incidence in adults and children in the Western U.S. The most predominant fumigant, metam, was also found to be associated with cancer incidence among adults. They developed a model to predict cancer incidence among adults using pesticide usage information.

Because of the novelty of epigenetic science, there is a dearth of research that looks at the potential epigenetic effects of these fumigants. However, a recent metanalysis of literature published between 2005 to 2020 concluded that chronic exposure to pesticides (insecticides and herbicides, not fumigants) could lead to epigenetic modifications (Rohr et al., 2024).

Table 1.2. Summary of fumigants and their human health impacts, environmental impacts, and product efficacies (DPR, 2024c; DPR, 2024g; DPR, 2024h; DPR, 2024i; Holmes et al., 2020). See below for definitions.

								Toxicological Endpoints			
Active Ingredient	**Chemical Class**	**Restricted Use Material**	**VOC**	**TAC**	**Potential Groundwater Contaminant**	**PISP Cases (1992–2019)**	**Use in 2022 (lbs of active ingredient)**	**Acute Toxicity**	**Chronic Toxicity**	**Product Efficacy***	**DPR Reevaluation**
1,3-D	Organochlorine	Yes	Yes	Yes	No	329	9,748,837	55 ppb	0.21–0.56 ppb	+++	Concluded
Chloropicrin	Halonitroalkane	Yes	Yes	Yes	Yes	1,301	8,769,970	73 ppb	Under study	+++	Active
Methyl bromide	Organobromine	Yes	Yes	Yes	No	418	1,618,797	210 ppb	1 ppb	++++	Concluded
MITC generators: metam sodium	Organosulfur	Yes, with exceptions	Yes	Yes	No	980	3,630,276	220 ppb	0.1 ppb	+++	Concluded
MITC generators: metam potassium	Organosulfur	Yes, with exceptions	Yes	Yes	No	61	8,005,692	220 ppb	10–42 ppb	+++	Concluded

Note. PISP - Pesticide Incidence Survellience Program 1992 to 2019 pesticide illness cases and incidents. Bystanders and general public exposure assumption is human daily exposure duration of 24 hours/day for 7 days/week. Occupational exposure durations are generally assumed to be 8 hours/day for 5 days/week. Based on the use pattern, seasonal workers were assumed to be exposed to MITC for 120 days per year.
*as estimated by Holmes et al. (2020) on strawberries in California, averaged across all pest targets and soil mobility ratings. ++++ excellent, +++ good, ++ fair, and + poor

The role of fumigant application methods in protecting human health and addressing environmental/ecological concerns

Emission reduction and mitigation measures for fumigants include proper field preparation prior to fumigation, using fumigants at reduced rates, size of buffer zones around the fumigation, set back distances to occupied structures, use of specialized tarps or soil compaction/sealing methods, depth into the soil profile of the injection, size of the field being treated at any one time, soil temperatures during injection, soil moisture content during injection, and combinations of several of the above practices. If tarps are used, then the time they must remain post injection is also important for emission reduction. Gao et al. (2013) showed the use of TIF reduced cumulative emissions by 90% over polyethylene and shank injected 1,3-D and chloropicrin without any tarp. Yates et al. (2016) found that tarp-less deep injection to 24 in (61 cm) reduced estimates of 1,3-D and chloropicrin emissions by 2 to 24% when compared to tarp-less injections at 18 in (46 cm). Given these data, a fumigant diffusion model concluded that 24-in injections will yield a 21% emission reduction overall.

Emissions from soil fumigation are affected by soil conditions (texture, moisture and organic matter content), weather, and surface barriers, as well as fumigant properties. Generally speaking, lower emissions are expected from soils with fine texture, high water content, high soil organic matter (SOM) content, and low temperatures compared to soils with coarse texture, low water content, low SOM content, and high temperature conditions.

Applicators and handlers of fumigants must wear proper personal protective equipment (PPE) including full- or half-face respirators, boots, gloves, suits, and protective eyewear; the specific requirements depend on the fumigant formulation and the work being conducted. Neighbors within a prescribed distance from the fumigation site must be notified seven days in advance and emergency management procedures are required. In the case of chloropicrin, fumigant monitoring around the application site is also required.

Work by Shen et al. (2016) found that biochar applied as a liquid slurry could prevent wind losses under field conditions, and reduced emissions as well as VIF. These findings warrant additional research into how this work could be applied in crops and regions where applications are currently done without tarps.

All the mitigation measures mentioned above have been studied and found to reduce emissions. However, they can fail; tarps may be damaged by animals or winds, and people may accidently and unknowingly enter buffer zones.

31. **FINDING:** At present, totally impermeable film (TIF) is the most effective method for significantly reducing offsite 1,3-D and chloropicrin emissions. However, it is only commonly used while pre-plant fumigating strawberry, cane berries, fresh-market tomatoes, peppers, and ornamental fields.

32. **CONCLUSION:** TIF use during the pre-plant fumigation for other crops (e.g., almonds, grapes, carrots, and sweet potatoes) would decrease the emissions associated with 1,3-D and chloropicrin fumigation. However, increasing the use of TIF in crop settings that do not currently use tarps will increase plastic use and waste.

33. **FINDING:** Early research suggests that biochar and liquid slurry have the potential to reduce emissions from fumigation.

Section 1.9: Tradeoffs (concerns and benefits) associated with the use of fumigants

Benefits

The use of fumigation by agricultural industries has sustained intensive specialty crop production which can support the economic viability of rural communities to the extent that economic benefits are widely distributed within the community (Olver and Zilberman, 2022).

Crop yield increases and production in fields that might otherwise not be productive due to pathogen presence are routinely reported after the use of both fumigants on strawberries, vegetables, nut and fruit trees, and grapevines in California and elsewhere. Higher yields with fewer natural resource inputs (e.g., land and water) results in higher resource use efficiency. Higher food production and resource use efficiency then ultimately makes more food available for consumers, potentially at a lower cost. When the crops in question are part of a healthy diet, such as high value fruits and vegetables, this can be an additional public good. Use of pre-plant soil fumigants in vegetatively propagated crops (strawberry, grapes, cane berries, fruit and nut trees) provides the benefit of clean, healthy planting stock, which protects the growers from diseases and pests thus avoiding economic losses. Additionally, use of 1,3-D and chloropicrin fumigation prior to planting may reduce the need for other agricultural pesticides, herbicides, or nematicides later in the crop production cycle. This may have either positive or negative consequences for occupational and bystander exposures, depending on the nature and use pattern of the other pesticides that may be used.

Agricultural productivity and the broader natural resources of California can be protected by controlling aggressive pathogens, nematodes, and invasive species that can be introduced first into California through illegal or accidental importation by travelers, crops, planting stock, or equipment, and then moved into farmers' fields due to spread via poor nursery practices or other means. These introduced pathogens or pests can then not only harm agricultural production, potentially increasing pesticide use, they can also move into native vegetation stands of plants that can be harmed by these pathogens, reducing regional biodiversity. CDFA has programs to prevent the introduction of invasive species and aggressive foreign pathogens, which is part of an integrated approach to protect California's agricultural and natural resources. Having fumigant tools to be used when needed is also part of such an approach. Examples of recent invasive species causing damage to important California crops include peach root-knot nematode (*Meloidogyne floridensis*) introduced from Florida which can cause damage to the Prunus rootstocks 'Nemaguard', 'Flordaguard', 'Guardian', 'Okinawa', and 'Nemared', all of which were resistant to *M. incognita, M. javanica,* and *M. arenaria* (Westphal et al., 2019). *Phytophthora ramorum*, the cause of Sudden Oak Death, was likely introduced via contaminated nursery plants and has caused major damage to oak woodlands throughout the state (Rizzo et al., 2005).

Concerns

Beyond the human health and environmental concerns discussed above, another concern with agricultural chemicals is whether the target pests may develop resistance to the chemistries after continued use. There are reports of certain microbial populations using fumigants like metam sodium as carbon and nitrogen sources and their populations increasing after multiple uses in a field. Resistance to fumigation is not considered highly likely to occur due to the broad-spectrum mode of action of fumigants, lack of residual activity, and rapid dissipation. In addition, fumigants are highly toxic and assumed to have multiple modes of action, making it difficult for microorganisms, nematodes, or weeds to acquire multiple genetic mutations simultaneously or experience sublethal exposures over long periods of time that would allow resistance development to occur. Nevertheless, there remains a possibility that fungal pathogens, nematodes, and arthropod pests could develop resistance to chloropicrin or 1,3-D, especially given that both California and Florida strawberry growers have relied on these fumigants, either individually or in combination, for over 60 years (Noling and Becker, 1994; Ruso, 2006; Baggio et al., 2022). Resistance to the fumigant phosphine, for example, has already been reported in multiple pest insect species (Nayak et al., 2020).

> 34. **FINDING:** To date, there have been no reports of pathogens, nematodes, weeds, or arthropod pests developing resistance to the pre-plant soil fumigants 1,3-D and chloropicrin. However, insect pest resistance to phosphine has been reported.

> 35. **CONCLUSION:** It is important to continue to watch for signs of resistance to fumigants developing in pathogen, nematode, weed, and arthropod pest populations. This would manifest as a loss of disease or weed control following use of the fumigants where previously control was achieved.

Another concern relates to fumigants disrupting soil ecosystems, rendering them more vulnerable to pest reinfestation from the field edge, from below the treatment depth, or via aerial spores landing on fumigated soil post treatment. Some pathogens, in addition to colonizing and killing living plants as pathogens, have a saprophytic stage which enables them to grow and reproduce on dead and dying plant tissue and other soil microbes killed by the fumigation and from which they can then invade healthy plants once they encounter them post planting (Marois et al., 1983). Generally, post fumigation with 1,3-D and chloropicrin, the microbial and nematode community, including pathogens and beneficial microbes, changes in different ways depending on the soil type, organic matter and soil moisture content, and the makeup of the original resident microbial and nematode community. Studies have shown that the microbial community often returns to a similar composition although with a lower population of target pathogens or nematodes, as soon as 6 weeks post fumigation, or up to 6 months later. Other times, it shifts permanently, especially if repeated fumigation treatments have been applied over multiple years (Li et al., 2022).

> 36. **FINDING:** A particular crop production system may become dependent on the use of fumigants to be economically viable and require the continued use of costly external inputs which may not always be available due to supply issues, economic or regulatory related decisions of the manufacturer or distributor, or direct regulatory actions. This may especially be true if the use extends over many years and influences decisions about research into developing alternative control methods.

There are concerns about unequal distribution of the different costs and benefits across different human populations and communities. For example, the costs are not incurred by the same populations that reap the benefits. The cost is paid by the workers and their families in the form of adverse health outcomes; the beneficiaries are consumers who may live in another state and enjoy the nutritional benefits without any exposure. These unequal costs have led to questions around environmental justice and how it can and should be addressed. In addition, disadvantaged communities often experience multiple other risk factors such as exposure to heavy metals and poor nutrition due to low incomes, which increase their vulnerability to any particular risk factor. Finally, some subpopulations may be more vulnerable to exposures, such as the elderly, children, and pregnant women.

In so much as pre-plant fumigation with 1,3-D and chloropicrin has been shown to increase yields, which is certainly why growers use the chemicals, this increase in product supply must be reconciled with the broader commodity product supply, or oversupply, and related prices. Solutions to supply questions will be commodity specific and likely reside with the growers, shippers, and relevant commodity boards.

Section 1.10: Use of the fumigants in other states and countries

Other U.S. states

1,3-D and chloropicrin are federally registered. Their use across states is driven by the crops being grown, their value, and their specific pathogen, weed, and nematode populations, as well as state-imposed regulations. California has the greatest number of high-value specialty crops grown and the most stringent regulations on use of fumigants and other pesticides. In 2014, Gunier et al. (2018) estimated that 50% of all fumigant use globally occurred in just five U.S. states: California, Florida, Washington, Idaho, and Oregon.

The U.S. Geological Survey (USGS) provides national pesticide use data from farm surveys, multi-county Crop Reporting Districts (CRD), using harvested crop acreage by county from the USDA Census of Agriculture to calculate median pesticide use rates. In 2018, the most recent year that data is available, 1,3-D use was reported as 40–60 million pounds, up from 27–50 million pounds in 1992 (USGS, 2018). 1,3-D use nationally, like in California, has variable use trend, with two peaks—one of 72 million pounds in 1996 (use in California had been stopped by regulatory action from 1991–1995), and another peak of 75 million pounds in 2009. Use of 1,3-D peaked in California in 2015 at 16 million pounds (see ***Figure 1.8*** and ***Figure 1.9*** from earlier in this chapter), whereas total U.S. use that year was 38 to 47 million pounds, with California therefore using 34 to 42% of 1,3-D pounds applied. The range of pounds reported in this dataset is due to it coming from surveys of pesticide use and acreage estimates for almost all states except for California, where they use DPR's reporting data. Chloropicrin was reportedly used at 20–33 million pounds in the U.S. in 2018, and shows a steady increase over this time, up from 5–7 million pounds in 1992 (USGS, 2018); California's use of chloropicrin in 2018 was 7.48 million pounds which ranges from 23 to 37% of total U.S. use depending on the low versus high USGS pesticide use estimates mentioned above (USGS, 2018). Crops where 1,3-D and chloropicrin were most used across the U.S. included vegetables and fruit, orchards and grapes, and "other crops," with significant uses reported of 1,3-D on cotton.

Florida researchers have investigated the drip application of the fumigant ethanedinitrile (EDN) under TIF and found it effective against some weeds, nematodes, and Macrophomina charcoal rot in strawberry (Yu et al., 2019). EDN was discovered in 1815 but was not manufactured on a large scale until the late nineteenth century and is now used in other industries such as chemical synthesis, pharmaceuticals, and plastics. EDN is not registered for commercial use as a pre-plant fumigant in the U.S.

Other countries

1,3-D and chloropicrin are both either sold and/or registered in over 30 countries around the world. In most countries, registration procedures are the same or similar to the U.S.: fumigants are registered after each country's regulatory review, ultimately resulting in end-use labels with specific directions on approved use conditions, target pests, crops, etc. To the best of our knowledge, for the 30 countries where these fumigants are used, there are no publicly available data on the pounds applied nor acres treated.

In the European Union (EU), after the phaseout of methyl bromide in 2005, both 1,3-D and chloropicrin were used as alternatives for several years. However, they were then pulled by their manufacturers and distributors—1,3-D in 2010 and chloropicrin in 2013—to gather more data and complete more studies as required by new regulations. Both fumigants are now in a data generation phase with likely dossier submissions to their Rapporteur Member State (RMS) by 2025 or 2026. In the EU, the main RMS is Greece, while for chloropicrin the Co-RMS is Italy, and for 1,3-D the co-RMS is Belgium. The approval process is long, with decisions expected three to five years after dossier submission. In the meantime, each fumigant can be allowed under Emergency Use Derogations (EUD) in countries that grant them. Those EUDs are granted in 120-day windows for specific crops in specific regions (Villarino et al., 2021).

EUDs are used in the EU because all pesticides need to first go through Annex 1 listing (i.e., up for EU-wide approval) before they can be registered in individual EU member countries (which are called Annex 3 registrations). It is a similar process to the U.S., where U.S. EPA registration is needed first (akin to Annex 1 in the EU) before a product can be registered in individual states (akin to Annex 3). However, there are mechanisms that allow emergency use in the U.S. as the main registration process moves along (e.g., Section 18/Emergency Use labels), which is similar to the EUDs in the EU. In the U.S., and especially the EU, registration processes can take many years (M. Stanghellini, pers.comm.; Villarino et al., 2021). Dazomet, metam sodium, and metam potassium are still allowed for use in the EU but only once every three years at the maximum rate (Villarino et al., 2021; de los Santos et al., 2021).

EUDs granted by the European Commission (the executive arm of the EU) for 1,3-D and/or chloropicrin, or both, included eight uses between 2016 and 2021, with seven for Spain and one for Greece. These eight EUDs were granted for strawberries, raspberries, peppers, tomatoes, cucumbers, squashes, and eggplants (European Commission, 2024). Between 2016 and 2024, the European Commission granted 22 EUDs for MITC-related fumigants as alternatives to 1,3-D and chloropicrin. These EUDs were issued for use in Belgium, Spain, France, Portugal, Denmark, and Hungary, and for use on strawberries, cane berries, grapes, peppers, tomatoes, sweet potatoes, carrots, forest tree nurseries, and others (European Commission, 2024). Data on pounds or liters applied or acres treated are not available through this public database.

In 2024, there were only two countries in the EU with EUDs for 1,3-D: Italy and Greece. Dow Chemical Company (Dow), Kanesho Soil Treatment (KST), and Agroquímicos de Levante (AQL) are the main manufacturers for the 1,3-D active ingredient and 1,3-D products in the EU. 1,3-D products are available in either emulsifiable concentrate (EC) form (which includes oils and solvents to facilitate drip application) or in AL form, which includes only 1,3-D without emulsifiers to be shank injected. In Italy, total use of 1,3-D from Dow and KST was approximately 2.5 million liters in 2024, inclusive of both EC and AL formulations (S. Burt, Dow, 12/9/2024, pers. comm.). In Greece, total 1,3-D use from Dow and KST was approximately 100,000 liters; however, only the drip applied EC formulation is authorized in Greece (S. Burt, 12/9/2024, pers. comm.). Thus, using a conversion rate of 2.68 pounds per liter, close to 7 million pounds of 1,3-D product was sold in Italy and Greece through the EUD regulatory mechanism in 2024 alone.

According to Teleos, a distributor for Dow, another 3 million pounds were sold in 2024 across Israel, Morocco, and New Zealand, resulting in a total of more than 10 million pounds sold across these six countries in 2024 (***Table 1.3***).

AQL manufactures 1,3-D products in both Spain and China and distributes these products to 35 countries. AQL reported that, in 2015 (the most recent year for which information was publicly available), they had produced 4,200 metric tons (equivalent to 9.3 million pounds) of product that included both 1,3-D and chloropicrin as active ingredients (AQL, 2022). There may be other manufacturers and distributors that produce and sell 1,3-D products in other countries; however, data regarding these sales were unavailable.

These estimates of pounds of product sold are not directly comparable to data presented in ***Section 1.7*** for California since these estimates are for total product weight as opposed to pounds of active ingredient.

Table 1.3. Sales of 1,3-D product in select countries (in liters) and yearly totals in (liters and pounds). Note that yearly totals are incomplete as not all countries where 1,3-D is distributed are represented in these data. Data were provided courtesy of Dow and Teleos representatives.

Manufacturer or Distributor[†]	Year	Spain	Israel	Italy	Morocco	Greece	New Zealand	South Africa	Yearly totals (liters)	Yearly totals (pounds)[*]
Teleos (Dow)	2022	178,400	256,000	1,310,440	634,833	56,662	16,000	103,680	2,556,015	6,850,120
Teleos (Dow)	2023	56,650	256,000	1,029,790	567,958	40,248	0	17,280	1,967,926	5,274,042
Teleos (Dow)	2024	0	256,000	1,037,760	863,257	40,942	16,000	0	2,213,959	5,933,410
KST	2024	0	0	1,462,240	0	59,058	0	0	1,521,298	4,077,079

[†] Dow and KST are both manufacturers and distributors of 1,3-D, while Teleos is a licensed distributor of 1,3-D for Dow.
[*] Data were provided by Dow and Teleos in liters of product sold, which were then converted to pounds using a conversion rate of 2.68 pounds per liter.

The U.S. Chloropicrin Manufacturer's Task Force provided estimates of annual chloropicrin use by region based on an average over the past three years. The data indicate that North America uses the most chloropicrin, followed by Japan, China, and Europe, with a combined total of approximately 55 million pounds of active ingredient annually across these regions (***Table 1.4***). As noted, chloropicrin is undergoing registration in the EU and is currently used under an EUD in Italy and Greece.

Table 1.4. Yearly estimates of chloropicrin use (in pounds of active ingredient), representing the average amount sold per year over the last three years (2022-2024). These estimates were provided courtesy of the U.S. Chloropicrin Manufacturer's Task Force and are representative of multiple international suppliers of chloropicrin (1/27/2025, pers. comm.).

Region	Pounds of active ingredient	Primary crops/sites
North America (Canada, Mexico, and the U.S.)	25,500,000	Berries, brassicas, legumes, onions, potatoes, solanaceous crops, tobacco, and tree and vine replants.
Japan	15,000,000	Sweet potatoes
China	9,000,000	Berries and solanaceous crops
Latin America	1,000,000	Berries, melons, legumes, onions, pineapples, solanaceous crops, tobacco, and tree and vine replants
Europe †	3,000,000	Berries
Africa	600,000	Berries, legumes, onions, potatoes, solanaceous crops, and tree and vine replants.
Australia and New Zealand	1,200,000	Berries, brassicas, onions, and pineapples.
Total	**55,300,000**	

† Permitted under Emergency Use Derogations (EUD) while Annex I review is in process.

> 37. **FINDING:** 1,3-D continues to be used for pre-plant soil fumigation in numerous countries, including members of the European Union where it is used under an Emergency Use Derogation (EUD) while undergoing registration. More than 10 million pounds of product were sold across 6 countries in 2024.

> 38. **FINDING:** Chloropicrin continues to be used for pre-plant soil fumigation in numerous countries, with an estimated annual average of 55 million pounds of active ingredient sold across seven regions, including within the European Union under an Emergency Use Derogation (EUD).

While in theory 1,3-D and chloropicrin are not currently banned in the EU or the United Kingdom, their use is significantly restricted due to the regulatory restrictions and registration review processes outlined in this section. Therefore, soilless production (also known as substrate production) has greatly advanced in these countries, especially for high value crops such as strawberries, cane berries, and blueberries, as well as tomatoes. Its popularity has also grown due to the high cost of labor (Lieten, 2013). Soilless production is reported to enable a 30% increase in harvest labor efficiency (Lieten, 2013), although this may not hold true for labor in California.

In the United Kingdom, nearly 80% of strawberries are grown in tabletops using gutters with bags of coconut coir/fiber mixes usually grown under polyethylene macrotunnels. These macrotunnels provide rain protection, warmer temperatures, and extend the growing season, all of which improve grower profitability in this costly production system. Cane berries and blueberries are also grown under macrotunnels in pots with substrate made from coconut coir fiber and some peat and other materials. A smaller percentage of these same crops are also grown in substrate but in heated and carbon dioxide-enriched greenhouses for year-round production near the large population centers in Northern Europe.

Beyond soilless production, other non-fumigant pre-plant soil treatments such as biosolarization and anaerobic soil disinfestation (see ***Chapter 2*** for more details) have been developed and adopted in the EU, particularly in Spain and the Netherlands, as well as in Israel and Egypt. In addition, many countries use pathogen suppressive crop rotations and cover crops in both organic and conventional production systems. Where available, specific host resistance to key pathogens, nematodes, and arthropod pests is also being employed, either individually or as part of integrated control programs. Steam soil disinfestation has been investigated and deployed in smaller scale greenhouses and plant propagation nurseries in Italy, Norway, the Netherlands, and Japan. These alternatives face similar challenges in the EU and the United Kingdom as they do in the U.S., with the exception of soilless production methods, including tabletops, which have gained widespread adoption in the United Kingdom and northern EU countries such as the Netherlands and Belgium. This adoption is due to the advantages afforded by improved labor efficiency, government subsidies for agricultural infrastructure, and local permitting restrictions which differ significantly from those in the U.S.

In Australia, both fumigants are allowed for pre-plant soil fumigation in fruit and nursery plant propagation treatments. In addition, ethanedinitrile (EDN) is registered for commercial use as a pre-plant soil fumigant in Australia. EDN was discovered in 1815 but was not manufactured on a large scale until the late nineteenth century. It is now used in other industries such as chemical synthesis, pharmaceuticals, and plastics. EDN registration as a pre-plant fumigant is reported to be pending in other countries (Draslovka Services Group, 2024). In Australia, soilless production is also used for strawberries, cane berries, and blueberries.

In Mexico, commercially available fumigants include chloropicrin; metam sodium; metam potassium; dazomet; 1,3-D; a 1,3-D chloropicrin mixture; and, recently, dimethyl disulphide (DMDS), either alone or in combination with chloropicrin (Lopez-Arando et al., 2016). Soilless production is also used in Mexico for blueberries, cane berries, and strawberries.

Both 1,3-D and chloropicrin are registered and are reported to be used for pre-plant fumigation in China. Data on other fumigants used in China are not available. China has also been using soilless production for strawberries, cane berries, and blueberries.

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Chapter 2: Fumigant Alternatives

Section 2.1: Chapter overview

There are a variety of potential fumigant alternatives at various stages of development and deployment in California and beyond. Broadly, they use several biological, chemical, thermal, and cultural approaches to inactivating, resisting, or avoiding soil pests and pathogens (summarized in ***Table 2.1***). For the purpose of this review, alternatives to 1,3-D and chloropicrin are categorized as either non-biological chemical methods (meaning they use synthetic chemical pesticides) or non-chemical and biological methods (referring to methods that rely on heating, pest avoidance, biological resistance, host disruption, changes to soil reduction-oxidation potential, or **biopesticide** to inactivate soil pests).* In this way, conventional, commercialized, synthetic soil pesticides are distinguished from alternatives that generally use very different pest control mechanisms and, by extension, have differing environmental and human health implications.

Across the next 12 sections and for each of the 12 alternatives explored, we summarize 1) the fumigant alternative itself; 2) the crop-pest combinations for which the alternative is used and the scale of that use; 3) the effectiveness and duration of pest control provided by the alternative; 4) any known production yield effects; 5) costs associated with the initial set-up, implementation, and maintenance for the alternative method; 6) any additional land preparation, equipment needs, labor, and cultural practices with the fumigant alternatives (that are not needed for traditional fumigation methods); and lastly, 7) the availability, ease, and reliability of obtaining or implementing the alternative method. Broader takeaways regarding the state of the literature on the above are summarized in ***Section 2.14***. Select studies included in this review are summarized in ***Appendix B***.

We also explore the possible human health, environmental, and ecological impacts of these alternatives (***Section 2.15***); additional plant back restrictions of fumigant alternatives that extend beyond current fumigation methods (***Section 2.16***); negative and unintended consequences associated with fumigant alternatives (***Section 2.17***); the potential benefits of adopting and promoting the wide-scale use of fumigant alternatives in California (***Section 2.18***); and support and subsidies made available in other countries for fumigant alternatives (***Section 2.19***). Because there are important similarities among many of the fumigant alternatives that hold significance for these considerations, these impacts are explored in summary form across Sections 2.15–2.19.

Lastly, we conclude by sharing our perspectives on fumigant alternatives that provide the best trade-offs between effectiveness and the human health and environmental concerns associated with their use (***Section 2.20***).

Chapter 2 contains 28 Findings, 17 Conclusions, and 5 Recommendations.**

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*Bolded terms can be found in the glossary.

****Finding**. Fact(s) the study team finds that can be documented or referenced and that have importance to the study. **Conclusion**. A reasoned statement the study team makes based on findings. **Recommendation**. A statement that suggests an action or consideration as a result of the report findings and conclusions.

Table 2.1. Alternative strategies to fumigation with 1,3-D and/or chloropicrin, along with their general modes of action for pest control.

Alternative	Summary	Soil pest inactivation or mitigation mechanism(s)	Chemical or non-chemical method[1]	Pre-plant or post-plant application[2]	Pest inactivation targets[3]	Use constraints	Possible environmental trade-offs on farms	Potential soil health benefits relative to 1,3-D and chloropicrin fumigation	Examples of potentially compatible crops that currently use fumigation with 1,3-D and chloropicrin[4]
Alternative fumigants	Fumigants that are not 1,3-D or chloropicrin are drip, sprinkler, or shank applied to the soil. A taurpaulin cover may or may not be used.	Major alternative fumigants often rely on isothiocyanate compounds, which have broad biocidal activity when present at a critical concentration, although the mechanism of toxicity is not well understood.	Chemical	Pre-plant	Broad - inactivates nematodes, microbial pathogens, weed propagules	State and federal regulations that are used to determine permissible applications and emission control measures for 1,3-D and chloropicrin generally apply to alternative fumigants due to shared human and environmental safety risks. Some alternative fumigants are not registered for use in California.	Likely to have similar effects as 1,3-D and chloropicrin.	Likely to have similar effects as 1,3-D and chloropicrin.	Carrot, onion, potato, tomato, strawberry, sweetpotato
Non-fumigant pesticides	Non-volatile fungicides, nematicides, or broad biocides are applied to the soil via drip irrigation, shank, sprinkler, or granular incorporation methods.	Depending on the compound, mechanisms may include enzyme inhibition that leads to disruption in neurotransmitters or metabolic processes.	Chemical	Pre- and post-plant	Narrow - individual pesticides typically inactivate a subset of pest types (e.g., nematodes or fungi)	For soil application, must be able to use chemigation or incorporate granules into soil. Some non-fumigant pesticides are not registered for use in California.	Non-volatile, water soluble pesticides may be susceptible to runoff and create toxicity in non-target environments.	Possible decreased immediate inactivation of non-target soil organisms due to narrower activity of most non-fumigant pesticides.	Eggplant, melon, onion, pepper, potato, sweetpotato
Biologically derived pesticides and biocontrol agents	Biologically derived pesticides are added to the soil through surface or subsurface application techniques or are released through the degradation of incorporated biomass. Biocontrol agents in suspension or on a solid matrix are incorporated into soil.	Biologically derived pesticides are highly varied, and mechanisms can include enzyme inhibition, cell membrane disruption, and disruption of protein synthesis, but often the mechanism is not well understood. Biocontrol agents may parasitize, outcompete, or inhibit pests through production of antagonistic compounds.	Chemical and non-chemical (biological)	Pre- and post-plant	Narrow - individual biologically derived pesticides or biocontrol agents typically inactivate a subset of pest types (e.g., nematodes or fungi)	For soil application, must be able to use chemigation or incorporate granules into soil. Certain biopesticides may not be registered for use in California.	Possible unknown or unintended effects on non-target soil organisms or soil ecology.	Possible decreased immediate inactivation of non-target soil organisms due to narrower activity of several biologically derived pesticides and biocontrol agents.	Eggplant, tomato, strawberry

Alternative	Summary	Soil pest inactivation or mitigation mechanism(s)	Chemical or non-chemical method[1]	Pre-plant or post-plant application[2]	Pest inactivation targets[3]	Use constraints	Possible environmental trade-offs on farms	Potential soil health benefits relative to 1,3-D and chloropicrin fumigation	Examples of potentially compatible crops that currently use fumigation with 1,3-D and chloropicrin[4]
Anaerobic soil disinfestation	Soil is amended with labile (easily decomposed) organic matter, wetted, and covered with opaque tarps.	Combined stresses of moderate temperature increase, decreased oxygen, and bio-pesticides (either endogenous to soil amendments or produced through fermentation of the amendments) inactivate a broad spectrum of soil pests.	Non-chemical (biological and thermal)	Pre-plant	Broad - inactivates nematodes, microbial pathogens, weed propagules	Several weeks of hot, dry weather are typically required along with access to compatible organic matter soil amendments.	Possible emission of biologically produced carbon dioxide, methane, or nitrous oxide due to anaerobic breakdown of amended organic matter. Possible nitrate leaching if amendments contain excess nitrogen. Emission of volatile organic compounds produced through fermentation should be considered.	Addition of organic matter to soil may benefit soil water holding capacity, soil texture, and plant nutrient content of soil.	Eggplant, pepper, potato, strawberry, tomato
Biosolarization	Soil is amended with labile (easily descomposed) organic matter, wetted, and covered with clear tarps.	Combined stresses of high temperature, decreased oxygen, and bio-pesticides (either endogenous to soil amendments or produced through fermentation of the amendments) inactivate a broad spectrum of soil pests.	Non-chemical (biological and thermal)	Pre-plant	Broad - inactivates nematodes, microbial pathogens, weed propagules	Several weeks of hot, dry weather are typically required along with access to compatible organic matter soil amendments.	Possible emission of biologically produced carbon dioxide, methane, or nitrous oxide due to anaerobic breakdown of amended organic matter. Possible nitrate leaching if amendments contain excess nitrogen. Emission of volatile organic compounds produced through fermentation should be considered.	Addition of organic matter to soil may benefit soil water holding capacity, soil texture, and plant nutrient content of soil.	Eggplant, pepper, potato, strawberry, tomato

Alternative	Summary	Soil pest inactivation or mitigation mechanism(s)	Chemical or non-chemical method[1]	Pre-plant or post-plant application[2]	Pest inactivation targets[3]	Use constraints	Possible environmental trade-offs on farms	Potential soil health benefits relative to 1,3-D and chloropicrin fumigation	Examples of potentially compatible crops that currently use fumigation with 1,3-D and chloropicrin[4]
Cover or catch cropping	Various crops are grown between cash crops with the intent to cover and then be incorporated into soil rather than be harvested.	Host disruption can cause certain pests to die off or be outcompeted. Degradation of crop biomass in the soil produces isothiocyanates or other biologically derived pesticides.	Non-chemical (cultural)	Pre-plant	Narrow - depending on selection, termination, and incorporation of cover crops, a subset of pest types may be inactivated or have their host cycle disrupted (e.g., specific nematode or fungal species)	Additional materials and labor are required to establish and terminate cover crops during periods where fields may otherwise be fallow. Selection of cover crops must include those that disrupt the host cycle of target pests or contain biopesticidal compounds.	Additional field operations (and associated emissions from fuel use) are required to establish and manage the cover crops. Additional nutrient or herbicide inputs may also be needed. Emission of volatile isotiocyanate compounds from the decomposition of certain cover crops should be considered.	Addition of organic matter to soil may benefit soil water holding capacity, soil texture, and plant nutrient content of soil.	Eggplant, grape, pepper
Crop rotation	Different crops are grown on a given site each year.	Soil reservoirs cannot develop for pests with a narrow host range.	Non-chemical (cultural)	Not applicable, method uses selection of crops rather than soil treatment.	Narrow - depending on selection of rotated crops, a subset of pest types may have their host cycle disrupted (e.g., specific nematode or fungal species)	Rotated crops must be selected to disrupt the host cycle of target pests. Growers must have the knowledge and ability to cultivate each crop while ensuring that a market exists for each.	Depending on the crops rotated, additional fertilizer inputs and field operations (and associated emissions from fuel use) may be required compared to monoculture.	Depending on the crops rotated, soil organic matter and plant nutrients may be enriched in the soil.	Eggplant, melon, pepper, strawberry, squash
Resistant cultivars and rootstocks	Breeding and/or grafting is used to produce plants that are less susceptible to pest colonization and damage.	Plants produce compounds that inhibit pests or neutralize their toxins, have an enhanced immune response, and/or have epithelial tissues that are difficult for pests to penetrate.	Non-chemical (cultural)	Not applicable, method uses selection of crop varieties and grafts rather than soil treatment.	Narrow - resistant varieties or rootstocks typically exhibit resistance to a subset of pest types (e.g., nematodes or fungi) and do not inactivate weed propagules.	Varieties and rootstocks must be selected based on pest pressures at a given site and must also be compatible with the site's soil properties. Resistant varieties may have different sensory qualities compared to other varieties.	Additional nutrient inputs may be needed if crops require them for an enhanced immune response.	Possible decreased inactivation of non-target soil organisms due to crops resisting pests rather than broadly inactivating soil organisms.	Almond, apricot, carrot, grape, melon, pepper, strawberry, walnut

Alternative	Summary	Soil pest inactivation or mitigation mechanism(s)	Chemical or non-chemical method[1]	Pre-plant or post-plant application[2]	Pest inactivation targets[3]	Use constraints	Possible environmental trade-offs on farms	Potential soil health benefits relative to 1,3-D and chloropicrin fumigation	Examples of potentially compatible crops that currently use fumigation with 1,3-D and chloropicrin[4]
Soilless cultivation	Crops are grown hydroponically or in solid non-soil substrates derived from minerals or biomass.	Crops avoid pest exposure by not being in contact with soil.	Non-chemical (cultural)	Not applicable, method uses alternative growing media rather than soil treatment.	Broad - avoids crop exposure to nematodes, microbial pathogens, weed propagules	For indoor soilless systems, greenhouses must be constructed. Unique field preparation and management practices are required for soilless systems in open fields. If using solid substrates, suitable substrates must be sourced that properly anchor plants and avoid phytotoxicity. Hydroponic or nutrient solution management systems are needed.	Significant new infrastructure, possible additional substrate inputs, and possible increased energy use for open-field soilless production or greenhouse production of crops.	Not applicable, as this technique avoids use of soil.	Lettuce, pepper, squash, strawberry
Solarization	Soil is wetted and covered with clear tarps.	Passive solar heating leads to thermal inactivation of soil pests.	Non-chemical (thermal)	Pre-plant	Broad - inactivates nematodes, microbial pathogens, weed propagules	Several weeks of hot, dry weather are typically required.	Possible emission of biologically produced carbon dioxide, methane, or nitrous oxide due to anaerobic breakdown of background organic matter.	Soil heating may accelerate leaching of nutrients from soil organic matter or make soil organic matter more amenable to biodegradation.	Lettuce, melon, pepper, raspberry, strawberry, tomato
Steam treatment	Mobile boiler generates steam that is surface- or injection-applied to the soil.	Steam heating leads to thermal inactivation of soil pests.	Non-chemical (thermal)	Pre-plant	Broad - inactivates nematodes, microbial pathogens, weed propagules	Access to specialized applicator equipment is required. Only small areas can be treated with a single applicator in time frames comparable to fumigation.	Increased on-farm fuel consumption and associated emissions to run steam generators.	Soil heating may accelerate leaching of nutrients from soil organic matter or make soil organic matter more amenable to biodegradation.	Lettuce, ornamental flowers, strawberry,

[1] Refers to treatment of areas planted with crops, not adjacent buffer zones, margins, or alleys between rows.

[2] Based on data cited in this chapter and in ***Appendix B*** regarding observed efficacy against soil pests commonly controlled by 1,3-dichlopropene or chloropicrin.

[3] Based on data cited in this chapter and in ***Appendix B*** for studies that used fumigation as a positive control to compare against.

[4] Example crops correspond to a selection of crops discussed in this chapter where there is either reported current use in California or at least one study has observed a positive effect on crop yield and/or quality in response to the treatment relative to an untreated soil control. This should not be interpreted as the treatment being universally effective across all cultivation regions or cultivation practices or that the treatment consistently achieves the same results as fumigation with 1,3-D or choloropicrin. In some cases, there may be examples of no effect or a negative effect in response to the soil treatment.

Section 2.2: Non-biological chemical method: Alternative fumigants

Overview

Alternative fumigants are available that inhibit the phytoparasitic **nematodes** (which feed on or live with plants) and microbial pathogens commonly managed with 1,3-D and chloropicrin. Among the major fumigants currently used in California, dazomet, metam sodium, and metam potassium exhibit varying levels of activity against nematodes and microbial pathogens. All three function by degrading into methyl isothiocyanate, which has broad-spectrum pesticidal properties. Although the biochemical mechanisms underlying the pesticidal activity of isothiocyanate are not fully understood, research suggests it may act through several processes: disrupting cell membranes inhibiting microbial quorum sensing (blocking the chemical signaling bacteria use to coordinate activity and virulence); preventing biofilm formation (stopping bacteria from forming protective layers); and suppressing mycotoxin production (reducing harmful toxins produced by fungi) (Wang et al., 2020; Ge et al., 2024). It is also possible to fumigate directly with isothiocyanate compounds, such as methyl isothiocyanate, benzyl isothiocyanate, and allyl isothiocyanate. These fumigants can be applied using drip or shank injection methods, along with impermeable films, similar or identical to the approaches used for fumigation with 1,3-D or chloropicrin (U.S. EPA, 2024). Dazomet can be applied in a granular form, where the granules are spread on the soil surface, mixed into the soil, and then covered with impermeable film to trap fumigant vapors. The soil is then wetted through drip lines to activate the fumigant and help it disperse through the treated area (AMVAC Chemical Corporation, 2017a).

Outside of organosulfur fumigants that rely on isothiocyanate, dimethyl disulfide is a fumigant with multiple modes of action against nematodes. Transcriptome analysis of *Meloidogyne incognita* (a root-knot nematode) following contact or fumigation exposure to dimethyl disulfide indicated effects on calcium channels—disrupting muscle and nervous systems—and inhibition of ATP synthase, which impairs cellular energy production (Wang et al., 2023). Additionally, there is evidence that dimethyl disulfide interferes with the production of key cell membrane components and causes membrane disruption in fungi (Tyagi et al., 2020). In addition to directly targeting pests and pathogens, dimethyl disulfide may also activate signaling pathways in plants that enhance the plant’s systemic immune response, effectively “priming” the plant for a stronger immune defense against pests (Tyagi et al., 2020). Dimethyl disulfide can be applied using the same drip irrigation, shank injection, and impermeable film covers used in fumigation with 1,3-D and chloropicrin (U.S. EPA, 2010).

Crop-pest combinations and scale of use

Metam sodium, metam potassium, and dazomet are registered for use in California, and California Department of Pesticide Regulation (DPR) pesticide use reporting data show that they are currently employed across many specialty crops. Application data for alternative fumigants are provided in DPR's 2021 Pesticide Use Report. The data for metam sodium and metam potassium are summarized in ***Table 2.2***. For context, the total acres harvested in 2021 for each listed crop are provided based on data from the California Department of Food and Agriculture (CDFA, 2023).

Table 2.2. Acreage and crop data for alternative fumigants.

Fumigant	Number of crops that use fumigant	Top five crops by acres treated	Acres treated	Number of applications	Acres harvested
Metam sodium	27	Carrot	5,843	89	61,400
		Pepper	3,290	135	11,100
		Potato	2,654	31	27,700
		Processing tomato	1,553	47	228,000
		Onion	1,240	13	45,300
Metam potassium	45	Processing tomato	10,743	227	228,000
		Strawberry	4,403	130	39,000
		Sweet potato	2,623	137	18,500
		Fruiting pepper	1,569	110	11,000 (all pepper types)
		Onion (dry)	1,406	17	45,300 (all onion types)

Metam sodium was applied for 27 crops, with the top five being carrot (89 applications, 5,843 acres treated), pepper (135 applications, 3,290 acres), potato (31 applications, 2,654 acres), processing tomatoes (47 applications, 1,553 acres), and onion (1,324 applications, 1,240 acres) (DPR, 2021). Metam potassium (listed as potassium n-methyldithiocarbamate in the Pesticide Use Report), was used across 45 crops, and the top five crops were processing tomato (227 applications, 10,743 acres), strawberry (130 applications, 4,403 acres), sweet potato (137 applications, 2,623 acres), fruiting pepper (110 application, 1,569 acres), and onion (dry) (17 applications, 1,406 acres) (DPR, 2021). Fifty-eight applications of metam potassium (3,480 acres) were used for pre-plant fumigation without a specified crop. Dazomet saw relatively low usage in 2021, with just five applications and 10.5 acres treated for general pre-plant fumigation with no specific crop named (DPR, 2021). Methyl isothiocyanate was not used for any agricultural applications. Outside of California, metam sodium is used heavily for potato production in the U.S. Pacific Northwest. In 2005, 192,000 acres of potato were treated in this region (U.S. EPA, 2007). As of 2013, potato production in Washington, Oregon, and Idaho widely used metam sodium, with 90%, 82%, and 50% of acreage fumigated, respectively. Data were not available regarding the use of dazomet nationally.

Since metam sodium, metam potassium, and dazomet rely on isothiocyanate as the active ingredient, they have similar pest and pathogen targets. Studies have established effective concentrations of metam potassium for 90% reduction in *Fusarium oxysporum* (a soilborne fungus)*, Macrophomina phaseolina* (a fungal pathogen that causes charcoal rot)*, Meloidogyne javanica* (a root-knot nematode), and several common weeds (Khatri, Vallad, and Noling et al., 2021). Metam sodium has demonstrated effectiveness against fungal pathogens such as *Fusarium oxysporum, Fusarium solani*, and *Rhizoctonia solani*, as well as the nematode *Meloidogyne incognita* (Yücel et al., 2017). Research has also shown multiple isothiocyanate compounds exhibit strong activity against *Meloidogyne* spp. (Wu et al., 2011). Dazomet fumigation, while not fully effective, has achieved partial control of *M. incognita* (Cuadra et al., 2009).

Dimethyl disulfide is not registered for use in California and, as a result, is not listed in the 2021 DPR use report. Nationally, the U.S. EPA reported that approximately 2,000 acres of strawberries, tomatoes, and watermelon were treated annually with dimethyl disulfide between 2013 and 2017 (U.S. EPA, 2019). Research has shown this fumigant to be toxic to *Meloidogyne* spp. and *Fusarium oxysporum* (Gómez-Tenorio et al., 2018).

Allyl isothiocyanate is a compound produced in Brassicaceae plants (such as mustard, cabbage, and broccoli) that is also available in synthetic fumigant formulations. Fumigants containing allyl isothiocyanate are registered by the U.S. EPA (e.g., U.S. EPA, 2017 and U.S. EPA, 2024) and are also registered in several states for agricultural use (e.g., Florida and Georgia). However, this does not include California. Labels for registered fumigants containing allyl isothiocyanate indicate use for most common fungal pathogens (e.g., *Verticillium dahliea*, *Fusarium*, *Phytophthera*, and *Pythium* spp.), phytoparasitic nematodes (e.g., *Pratylenchus* and *Meloidogyne* spp.), and several major weeds (e.g., several broadleaf, grassy, and nutsedge weeds) and list a variety of compatible crops, which include tree nuts, stone fruit, root and tuber vegetables, strawberries, grapes, peppers, eggplant, and leaf vegetables, among others (U.S. EPA, 2017 and U.S. EPA, 2024). However, the acreage treated with these fumigants has not been reported.

Efficacy and duration of pest control

Metam sodium, metam potassium, and dazomet are broad spectrum fumigants that rely on generation of methyl isothiocyanate in the soil as the active pesticidal compound. Methyl isothiocyanate is broadly **biocidal**, and this is reflected in the large range of soil pests that are listed as targets on fumigant products containing these compounds; these include multiple plant parasitic nematodes, fungal and bacterial pathogens, and weeds (AMVAC Chemical Corporation, 1998, 2017a; Taminco U.S. Inc., 2019). Dimethyl disulfide fumigant products have similar broad biocidal activity that can target parasitic nematodes, microbial pathogens, and weeds (Arkema, Inc., 2016). Field and laboratory studies that examined pest and pathogen inactivation using metam fumigants have shown that broad spectrum control of weeds, *Meloidogyne* spp. nematodes, and major fungal pathogens (*Fusarium oxysporum* and *Macrophomina phaseolina*) is possible, often achieving greater than 90% or complete inactivation, although these effects were dose dependent for each pest target (Khatri, Vallad and Noling et al., 2021; Khatri, Vallad and Peres et al., 2021; Yücel et al., 2017). Although metam potassium proved effective for control of purple nutsedge and *Fusarium oxysporum,* up to 500 kg per hectare (~445 pounds per acre) of fumigant was needed (exceeding the manufacturer's recommended application rate of 390 kg per hectare (~348 pounds per acre)) to maximize nutsedge tuber inactivation and control *Fusarium* across the entire fumigated bed (Khatri, Vallad, and Noling et al., 2021).

Allyl isothiocyanate has a lower vapor pressure compared to methyl isothiocyanate, 1,3-D, or chloropicrin, meaning it is less prone to remaining in a liquid form rather than forming vapors that can diffuse throughout the soil (Zhang et al., 2023). Accordingly, a soil column study observed that allyl isothiocyanate applied via injection (at 20 cm depth, or 7.9 in) or surface drip had limited mobility in the soil (Zhang et al., 2023). Injected allyl isothiocyanate remained mostly localized within a 10 cm (3.9 in) radius of the injection location and drip-applied fumigant traveling 15 to 30 cm (5.9 to 11.8 in) from the point of application (with rapid drop-off in concentration over time at distances of 20 to 30 cm (7.9 to 11.8 in)) (Zhang et al., 2023). Measurement of mortality in several weed species showed that efficacy dropped off rapidly at 20 cm (7.9 in) depth and 15 cm horizontal distance from the point of drip application (Zhang et al., 2023). Inactivation of *Fusarium*, *Phytophthora*, and *Meloidogyne* spp. was confined to similar regions, with *Phytophthora* being most resistant (inactivation primarily in the upper 10 cm (3.9 in) of soil and within 10 cm horizontal distance of the point of drip application) (Zhang et al., 2023). A field trial for control of *Macrophomina phaseolina* in Florida strawberry production also showed challenges with allyl isothiocyanate mobility in soil, highlighting the importance of fumigant distribution at the time of application (Baggio et al., 2018). A Florida tomato trial measured inactivation of *Fusarium oxysporum*, purple nutsedge (*Cyperus rotundus*), and nematodes (*Meloidogyne*, *Belonolaimus*, and *Criconemella* spp.) (5 to 25 cm (2.0 to 9.8 in) depths sampled) and found that allyl isothiocyanate applied via shank at 367 kg per hectare (327 pounds per acre) most consistently matched the efficacy of 1,3-D and chloropicrin for inactivation of *F. oxysporum*, *Criconemella* nematodes, and purple nutsedge (Yu et al., 2019b).

A study examining allyl isothiocyanate fumigation in cut flowers and strawberry production in California found that the fumigant delivered partial or inconsistent control of several weeds, *Fusarium oxysporum*, *Pythium ultimum*, *Verticillium dahliae*, and citrus nematode (*Tylenchulus semipenetrans*), but also observed that performance, particularly at greater soil depths (18 in), was enhanced by blending allyl isothiocyanate with methyl isothiocyanate (Hoffman et al., 2020).

Studies that compared the effectiveness of dimethyl disulfide or dazomet against 1,3-D or chloropicrin for inactivation of various fungal pathogens and plant parasitic nematodes (e.g., *Meloidogyne* spp., *Fusarium* spp., *Pythium* spp.) revealed varying levels of control. For instance, dimethyl disulfide matched the *Meloidogyne* spp. suppression of fumigation with 1,3-D (achieving approximately 40 to 80% reduction depending on soil texture) and achieved similar reductions in root **galling** to fumigation. However, while some fungal pathogen levels (e.g., *Fusarium oxysporum*, *Rhizoctonia solani*) in the soil remained suppressed by roughly 15 to 20%, depending on sampling time and soil type, others (e.g., *Fusarium solani*, *Olpidium bornovanus*, *Pythium aphanidermatum*) did not significantly differ from levels observed in untreated soil (which was also often the case for 1,3-D) (Montiel-Rozas et al., 2019). *P. aphanidermatum* and *Pythium* G1 showed significant increases in root-associated levels following fumigation with dimethyl disulfide compared to untreated controls in sandy loam soil (Montiel-Rozas et al., 2019). For dazomet, the fumigant achieved roughly 85% reduction in total soil nematodes, approaching the effectiveness of chloropicrin (Harris, 1991). In one of two trials, dazomet also matched the *Verticillium dahliae* control (>97% reduction) of chloropicrin; however, the second trial showed a more muted control effect, and dazomet showed no effect on weeds (Harris, 1991).

Similar to fumigation with 1,3-D and chloropicrin, use of alternative fumigants only inactivates soil pests at the time of application. As a result, the duration of pest control depends on the time required for pests to recolonize the soil or any remaining pest populations to rebound either in the same growing season or the following rather than the persistence alone of the active ingredient. The federally registered labels for metam sodium and metam potassium products indicate at least two applications each year (before planting and after harvest) (AMVAC Chemical Corporation, 1998; Taminco U.S. Inc., 2019). Dazomet and dimethyl disulfide products are similarly recommended for pre-plant usage ahead of each crop listed on product labels (AMVAC Chemical Corporation, 2017a; Arkema, Inc., 2016). This is consistent with data from a melon cropping study that showed a rebound effect for certain root-associated fungal pathogens within three months of fumigation with dimethyl disulfide (Montiel-Rozas et al., 2019).

Production yield effects

Studies have demonstrated marked yield improvements for various alternative fumigants to 1,3-D and chloropicrin. For instance, metam sodium fumigation resulted in a 250% increase in pepper yield compared to untreated controls when used for fungal pathogen suppression (Yücel et al., 2017). Similarly, a 17 to 32% increase in potato yield was obtained for potatoes in metam sodium-treated soils compared to untreated soil (Tsror et al., 2005). Metam potassium and metam sodium were observed to improve tomato yield, with metam sodium having the stronger effect (Himelrick and Boyhan, 1998). For strawberries, a multi-year study in California compared metam sodium fumigation to fumigation with 1,3-D and chloropicrin and untreated controls (Ajwa and Trout, 2004). Yield results varied; in one year, no differences in marketable yield were observed between the control and fumigated treatments. In the second year, metam sodium significantly improved yield compared to untreated soil, and the increase was not significantly different from that achieved following fumigation with 1,3-D and chloropicrin. In the final year of the study, metam sodium continued to outperform untreated controls, but certain metam fumigation treatments failed to match the yield increases obtained with 1,3-D and chloropicrin, even when the application rate was nearly double that of 1,3-D and chloropicrin. In general, yield increases from metam sodium were lower than those observed for 1,3-D and chloropicrin, although the differences were often not statistically significant. This outcome was reinforced by data from a study comparing metam sodium to combinations of methyl bromide and 1,3-D or chloropicrin in California and Florida strawberry production (Haglund, 2000). The data showed that metam sodium alone did not improve yield over untreated controls. Notably, the addition of 1,3-D to metam sodium was required to achieve yield increases comparable to the methyl bromide mixtures. However, different application methods were used across the fumigants (shank, drip, or spray), and this could have impacted the effectiveness of certain treatments. Overall, these results agree with other data showing that metam fumigants are generally less effective for fungal pathogen and nematode control compared to 1,3-D and chloropicrin (Holmes et al., 2020). Fumigation with dimethyl disulfide resulted in significant and consistent improvements to cucumber yield (approximately 150 to 160% over untreated controls), matching the performance of fumigation with 1,3-D or methyl bromide and exceeding the yield increase observed after fumigation with dazomet (Yan et al., 2019).

Yield assessments following allyl isothiocyanate fumigation have shown inconsistent results. In two California field trials comparing allyl isothiocyanate fumigation to fumigation with 1,3-D and chloropicrin in strawberry cultivation, one trial failed to detect any differences in marketable yield between untreated controls and any fumigated treatments while the other trial showed a 10% increase in marketable yield only when allyl isothiocyanate was mixed with 1,3-D and chloropicrin (Hoffman et al., 2020). However, the latter trial did not include a control with 1,3-D and chloropicrin alone, making it difficult to isolate the effect of allyl isothiocyanate (Hoffman et al., 2020). In another set of California strawberry trials, allyl isothiocyanate shank-applied at 270 to 340 pounds per acre (303 to 381 kg per hectare) or drip-applied at 207 to 403 pounds per acre (232 to 452 kg per hectare) was able to achieve marketable yield increases on par with 1,3-D and chloropicrin fumigation (Ajwa, 2016). A series of three Florida trials studying allyl isothiocyanate fumigation (drip-applied at 183 to 367 kg per hectare, or 163 to 327 pounds per acre) in tomato production did not detect a significant yield benefit in 2 of the 3 trials (Yu et al., 2019b). In the third trial, a 70% yield increase relative to the untreated control was observed at the 229 kg per hectare (204 pounds per acre) application rate (Yu et al., 2019b).

Costs associated

A cost-benefit analysis of various fumigants for nematode control in Spain compared fumigation with metam sodium or dazomet (using application rates recommended by the manufacturer) to fumigation using 1,3-D and chloropicrin (Talavera-Rubia et al., 2022). Treatment costs were reported in euros (€) per hectare but are presented here in U.S. dollars per acre using an exchange rate of $1.09 per € at the time of writing. Treatment costs for fumigation with metam sodium or dazomet were reported as $375 per acre and $873 per acre, respectively, and the application rates were observed to yield similar levels of nematode suppression (roughly 51% control). The cost of fumigation with 1,3-D and chloropicrin fell between these values at $684 per acre, but the researchers noted that 1,3-D and chloropicrin outperformed both alternatives with 82% nematode control. Given possible differences in agricultural practices, climate, soil properties, and local markets for agricultural supplies and labor in Spain versus the U.S., the deployment costs may differ for California growers. Cost data are limited in California, but a 2004 cost and return study for production of fresh market and processing carrots determined the cost of metam sodium fumigation to be $145 per acre ($241 per acre in 2024 dollars) (Meister, 2004a; Meister, 2004b).

Additional requirements for use

Alternative fumigants generally utilize the same application and emission control methods as 1,3-D and chloropicrin. As a result, there should be minimal differences in the shank application, drip application, or tarp application methods used. Dazomet is available in granule form. Accordingly, a drop spreader is needed to apply the granules to the soil surface. Tillage may be used to incorporate the granules into the soil, which is followed by sealing and wetting of the soil. This can involve smoothing and compacting the soil followed by irrigation, or it can entail laying of drip lines and covering the soil with impermeable film (AMVAC Chemical Corporation, 2017b).

Availability, ease, and reliability

Alternative fumigants are commercially available and, for those registered in California, may be used through the same applicator services that offer fumigation with 1,3-D and chloropicrin. These fumigants use the same tractor implements as 1,3-D and chloropicrin to apply the pesticide and cover the soil with impermeable film. Additionally, these fumigants share a similar regulatory framework in California insofar as there are defined access restrictions, buffer zone requirements, and block size limits for each fumigant. As a result, alternative fumigants have similar ease of sourcing and implementation as 1,3-D and chloropicrin.

> 39. **FINDING:** Metam sodium and metam potassium are currently used in several California cropping systems. These fumigants can be used with similar soil preparation, application, and tarp covering practices compared to 1,3-D and chloropicrin.

> 40. **CONCLUSION:** Metam sodium and metam potassium can serve as broad spectrum soil fumigants, similar to 1,3-D and chloropicrin. However, the duration of soil pest control and the application rates for these fumigants can differ compared to 1,3-D and chloropicrin.

Section 2.3: Non-biological chemical method: Non-fumigant pesticides

Overview

Pesticides that are not volatile, and thus not suitable for fumigation, may be applied to crops or to the soil via spraying, chemigation (applying chemicals through an irrigation system), or mixing in granular formulations. Popular non-fumigant nematicides include N-methyl carbamate (also called oxamyl, e.g., Vydate), fenamiphos (e.g., Nemacur), ethoprop (e.g., Mocap), fluensulfone (e.g., Nimitz), fluazaindolizine (e.g., Salibro Reklemel active), and terbufos (e.g., Counter). Fluopyram (e.g., Velum One) is a fungicide with nematicidal activity (Nnamdi et al., 2022; Watson et al., 2023). Oxamyl, ethoprop, fenamiphos, and terbufos act to inhibit the enzyme acetyl cholinesterase, disrupting the function of this enzyme and its critical role in regulating neurotransmitters. This results in paralysis and death of nematodes when they have sufficient exposure to the pesticide. The mechanisms of fluensulfone and fluazaindolizine are distinct from other non-fumigant nematicides and are the subject of active research (Kearn et al., 2014; Matera et al., 2021). Fluopyram inhibits the enzyme succinate dehydrogenase, which disrupts energy metabolism in nematodes and fungi such that they are no longer able to respire and die as a result (Bouillaud, 2023).

Crop-pest combinations and scale of use

The product labels for major commercial versions of each non-fumigant pesticide specify susceptible pests and the crops or regions where the nematicide is effective. For the broad spectrum nematicides, these include:

- Vydate (oxamyl) (DuPont, 2008): Bulb (*Ditylenchus dipsaci)*, citrus (*Tylenchulus semipenetrans),* lesion *(Pratylenchus* spp.), reniform (*Rotylenchulus reniformis*), ring (*Criconemella* spp.), root knot (*Meloidogyne* spp.), spiral (*Helicotylenchus* spp. and *Rotylenchus* spp.), sting (*Belonolaimus* spp.), stubby root (*Trichodorus* and *Paratrichodorus* spp.), and/or stunt (*Tylenchorhynchus* spp.) nematodes.
- Mocap (ethoprop) (AMVAC Chemical Corporation, 2017b): Burrowing (*Radopholus similis*), cyst (*Heterodera* spp.), dagger (*Xiphinema* spp.), lesion, reniform, ring, root-knot, lance (*Hoplolaimus* spp.), spiral, sting, stubby root, and/or stunt nematodes.
- Nemacur (fenamiphos) (Bayer Crop Science, 2003): Label only specifies nematodes generally.
- Nimitz (fluensulfone) (ADAMA, 2016): Lance, lesion, potato cyst (*Globodera* spp.), root-knot, sting, and/or stubby root nematodes.
- Counter (terbufos) (AMVAC Chemical Corporation, 2021): Cyst, dagger, lance, lesion, root-knot, spiral, stunt, sting, and/or stubby root nematodes.
- Salibro Reklemel active (fluazaindolizine) (Corteva Agriscience, 2023): Citrus, lesion, dagger, pin (*Paratylenchus hamatus*), ring, root-knot, sting, and/or stubby root nematodes.

Oxamyl, ethoprop, and fluensulfone are registered for nematode control in California and are represented in the 2021 DPR Pesticide Use Report. The use data for these pesticides are provided in ***Table 2.3***.

Table 2.3. 2021 DPR use data for non-fumigant nematicides and fungicides.

Name	Pounds applied [number of applications]	Crops
Oxamyl	25,969.28 [961]	Cantaloupe, **celery***, **cotton****, daikon, eggplant, garlic, melon, **onion (dry)***, **pepper** (**fruiting*** and spice), **potato***, pumpkin, squash, summer squash, **tomato** (**fresh market*** and processing), watermelon, zucchini
Ethoprop	9,489.73 [227]	Bean (unspecified), cabbage, outdoor flowers, potato, sweet potato
Fluensulfone	4,718.53 [35]	Cantaloupe, pepper (fruiting), squash, tomato (fresh market and processing), watermelon

*Over 2,000 acres treated
**Over 10,000 acres treated

Although they are not used in California, product labels for major fenamiphos, terbufos, and fluazaindolizine products list compatible crops. For fenamiphos, these include apple, asparagus, banana, beet, cabbage, cherry, citrus, eggplant, grape, nectarine, peach, peanut, pineapple, raspberry, strawberry, and tobacco (Bayer Crop Science, 2003), and for terbufos these include corn, sugar beet, and grain sorghum (AMVAC Chemical Corporation, 2021). Fluazaindolizine may be used with almond, apricot, bell pepper, carrot, cherry, cucumber, citrus, eggplant, grape, peach, squash, sweet potato, tomato, walnut, and watermelon crops in addition to a wide range of other crops (which does not include strawberries) (Corteva Agriscience, 2023).

Efficacy and duration of pest control

Similar to 1,3-D, chloropicrin, and other fumigants, non-fumigant pesticides only inactivate soil pests at the time of application. Duration of control will depend on the time required for pests to rebound in numbers and/or recolonize the soil rather than persistence of the active ingredient.

Data comparing certain non-fumigant pesticides (oxamyl and fenamiphos) to 1,3-D observed that oxamyl did not affect *Meloidogyne* spp. levels on melon roots, whereas fumigation with 1,3-D delivered significant reduction. Fenamiphos reduced melon root-associated *Meloidogyne* spp. by approximately 40% in a sandy loam soil but had no effect in clay loam. In contrast, 1,3-D showed reductions in both soil types (Montiel-Rozas et al., 2019). A sweet potato cropping study that compared inactivation of the nematode *Rotylenchulus reniformis* with 1,3-D and an array of non-fumigant pesticides (including oxamyl, fluopyram, fluensulfone, and fluazaindolizine) found that only oxamyl and fluopyram achieved significant reductions compared to non-fumigated control soils, but this control effect was not apparent across most time points and test sites (Watson et al., 2023).

In contrast, comparison of fluopyram, oxamyl, fluensulfone, and fluazaindolizine to fumigation with 1,3-D and 1,3-D with chloropicrin in a pepper-squash rotation showed that the non-fumigant pesticides could generally match the root galling control achieved with fumigation (Nnamdi et al., 2022). For fluensulfone, the reduction was significantly greater than that for the fumigants. Likewise, soil levels of the plant-parasitic nematodes *Meloidogyne incognita*, *Paratrichodorus* spp. and *Mesocriconema* spp. were not significantly different between fumigated soils and those treated with the non-fumigant pesticides during a pepper-squash rotation (Nnamdi et al., 2022). Examination of *M. incognita* inactivation in response to fluazaindolizine application in a squash production system showed that two applications across the growing season was most effective, delivering a 58.4 to 63.6% reduction in soil *M. incognita* populations and 26% reduction in root galling index compared to untreated soils (additionally, this exceeded the performance of two applications of oxamyl) (Qiao et al., 2021). An aqueous in vitro comparison of fluazaindolizine, oxamyl, and fluopyram treatment effects on motility reduction for dagger nematode (*Xiphinema index*) found the effects to be variable and inconclusive (Tzortzakakis et al., 2024). For instance, one experiment showed that 1 ppm fluazaindolizine resulted in similar motility reduction for dagger nematode (*Xiphinema index*) compared to 1 ppm fluopyram (79 to 89% immotile after 24 hours exposure), and this exceeded treatment with 12.5 ppm oxamyl (52.5% immotile after 24 hours exposure) (Tzortzakakis et al., 2024). However, by 72 hours of exposure, complete or near complete immobility was seen for all nematicides (Tzortzakakis et al., 2024). In additional repeat experiments, 1 ppm fluopyram and 12.5 ppm oxamyl performed similarly, while fluazaindolizine significantly underperformed, or all three nematicides performed similarly (Tzortzakakis et al., 2024). When compared in an outdoor potted fig study, only fluazaindolizine applied at 2 kg per hectare (1.8 pound per acre) consistently reduced dagger nematode populations in the soil, achieving a 46% decrease compared to untreated soil; oxamyl at 2 kg per hectare (1.78 pounds per acre) and fluopyram at 0.25 kg per hectare (~3.6 ounces per acre) failed to show a significant change in soil nematode levels compared to the control (Tzortzakakis et al., 2024). A multi-year greenhouse trial comparing soil densities of *M. incognita* following fumigation with 1,3-D and chloropicrin or treatment with non-fumigant nematicides found that these nematicides showed moderate reductions in nematode levels (51 to 64% reduction) but did not match the effectiveness of 1,3-D and chloropicrin (82% reduction) (Talavera-Rubia et al., 2022).

Production yield effects

An investigation of multiple non-fumigant nematicides, including oxamyl and ethoprop, in tomato production found that although nematode suppression was high, none led to improved root or shoot growth compared to plants in untreated infested soils (Radwan et al., 2012). Similarly, application of fluopyram in tomato production for nematode control resulted in nematode suppression but had no effect on tomato yield compared to untreated controls (Meza et al., 2021). In contrast, oxamyl and the nematicide aldicarb consistently increased potato yield by 9 to 20% compared to untreated controls (Hafez and Sundararaj, 2009). In a study that applied multiple non-fumigant pesticides (aldicarb, carbofuran, ethoprop, oxamyl, phenamiphos, and terbufos) to control sting nematode (*Belonolaimus longicaudatus*), oxamyl delivered the greatest pepper yield benefits (approximately 250% over untreated controls) (Rhoades, 1981). An examination of fluazaindolizine application to suppress *M. incognita* in squash production observed a 10 to 67% increase in yield compared to untreated controls (a result similar to oxamyl treatment) (Qiao et al., 2021). These results show that common non-fumigant pesticides do not appear to have universal yield effects; rather, yield benefits may relate to specific combinations of pesticides, pests, environmental conditions, and target crops.

Costs associated

A cost analysis performed in Spain examined several of the non-fumigant nematicides listed above (Talavera-Rubia et al., 2022). Specifically, oxamyl, fluopyram, and fenamiphos were $71 per acre, $97 per acre, and $428 per acre, respectively, when applied at the rates recommended by the manufacturer (values converted from original values reported in € per hectare using an exchange rate of $1.09 per €). While all non-fumigant nematicides were less expensive than fumigation ($684 per acre), it was noted that none matched the nematode inactivation of 1,3-D and chloropicrin. Since the nematode control effectiveness of fumigation in this study was observed to be 82% and the inactivation rates for the non-fumigant pesticides ranged 55 to 64%, there may be avenues to enhance effectiveness through increasing application rates or frequency that still result in lower costs than fumigation (particularly for oxamyl and fluopyram, given the large cost difference relative to fumigation identified in this study).

Additional requirements for use

Liquid formulations of non-fumigant pesticides can be applied to soil using drip methods that overlap with fumigant techniques. Chemigation may also be used, which utilizes common irrigation methods (e.g., furrow, drip, sprinkler) to deliver the pesticide. The need to introduce the pesticide to irrigation water, like chemigation with fumigants, represents the primary deviation from standard irrigation practices. For granulated pesticide formulations, surface application and incorporation into the soil through discing or tillage are required. However, this may not represent a deviation from fumigation practices, since tillage is also used to loosen compacted soil ahead of fumigation to promote fumigant dispersion.

Availability, ease, and reliability

Certain non-fumigant pesticides that target soil pests are registered for use in California and are commercially available (i.e., ethoprop, fluensulfone, oxamyl). Others are commercially available and can be used outside of California (e.g., fenamiphos, fluazaindolizine, terbufos). These pesticides are available in liquid or solid granular formulations. Liquid product can be applied using chemigation methods that growers may already use for fertigation (applying fertilizer through an irrigation system) or that overlap with irrigation systems, such as sprinkler, drip, floor, border, and furrow irrigation methods. Granules are spread on the soil surface and then incorporated into the upper soil layer using discing or tillage. The use of common application methods and general low risk of **phytotoxicity** for these pesticides removes barriers to implementation for growers.

41. **FINDING:** Several non-fumigant pesticides are currently used in California to control soil pests. These pesticides target a narrower range of soil pests relative to 1,3-D and chloropicrin. By extension, and in contrast to fumigation, their more targeted action can allow for application during crop growth and not just during the pre-plant period. However, pest control effectiveness relative to 1,3-D and chloropicrin is inconsistent.

42. **CONCLUSION:** Non-fumigant pesticides are unlikely to match the broad-spectrum soil pest control of 1,3-D and chloropicrin unless used in combination or with other pest control measures. They may be useful in cases where phytoparasitic nematodes are the primary pest pressure or where there is need for nematode control post-planting, but research is needed to determine the pesticide application, environmental, pest, and crop variables that affect pest inactivation and influence yield outcomes.

Section 2.4: Non-chemical and biological method: Anaerobic soil disinfestation and biosolarization

Overview

Anaerobic soil disinfestation and **biosolarization** both involve incorporation of organic matter into moist soil and covering the soil with tarps (see ***Figure 2.1***). As originally conceptualized, anaerobic soil disinfestation used opaque tarps, and biosolarization employed clear tarps. However, the terms are now often used interchangeably in many scientific articles and common discourse. The tarps limit oxygen diffusion into the soil, promoting anaerobic activity by microorganisms in the soil as they digest the organic matter amendments. Such fermentation in the soil can produce biochemicals with pesticidal activity such as certain natural isothiocyanates, organic acids, and ketones, which are also retained in the soil due to the tarps (Hewavitharana et al., 2014; Shea et al., 2021a). The tarps also facilitate soil heating, either by absorbing solar radiation when using opaque tarps or creating a greenhouse effect when using clear tarps. This heating can thermally inactivate pests, and supports microbial activity that decreases soil oxygen and promotes anaerobic fermentation, thereby producing fermentative biochemicals with pesticidal activity.

Figure 2.1. A field is prepared for anaerobic soil disinfestation. (**A**) A tractor applies rice bran to a field. Rice bran will serve as a carbon source to stimulate microbial activity. (**B**) A rototiller incorporates the rice bran into the soil. (**C**) Soil beds are constructed, drip irrigation lines are laid, and tarps are applied to seal the beds, trapping moisture and preventing oxygen from entering the soil so as to maintain anaerobic conditions. Photos: Joji Muramoto.

The selection of organic matter amendments can influence the types and levels of biologically derived pesticides in the soil (Hewavitharana et al., 2014; Achmon et al., 2016). In general, amendments should be readily degradable by soil microorganisms (**labile**) and contain sufficient nutrients for soil microorganisms to avoid a nutrient limitation that could temper fermentation. The organic amendments should supply microorganisms with labile forms of carbon, as the carbon to nitrogen ratio is an important driver of determining how quickly the material can be broken down and efficiently consumed by resident microorganisms in order to create anaerobic conditions. Early research on anaerobic soil disinfestation and biosolarization used amendments like molasses and composted poultry litter (Rosskopf et al., 2010), rice or wheat bran (Momma et al., 2006), ethanol (Momma et al., 2010), and mustard seed meal (Stapleton and Banuelos, 2009)—all of which are byproducts of related crops and their food products such as sugar, white rice and bread, and canola oil production. Research into a variety of organic matter residues is an ongoing focus, with ease of handling and use, availability, and price being key. Using byproducts recycled from food processing as soil amendments for anaerobic soil disinfestation and biosolarization adds to the sustainability of this approach. Other byproducts investigated include tomato skins and seeds from tomato processing (Achmon et al., 2016), grape skins and seeds from winemaking (Serrano-Pérez et al., 2017), spent grain from brewing (Serrano-Pérez et al., 2017; Liu et al., 2023, Daugovish et al., 2023), wheat middlings (Daugovish et al., 2023), coffee grounds (Daugovish et al., 2021), almond hulls (Holtz et al., 2018; Fernandez-Bayo et al., 2020; Shea et al., 2022), and olive pomace from oil pressing (Domínguez et al., 2014) have successfully resulted in biologically derived pesticide formation or pest suppression during biosolarization or anaerobic soil disinfestation trials. *Brassica* biomass and poultry manure can also be effective soil amendments (Stapleton and Banuelos, 2009; Domínguez et al., 2014).

Anaerobic soil disinfestation and biosolarization combine multiple pest stressors. Possible contributors to pest inactivation include soil heating (Shrestha et al., 2016), oxygen depletion during fermentation (Achmon et al., 2018), biologically derived pesticide accumulation due to fermentation or through leaching of biochemicals with pesticidal activity from the soil amendments (Oka, 2010), and changes in the resident soil microbiome including increases in known biological control organisms (Mazzola et al., 2020). The use of multiple inhibition mechanisms provides redundancy, potentially compensating for the absence or reduced effectiveness of some mechanisms due to varying environmental conditions.

Crop-pest combinations and scale of use

Data are scarce concerning the commercial use of biosolarization and anaerobic soil disinfestation. Within the California organic strawberry industry, it is estimated that roughly 2,500 acres (approximately 50% of production acreage for organic strawberries) employ some form of these techniques, with most of this adoption occurring in the last 10 years (Hsu, 2024). Moreover, there are California companies that assist growers with treating their fields for biosolarization or anaerobic soil disinfestation—by supplying or applying drip tape, specialized biosolarization plastic tarps, carbon sources, and tools for measuring anaerobicity—similar to how growers work with commercial applicators to fumigate fields with 1,3-D or chloropicrin.

Research has indicated that biosolarization and anaerobic soil disinfestation can suppress a broad range of soil pests and pathogens and is compatible with multiple crops. As the selection of tarp material differentiates the two techniques, with biosolarization using transparent tarps to promote greater soil heating, it is reasonable to assume that the pest control observed for anaerobic soil disinfestation is also achievable through biosolarization. A meta-analysis of anaerobic soil disinfestation studies found the technique was capable of suppressing fungal, bacterial, and **oomycete** pathogens (Shrestha et al., 2016). These include species within the genera *Fusarium*, *Pythium*, *Phytophthora*, *Sclerotium*, *Verticillium*, *Rhizoctonia*, and *Macrophomina* (Shrestha et al., 2016). The same review found that the overall effect of anaerobic soil disinfestation on nematode inactivation was most pronounced for the genus *Globodera*. Several studies suggest that control of *Meloidogyne* spp. and *Pratylenchus* spp. nematodes via biosolarization and anaerobic soil disinfestation is possible (Fernandez-Bayo et al., 2020; Shea et al., 2022; Wu et al., 2024).

A review of crop yield effects following anaerobic soil disinfestation showed that eggplant exhibited the most consistent increase compared to untreated and fumigated soils and that other crops, such as bell pepper, strawberry, tomato, and potato, were more variable in their performance (Shrestha et al., 2016). Results from individual studies confirm that it is possible to achieve yield benefits relative to untreated control soils for tomatoes, strawberries, and almonds grown in soils following biosolarization or anaerobic soil disinfestation (Browne et al., 2017; Guo et al., 2017; Achmon et al., 2018; Song et al., 2020; Daugovish et al., 2023; Song et al., 2023). However, additional research is needed to define the process and environmental variables that maximize the effectiveness of biosolarization and anaerobic soil disinfestation.

Efficacy and duration of pest control

Biosolarization and anaerobic soil disinfestation are capable of significant reduction in the population or activity (high-level suppression) of fungal pathogens. Various studies summarized in ***Appendix B*** show variability in the suppression of major fungal pathogens such as *Fusarium* spp., *Phytophthora* spp., *Rhizoctonia solani*, *Verticillium dahliae*, and *Macrophomina phaseolina*. However, inactivation of these pathogens to below the detection limit was observed across several studies and treatment conditions, which speaks to the impacts of soil amendment type, soil depth, and weather on effectiveness (Shrestha et al., 2021). Notably, enrichment, rather than inactivation, of *Fusarium oxysporum* was observed during ASD in soil pots when the soil lacked sufficient microbial activity to create a persistent anaerobic condition in the soil (Henry et al., 2020). Control of phytoparastic nematodes, such as *Pratlyenchus* spp. and *Meloidogyne* spp., was relatively higher. This was demonstrated in a **meta review** of multiple studies, which showed that fungal pathogen inactivation averaged 64% while plant parasitic nematode inactivation averaged 90% (Lopes et al., 2022). Similarly, a **meta-analysis** of 533 studies reinforced this finding by observing that anaerobic soil disinfestation was, on average, capable of 70% suppression of fungal, bacterial, and oomycete pathogens, although control varied for individual pathogens, and that plant parasitic nematodes showed 37% reduction (Shrestha et al., 2016). Inhibition was most pronounced for nematodes in the genus *Globodera* (56% reduction) but was not significant for the *Meloidogyne* and *Pratylenchus* genera (Shrestha et al., 2016). However, there may be a confounding effect of study scale since greater inactivation was seen in large field trials compared to small field plots (Shrestha et al., 2016). There are limited data concerning the duration of pest control following biosolarization or anaerobic soil disinfestation, but one study using anaerobic soil disinfestation with rice bran amendment observed suppression of *Verticillium dahliae* for 2 years post-treatment (Rosskopf et al., 2015).

Production yield effects

A comprehensive review of anaerobic soil disinfestation research found that the technique was capable of achieving an average yield increase of 30% over untreated controls and 6% increase over fumigated treatments (Shrestha et al., 2016). This primarily reflected trials with bell pepper, eggplant, strawberry, tomato, and potato. For most crops, the data suggest that anaerobic soil disinfestation conditions, such as temperature, duration, soil texture, and amendment type, can affect the likelihood of a yield increase (Shrestha et al., 2016). Additionally, the greatest yield benefits were associated with treatment durations of three weeks, use in sandy soil, and soil temperatures greater than 35˚C (95˚F). Biosolarization using tomato pomace (processing byproduct) amendments was observed to improve tomato yield in one of two trial years, with differences in plant-back time being the assumed cause of the variability (Achmon et al., 2018). Biosolarization with chicken and sheep manure amendments improved the yield of pepper compared to untreated soils (up to 32% increase) and soils fumigated with methyl bromide (up to 11% increase) in soils infested with *Meloidogyne incognita* (Ros et al., 2008). Moreover, the quality of pepper fruit was enhanced in the biosolarized soil relative to the fumigated soil (Ros et al., 2008). Soils biosolarized with chicken manure amendment elevated strawberry yield in soils containing the pathogen *Macrophomina phaseolina*, and the increase was similar to that seen with 1,3-D and chloropicrin fumigation (Chamorro et al., 2015). Additionally, anaerobic soil disinfestation using varying levels of amended rice bran or molasses showed that multiple treatments achieved marketable yield increases similar to fumigation with 1,3-D and chloropicrin (Mazzola et al., 2018). In soils that had not been fertilized ahead of treatment, anaerobic soil disinfestation with rice bran amendment delivered significantly greater yield increases than fumigation (Mazzola et al., 2018).

Costs associated

Costs for biosolarization and anaerobic soil disinfestation relate to materials and field operations to incorporate soil amendments, shape beds or smooth the soil surface, lay drip line, and mulch and subsequently remove the tarps. Of these steps, purchasing and incorporating the amendments are unique compared to conventional fumigation, while the application and removal of tarps is similar to fumigation. Installation of a drip irrigation system for biosolarization or anaerobic soil disinfestation may also be a unique requirement if shank-applied fumigation would otherwise be used or the subsequent crop does not use drip irrigation. Economic analyses for these fumigant alternatives are limited. However, a study that considered anaerobic soil disinfestation for fresh-market tomato production in Florida found that costs ranged from approximately $1,900 per acre to $2,900 per acre, depending on the quantity of soil amendments used (molasses and composted poultry litter) and the deployment location (Shi et al., 2019). For comparison, fumigation with 1,3-D and chloropicrin was determined to be approximately $1,800 per acre. A cost analysis of biosolarization using chicken manure amendment in Spain determined the process cost to be €2,700 per hectare ($1,191 per acre using $1.09 U.S. dollars per euro) versus €1,550 per hectare ($684 per acre) for fumigation with 1,3-D and chloropicrin (Talavera-Rubia et al., 2022). In the Florida study, soil amendments (molasses and composted poultry manure) accounted for 39 to 52% of the total cost, depending on the application rate (specifically, 741 gallons of molasses per acre and 4.5 tons of composted poultry litter per acre versus 1,482 gallons of molasses per acre and 9 tons of composted poultry litter per acre) (Shi et al., 2019). A California study in strawberry production identified anaerobic soil disinfestation costs to be roughly $2,000 to $3,000 per acre, with the types of amendments used accounting for the range in cost (Shennan et al., 2012). Another California strawberry production study conducted by the same team indicated much higher costs for anaerobic soil disinfestation (up to €44,917 per hectare, or $18,185 per acre added cost compared to untreated soils), but these were comparable to, and sometimes less than, fumigation costs for 1,3-D and chloropicrin at each field site (Shennan et al., 2018; see ***Table 2.4*** for summary). Moreover, all trials showed an expected increase in net returns owing to enhanced yield following anaerobic soil disinfestation relative to untreated control soils. However, net return figures varied relative to fumigation, with anaerobic soil disinfestation achieving 92 to 96% of the net returns obtained through fumigation in instances where anaerobic soil disinfestation and fumigation had similar yields (Shennan et al., 2018; see ***Table 2.4*** for summary).

Table 2.4. Treatment costs and net revenues above treatment and harvest costs are compared for anaerobic soil disinfestation (ASD) and fumigation with 1,3-D (37.1% of mixture) and chloropicrin (56.6% of mixture), marketed as Pic-Clor 60. Select data are adapted from Sheenan et al. (2018).

Field site location; trial years	Treatment in metric tons (Mg) or kilograms (kg) per hectare	Treatment cost ($/hectare) [$/acre]	Treatment cost above untreated control ($/hectare) [$/acre]	Net revenue above treatment and harvest costs ($/hectare) [$/acre]
Castroville; 2010–2011	Untreated control	($54,072) [$21,891]	--	($48,665) [$19,702]
	ASD three weeks with rice bran at 20 Mg ha^{-1}	($67,900) [$27,490]	($13,828) [$5,598]	($48,016) [$19,440]
	ASD three weeks with rice bran at 17.8 Mg ha^{-1} plus mustard seed meal at 2.2 Mg ha^{-1}	($72,484) [$29,346]	($18,412) [$7,454]	($46,020) [$18,632]
	ASD six weeks with rice bran at 20 Mg ha^{-1}	($67,166) [$27,193]	($13,094) [$5,301]	($47,169) [$19,097]
	ASD six weeks with rice bran at 17.8 Mg ha^{-1} plus mustard seed meal at 2.2 Mg ha^{-1}	($71,394) [$28,904]	($17,322) [$7,013]	($44,852) [$18,159]
	Bed fumigation with Pic-Clor 60, 337 kg ha^{-1}	($57,948) [$23,461]	($3,876) [$1,569]	($45,234) [$18,313]
Watsonville; 2010–2011	Untreated control	($40,941) [$16,575]	--	($36,847) [$14,918]
	ASD with rice bran at 20 Mg ha^{-1}	($69,913) [$28,305]	($28,972) [$11,730]	($50,015) [$20,249]
	ASD with rice bran at 16.7 Mg ha^{-1} plus mustard seed meal at 3.3 Mg ha^{-1}	($76,995) [$31,172]	($36,054) [$14,597]	($37,555) [$15,204]
	Bed fumigation with Pic-Clor 60, 337 kg ha^{-1}	($68,064) [$27,556]	($27,123) [$10,981]	($54,338) [$21,999]

Field site location; trial years	Treatment in metric tons (Mg) or kilograms (kg) per hectare	Treatment cost ($/hectare) [$/acre]	Treatment cost above untreated control ($/hectare) [$/acre]	Net revenue above treatment and harvest costs ($/hectare) [$/acre]
Watsonville; 2011–2012	Untreated control	($39,573) [$16,021]	--	($35,615) [$14,419]
	ASD with rice bran at 20 Mg ha^{-1}	($73,653) [29,819]	($34,080) [$13,798]	($53,380) [$21,611]
	ASD with rice bran at 16.7 Mg ha^{-1} plus mustard seed meal at 3.3 Mg ha^{-1}	($84,490) [$34,206]	($44,917) [$18,185]	($57,012) [$23,082]
	Bed fumigation with Pic-Clor 60, 337 kg ha^{-1}	($86,239) [$34,915]	($46,666) [$18,894]	($70,695) [$28,621]
Santa Maria; 2011–2012	Untreated control	($100,604) [$40,730]	--	($90,544) [$36,657]
	ASD with rice bran at 20 Mg ha^{-1}	($120,211) [$48,668]	($19,607) [$7,938]	($95,340) [$38,599]
	ASD with rice bran at 16.7 Mg ha^{-1} plus mustard seed meal at 3.3 Mg ha^{-1}	($120,733) [$48,880]	($20,129) [$8,149]	($86,626) [$35,071]
	ASD with rice bran at 20 Mg ha^{-1} plus fish emulsion[*]	($123,913) [$50,167]	($23,309) [$9,437]	($88,534) [$35,844]
	Bed fumigation with Pic-Clor 60,337 kg ha^{-1}	($117,704) [$47,653]	($17,100) [$6,923]	($99,014) [$40,087]

[*] Acidified fish emulsion diluted 1:50 with water applied twice monthly at 140 liters per hectare.

Both the Shennan et al. studies (2012 and 2018) highlighted the influence of amendment cost on the overall treatment cost for anaerobic soil disinfestation and, by extension, potential net returns for growers. Accordingly, using lower value organic matter amendments, sourcing amendments that are produced near agricultural fields and thus have minimal transportation costs, and identifying the minimum amendment rate to achieve pest control will be important for minimizing process cost. Labor costs were also elevated compared to fumigation (35 to 41% of overall cost), but the researchers noted that anaerobic soil disinfestation was a complex process for the workers and that mechanization to combine multiple field preparation steps into fewer tractor passes will improve process economics. This was in contrast to fumigation, where there is already a great degree of mechanization such that the purchase cost of the fumigants represented over 60% of the overall fumigation cost and labor was just over 18% of the total process cost (Shi et al., 2019).

Although anaerobic soil disinfestation showed varying levels of increased cost over fumigation, it should be noted that this study determined that the additional yield increase offered by anaerobic soil disinfestation more than compensated for the additional treatment cost per acre (Shi et al., 2019). This may reflect the added benefits to soil health and fertility related to enrichment of organic matter in the soil beyond disinfestation (see discussion in ***Section 2.18***).

Additional requirements for use

Anaerobic soil disinfestation and biosolarization share some operations with fumigation. Namely, bed shaping, surface smoothing, and sealing with tarps are used in a similar fashion to soil fumigation. While there are certain fumigation conditions that do not involve sealing the soil with tarps, anaerobic soil disinfestation and biosolarization are reliant on tarps to create the solar heating and temporary anaerobic conditions required for fermentation to produce biologically derived pesticides. The sourcing and incorporation of compatible organic matter (to support soil fermentation) are distinctive aspects of biosolarization and anaerobic soil disinfestation that aren’t required for fumigation. Installation of drip lines under tarps is another requirement of anaerobic soil disinfestation and biosolarization, in order to supply water to the soil microorganisms responsible for fermentation. However, laying the drip lines is similar to the process used for establishing a drip application fumigation system.

Availability, ease, and reliability

As with solarization, biosolarization and anaerobic soil disinfestation can use existing implements and operations for laying drip lines and sealing soil with tarps. Impermeable films that can be purchased for fumigation can also be used for biosolarization and anaerobic soil disinfestation. Like solarization, these techniques also rely on certain weather and climate conditions to achieve optimal pest suppression such that there are timing and location restrictions to ensure sufficient heating. For California growers, deployment in summer in the Central Valley and low desert promotes greater heating, whereas coastal regions are generally cooler and present more challenges for use (Stapleton et al., 2008). Deployment timing restrictions may create additional challenges if the ideal biosolarization or anaerobic soil disinfestation period overlaps with other field activities, such as crop rotations, cover cropping, or field preparation for planting. However, since biosolarization employs multiple potentially synergistic stresses (e.g., heating, oxygen depression, biologically derived pesticide production), the treatment duration can be as short as eight days instead of the four to eight weeks needed for solarization (Achmon et al., 2018). The need to source compatible organic matter amendments is an additional unique task for anaerobic soil disinfestation and biosolarization compared to other fumigant alternatives, which may require new communications and agreements with food processors or feed suppliers.

Furthermore, it is important that growers have sufficient knowledge of these techniques or external guidance to select the amendment types and application rates that will be effective while minimizing the risk of residual phytotoxicity. This presents an initial hurdle to implementation.

The reliability of pathogen control of ASD can be compromised if particular pathogens are present in soils being treated under certain environmental conditions. In fact, *Fusarium oxysporum* f. sp. *fragariae*—the cause of Fusarium wilt of strawberry—was found to increase in soils on the Central Coast during the cooler fall timing of some trials using rice bran, as did the incidence of the disease (Henry et al., 2020). This necessitates knowing the pathogens present in fields prior to treating them and ensuring the environmental and process conditions are sufficient to induce an anaerobic soil condition and lethal effect against those targets, especially if the target pests or pathogens are capable of growing on residual crop biomass in soil (Henry et al., 2020).

> 43. **FINDING:** ASD and biosolarization use organic matter amendments in tandem with solar heating to induce multiple stresses that can lead to broad spectrum pest control. The addition of organic matter to the soil can provide secondary benefits to soil and crop health.

> 44. **CONCLUSION:** ASD and biosolarization can match the pest control and yield benefits of fumigation under certain conditions related to weather and climate, cropping system, and soil amendments. The types and levels of organic matter amendments used are key factors in achieving broad spectrum pest control on par with fumigation. They also factor heavily into process cost.

> 45. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to define best practices for ASD and biosolarization. These practices should aim to maximize broad spectrum pest control effectiveness for California crops that currently rely on fumigation while also mitigating risks such as of nitrate leaching to groundwater or emission of greenhouse gases. DPR and/or other relevant California state agencies should consider supporting work to identify or develop supply chains for various organic matter streams that can be used in ASD or biosolarization and are cost-effective for growers.

Section 2.5: Non-chemical and biological method: Solarization

Overview

Solarization involves covering flattened, moist soil with clear tarps and burying the tarp edges. In this way, it is similar to biosolarization; however, unlike biosolarization, solarization does not involve organic matter soil amendments. Both the drip lines (or tape) and overlying tarps can be applied via tractor implements. The transparent, virtually impermeable or totally impermeable films used for fumigation may also be used for solarization (D'Emilio, 2017; McDonald et al., 2018). Additionally, there are tarp products that are commercially available and branded for use with solarization (e.g., Imaflex Inc. and Ginegar Plastic Products Ltd.). The clear tarps facilitate passive solar heating of the soil through a greenhouse effect. Solar radiation passes through the tarps and is absorbed by the soil, while the tarps trap infrared radiation emitted by the soil, reflecting or absorbing much of it. The tarps also prevent evaporation, allowing solar energy to accumulate and heat the soil (Marshall et al., 2013). The water in the soil acts to lower the soil's albedo—the fraction of light that the surface reflects—thereby resulting in more absorption of solar energy and heating. Soil moisture also increases the soil's thermal conductivity (Kurda et al., 2006), allowing for deeper heat penetration. However, a balance must be struck to achieve the soil moisture needed to promote these effects without adding excess water and depressing soil temperatures due to the high **specific heat capacity** of water (Al-Karaghouli and Al-Kayssi, 2001). Under ideal conditions, soil temperatures can reach up to 60˚C (140˚F) in the upper 5–15 cm (2–6 in) of soil (Doğan et al., 2013; Shea et al., 2022). Solarization effectiveness is dependent on weather and climate conditions and is best suited to areas with several weeks of hot, sunny, and dry weather (McSorley and Gill, 2010). In California, this corresponds to summer in the Central Valley and low desert (Stapleton et al., 2008). Treatment durations on the order of four to eight weeks are often needed for maximum pest inactivation (Wang and McSorley, 2008). Nevertheless, the reliance on soil temperature as the primary mechanism for pest suppression may limit control to the top 5–15 cm (2–6 in) of soil, depending on the temperature sensitivities of the target pests (Wang and McSorley, 2008; Yildiz et al., 2010).

Crop-pest combinations and scale of use

Crops that have shown yield increases following solarization (compared to untreated or fumigated controls) include tomatoes (Candido et al., 2008; Lombardo et al., 2012), dry beans (Ibarra-Jiménez et al., 2012), melons (Candido et al., 2008), lettuce (Hasing et al., 2004; Candido et al., 2011), peppers (Saha et al., 2007; Zayed et al., 2013), raspberries (Pinkerton et al., 2002), and strawberries (Hartz et al., 1993; Camprubí et al., 2007). It should be noted that one study observed a negative effect of solarization on strawberry yield (Samtani et al., 2017). Solarization research has shown inactivation of parasitic nematodes

(*Meloidogyne* spp.) (Candido et al., 2008; Lombardo et al., 2012), several fungal pathogens (*Phytophthora* spp., *Verticillium dahliae, Fusarium oxysporum*) (Hartz et al., 1993; Lombardo et al., 2012), and a variety of common weeds (Hasing et al., 2004; Candido et al., 2011; Samtani et al., 2017).

While solarization research has spanned several countries (some of which are represented in ***Appendix B***), there is little quantitative data on the scale of use in industrial agriculture, particularly in the U.S. There are limited reports of solarization use in commercial production of leaf vegetables in California (Stapleton et al., 2016), although the practice serves as a substitute for hand-weeding in organic cropping rather than as a replacement for fumigation. A survey of soil pest management practices in European strawberry production found that solarization was used on 1.3% of the total production acreage, with notably high adoption in Turkey (1,000 hectares (~2,471 acres), equivalent to 20% of production acreage) and Cyprus (30 hectares (~74 acres), equivalent to 50% of production acreage) (López-Aranda et al., 2016). Similarly, Egypt reported 1,150 hectares (~2842 acres) of solarized fields used for strawberry production, equivalent to 20% of production acreage (López-Aranda et al., 2016).

Efficacy and duration of pest control

Solarization studies summarized in ***Appendix B*** show that the technique is capable of high-level inactivation of plant parasitic nematodes and fungal pathogens. These include *Meloidogyne* spp., *Pratylenchus vulnus*, *Phytophthora* spp., *Verticillium dahliae*, *Fusarium oxysporum*, and a broad spectrum of weeds. The level of control varied among the studies, but the data generally show a greater than 60% reduction in target pests or disease symptoms associated with soil pests compared to untreated controls, and complete elimination of the pest targets was frequently achieved. In studies that compared solarization against fumigation with 1,3-D and chloropicrin, solarization could match or exceed the level of control observed with fumigation (see ***Appendix B*** for references).

Solarization only inactivates a fraction of the soil microbial community, and the microorganisms that persist following solarization can prevent reinfestation (Katan and Gamliel, 2009). This suppressive quality may be due to robust microorganisms that occupy niches that pests and pathogens would otherwise recolonize, or the residual microorganisms may parasitize or antagonize pest and pathogens through production of inhibitory compounds. However, suppressive effects can diminish over a period of months, and solarization may be required annually (Elmore et al., 1997).

Production yield effects

Solarization research has generally demonstrated yield benefits to diverse crops. Improved yield of dry beans was obtained in soils that were solarized for 60 days (1.5 versus 0.9 tons per acre in untreated soil) (Ibarra-Jiménez et al., 2012). A review of solarization research in potato production found that 9 to 74% improvement of yield over untreated controls was possible, dependent on location, variety, and solarization conditions (Singh et al., 2018). Under weed pressure, solarization resulted in yield benefits for lettuce on the order of 20% compared to untreated soils (Candido et al., 2011), and head weight was increased by 29% (Hasing et al., 2004). In studies that compared solarization to fumigation, lettuce yield improvement in solarized soil was similar to that in soils fumigated with 1,3-D and chloropicrin (Lombardo et al., 2012). Yield benefits were observed for raspberries (increased by a factor of 6 to 29 over untreated controls) grown in soils containing the fungal pathogen *Phytophthora fragariae* (Pinkerton et al., 2002). Considerable marketable yield improvements were also obtained for tomatoes and melons in solarized soils that were infested with *Meloidogyne javanica* (yield increased by a factor of 3.6 and 4.7 for tomatoes and melons, respectively, compared to untreated controls over three consecutive years of solarization) (Candido et al., 2008). Strawberry yield on a commercial farm in Spain increased by 24% versus untreated controls when grown in soil solarized for seven weeks (Camprubí et al., 2007), which was similar to the result obtained in field studies at Irvine, California, when strawberries were grown in soil that had been solarized for six weeks (12 to 30% yield increase over untreated controls) (Hartz et al., 1993). In contrast, a Virginia solarization trial found that strawberry yield did not improve compared to untreated soils (nor did fumigation with 1,3-D and chloropicrin improve yield) and in one solarization treatment, yield decreased compared to untreated soils (Samtani et al., 2017); however, weed pressure was the only pest factor considered. Conflicting yield results for strawberry growth in solarized soils may indicate variable yield effects based on the types of pests present or other environmental or process variables (e.g., weather, soil texture, treatment duration, soil moisture).

Costs associated

A cost analysis for solarization (including materials and labor needed for irrigation and tarping) for tomato production in Ethiopia determined the cost to be 72,606.46 Ethiopian birr/hectare ($1,023 per acre) (Gebreegziher et al., 2023). When the cost of hand-weeding was included to remove noxious weeds not suppressed by solarization alone (broomrape, in this case), the cost rose to $1,550 per acre. However, the greatest benefit to the cost ratio (weighing yield benefits against process cost) was achieved with solarization alone as opposed to solarization combined with hand-weeding or hand-weeding alone (Gebreegziher et al., 2023). This conclusion may be particularly relevant to California due to high costs for hand weeding (Tourte, 2016). Cost assessments for solarization in California, which were performed in the 1980s, found the treatment cost to be $200 per acre to $350 per acre ($617 per acre to $1,079 per acre in 2024, accounting for inflation) depending on whether rows or the entire field area were treated (Stapleton and DeVay, 1986). These figures should be interpreted with caution, as changes in material and labor costs since the 1980s would likely alter overall process costs.

Additional requirements for use

As with biosolarization and anaerobic soil disinfestation, solarization uses drip lines beneath tarps. Similarly, field operations and tractor implements that may be used to install fumigant drip application systems and lay tarps may also be used for solarization. As solarization is entirely reliant on achieving high soil temperatures that can inactivate pests and pathogens, it must be used during the hottest months of the year. Compared to fumigation, solarization carries a greater risk of creating scheduling restrictions and infringing on other field preparation activities.

Availability, ease, and reliability

Solarization relies on generation of high soil temperatures through passive solar heating. As a result, its use is restricted to locations and times of the year where hot, dry conditions can be achieved for several consecutive weeks. Additionally, treatment durations can span four to eight weeks, further restricting the timing to avoid conflict with other pre-plant field operations. Regarding material inputs and operations to implement solarization, the same drip irrigation systems currently used in commercial agriculture—as well as the impermeable films and applicators used in fumigation—can be used for solarization.

46. **FINDING:** Solarization has been studied for decades. Soil pest control and yield effects have varied based on location, crop, and pest type. Yield effects range from parity with fumigation to yield decreases relative to untreated controls. The scale of use of solarization in commercial California agriculture is unclear, as is the cost to deploy the technique.

47. **CONCLUSION:** Given its complete reliance on weather and climate conditions to achieve soil temperatures required for broad spectrum soil pest control, solarization will likely only be a possible fumigation alternative in cropping systems and regions that have a fallow period during several weeks of sustained hot, dry conditions.

Section 2.6: Non-chemical and biological method: Biologically derived pesticides and biocontrol agents

Overview

In this report, biopesticides refer to biologically derived pesticidal compounds and biocontrol agents. Biologically derived pesticides are pesticides obtained from organic matter (such as extraction of plant biomass) or the biological activity of an organism (such as a purification of a secreted compound from a fungal culture). Biological control agents (biocontrol agents) are live organisms that are antagonistic to pests. This aligns with the U.S. EPA definition for biopesticides (U.S. EPA, 2023). This definition also extends to biologically derived pesticide compounds generated or leached from organic matter incorporated into soil and compounds produced through microbial activity in the soil. Biologically derived pesticides that inhibit pests and pathogens can be macromolecules (such as proteins) or small molecules. This can be achieved through a variety of mechanisms, including disruption of the cell membrane or inhibition of critical enzymes in the target pest. Biocontrol agents are organisms that antagonize pests and pathogens by secreting biologically derived pesticides or through outcompeting, parasitizing, or consuming the target pest. Additionally, some biocontrol agents can stimulate immune responses in crops that allow them to better resist pests (Antil et al., 2023). Some biopesticide strategies overlap with other fumigant alternative methods. For instance, the breakdown of cover crop biomass in soil can produce biologically derived pesticides. These compounds can also be generated through fermentation in soil during biosolarization or anaerobic soil disinfestation, and some fumigants are chemically similar to biologically derived pesticides (e.g., isothiocyanates).

Crop-pest combinations and scale of use

DPR pesticide use reporting indicates that the use of biopesticides is growing in California. From 2012 to 2021, the acres treated with biopesticides have increased 51% to 8.4 million acres (DPR, 2023). However, the report provides aggregate metrics, and not all applied biopesticides may be relevant for pests and pathogens commonly controlled through fumigation with 1,3-D and chloropicrin. Nevertheless, two of the most widely used registered biochemical fungicides in the state are neem oil and margosa oil (***Table 2.5***). The neem tree extracts margosa oil and neem oil contain compounds that are active against *Meloidogyne* spp. nematodes and *Fusarium* spp. fungal pathogens (Hadian et al., 2011), two common soil pests that are often controlled with fumigation. However, this does not imply that current use of neem extracts is driven by soil pest control. Instead, their activity as foliar insecticides (applied directly to foliage) and miticides (Benelli at al., 2017) may account for current growth trends.

Table 2.5. 2021 DPR use data for Neem tree-derived biochemicals with pesticidal activity.

Name	Pounds applied [number of applications]	Crops
Clarified hydrophobic extract of neem oil	80,283.61 [7,445]	Almond, apple, artichoke, **arugula**[**], avocado, basil, bean, beet, blackberry, blueberry, bok choy, broccoli, Brussels sprout, cabbage, **cannabis**[*], cantaloupe, carrot, **cauliflower**[*], celery, cherry, chicory, Chinese amaranth, Chinese broccoli, chive, chrysanthemum (edible), citrus, collard, cucumber, daikon, dandelion green, date, dill, edible flowers, eggplant, fava bean, fennel, **grape**[*], grape (wine), herb (spice), industrial hemp, kale, kiwi, leek, lemon, lettuce (head and leaf), melon, mint, mushroom, mustard, mustard greens, greenhouse flowers, greenhouse plants in containers, greenhouse transplants, outdoor flowers, outdoor plants in containers, onion (dry), onion (green), orange, oregano, parsley, peas, pepper (fruiting), pistachio, plum, prune, radish, raspberry, rosemary, sage, spinach, squash, squash (summer), **strawberry**[*], swiss chard, tangelo, tangerine, thyme, tomato (fresh market and processing), tropical/subtropical fruit, turnip greens, vegetables (fruiting and leafy), walnut, watercress, watermelon
Margosa oil	50,903.66 [3,086]	Almond, artichoke, arugula, basil, bean, **beet**[*], **blackberry**[*], blueberry, bok choy, broccoli, Brussels sprout, cabbage, cannabis, carrot, **cauliflower**[*], celery, cherry, collard, corn, cucumber, daikon, dill, grape, grape (wine), industrial hemp, **kale**[*], leek, **lettuce** (head and **leaf**[*]), mizuna, mustard, greenhouse plants in containers, greenhouse transplants, outdoor flowers, outdoor plants in containers, outdoor transplants, nectarine, onion (dry), onion (green), parsley, peas, pistachio, potato, radicchio, radish, **raspberry**[*], spinach, squash, squash (summer), **strawberry**[*], sweet potato, swiss chard, tangerine, tomato (fresh market and processing), vegetables

[*] Over 2,000 acres treated
[**] Over 10,000 acres treated

The most widely used registered biocontrol agent in California is *Aspergillus flavus* strain af36, which has seen intense use in California pistachio production (nearly 300,000 acres treated in 2021) and comparatively less use in almond, corn, and fig (less than 10,000 acres treated) (DPR, 2021). However, this use may be motivated by controlling contamination by toxic fungal compounds (e.g., aflatoxin) rather than targeting soil pests typically controlled through fumigation. Several species of *Trichoderma* fungi are also used as biocontrol agents against pathogenic fungi like *Fusarium* spp. and *Phaeoacremonium* spp., and application overlaps substantially with the crops utilizing neem-tree derived pesticides (DPR, 2023). A variety of bacteria and fungi that naturally colonize the root zone of plants can antagonize parasitic nematodes, such as *Meloidogyne* spp., by disrupting various stages of the nematode lifecycle (Antil et al., 2023). Furthermore, several essential oils (e.g., from thyme and eucalyptus) have demonstrated robust broad spectrum nematicidal activity, which includes inhibition of *Meloidogyne* spp., *Pratylenchus* spp., and *Hoplolaimus* spp. (Catani et al., 2023). However, additional research and development is needed to bring these biopesticides to market.

Efficacy and duration of pest control

Extracts or processed biomass from various plants are currently available as commercial biologically derived pesticides. For example, extracts or powdered products produced from biomass of the neem tree (*Azadirachta indica*) (leaves, bark, or seeds) have shown activity against pests commonly controlled with soil fumigants, such as pathogenic fungi and parasitic nematodes. In vitro studies demonstrated that aqueous (water-based) neem leaf extracts were broadly fungicidal when applied to rot-causing pathogenic fungi isolated from yams, resulting in 73 to 97% inactivation (Ezeonu et al., 2018). Neem seed oil similarly exhibited inhibitory activity against *Fusarium* spp., reducing growth by 71 to 85% in a dose-dependent manner that differed between *Fusarium* species (Geraldo et al., 2010). Neem seed powder applied at 50 g per kg of soil (~0.8 oz per 2.2 pounds of soil) mitigated growth effects and reduced the disease index from 85 to 12% for greenhouse-grown tomato plants in infested soils containing both *Fusarium oxysporum* and *Meloidogyne incognita* (Hadian et al., 2011). Even greater, and sometimes complete, suppression of disease was observed when soil was only infested with one of the two targets (Hadian et al., 2011). When azadirachtin, one of the antimicrobial components of neem seeds, was added to potted soil at a rate of 30.72 mg per kg (~0.00049 oz per 2.2 pounds of soil), it resulted in >90% decrease in viable *M. incognita*, but this was 1,000 times higher than the manufacturer's recommended application rate (Ntalli et al., 2009).

Saponins are another class of plant-derived pesticides. They are known for their soap-like qualities, have broad spectrum pesticidal effects, and can be extracted from diverse plant sources. For example, over two dozen saponins were extracted from roots of the herb *Pulsatilla koreana*, and five showed the ability to achieve at least 99% inactivation of *Meloidogyne incognita* nematodes within a week of exposure, which matched the effectiveness of a synthetic commercial nematicide (fosthiazate) (Li et al., 2013). Similar levels of *M. incognita* inactivation were achieved with saponin-rich extracts from alfalfa and related species (*Medicago* spp.) (D'Addabbo et al., 2020). Saponin extracts from bark of the *Quillja saponaria* tree resulted in 36 to 59% inactivation of the pathogens *Pythium ultimum*, *Fusarium oxysporum*, *Alternaria solani*, and *Verticillium dahliae;* similarly, saponin extracts from the plant *Yucca schidigera* resulted in 54 to 100% inactivation of these pathogens, in addition to the fungal pathogen *Colletotrichum coccodes* (Chapagain et al., 2007). When used as a dip for seeds or young roots of tomato, saponins from quinoa reduced Fusarium wilt disease by 49 to 62% (Zhou et al., 2023).

Biocontrol agents are organisms that act as antagonists of pests and pathogens. For example, strains of the bacterium *Bacillus subtilis* can suppress fungal pathogens such as *Fusarium* spp. In a study that inoculated potato plants via irrigation water containing spores of the *B. subtilis* strain V26, Fusarium wilt disease was reduced by 55 to 61% compared to untreated controls, and positive effects on plant health were maintained for 60 days (Khedher et al., 2021). Similarly, *B. subtilis* strain Y-1 applied to apple seedlings reduced Fusarium wilt disease by up to 92% compared to untreated control (Ju et al., 2014), and strain IBFCBF-4 reduced Fusarium wilt in watermelon by 51% (Zhu et al., 2020). *Streptomyces lydicus* is another bacterium with fungicidal properties. When *S. lydicus* strain WYEC108 was applied to pea seeds, disease from *P. ultimum* was reduced by over 70% compared to the untreated control, and the protective bacteria persisted for at least 90 days (Yuan and Crawford, 1995).

A review of *Streptomyces* spp. as biocontrol agents highlighted that control of Fusarium wilt was variable, but in most reviewed studies at least 50% reduction in disease was reported (Bubici, 2018). *Trichoderma* is a genus of fungi that contains several species capable of inactivating soil pests and guarding plants against associated diseases. In a review of *Trichoderma* spp. biocontrol research, suppressive activity was identified for several major soil fungal pathogens and nematode pests, such as *Fusarium* spp., *V. dahliae*, *Pythium* spp., *Rhizoctonia solani*, and *Meloidogyne* spp., among others (Guzmán-Guzmán et al., 2023). Pest control data were highly variable based on the specific combination of *Trichoderma* sp. and pest target, but pest growth rates were often reduced by more than 50% compared to untreated controls, and complete inhibition was achieved for *Fusarium graminearum* (Guzmán-Guzmán et al., 2023). To further highlight variability in biocontrol agent effectiveness, a California strawberry trial examining inoculation with *Muscodor albus* strain SA-13 observed that the mortality of plants in *Verticillium dahliae*-infested soil did not significantly differ from mortality in untreated soils (Blauer and Holmes, 2019).

Production yield effects

Botanical extracts, such as those from the leaves, bark, or seeds of particular plants, have delivered yield benefits to several crops. For instance, neem tree extracts applied to tomatoes for nematode and *Fusarium* suppression found that the extract improved root and shoot fresh weight by 57% and 72%, respectively, compared to plants in untreated soils containing *Meloidogyne incognita* and *Fusarium oxysporum*, and plant vigor was similar to that seen in non-infested soils (Hadian et al., 2011). For *F. oxysporum* control on tomatoes, several botanical extracts were examined (neem leaf, neem oil, garlic, marsh paper plant, allamanda leaf, wood apple leaf, and betel leaf), and all but neem leaf extract resulted in improved yields compared to untreated control plants (Khatun et al., 2020). The greatest yield increase (47% over untreated control, which was similar to the yield improvement with a synthetic pesticide control) was associated with application of garlic extract (Khatun et al., 2020). When leaf and seed extracts from Moringa, Jatropha and Castor plants were used as nematicides to control *M. incognita* during tomato production, all extracts improved yield to varying degrees, with yield increases ranging from 108% to 170% over untreated controls (Oluwatayo et al., 2019). Introduction of microorganisms to the soil and directly to seeds or crops can also provide plant protection and improve yields. A study investigating the use of the fungus *Trichoderma harzianum* as a biocontrol agent for *F. oxysporum*, *Ralstonia solanacearum*, and *Meloidogyne* spp. increased eggplant yield by 222% compared to the untreated control plants grown in infested soil (Akter et al., 2021). Another eggplant study discovered that yield increase varied based on the *Trichoderma* species used for biocontrol of *F. oxysporum*, with *T. hamatum* delivering the greatest yield increase (110% to 127% over untreated controls) over two years (Abdel-Monaim et al., 2014). Soil inoculation with the bacterium *Bacillus velezensis* CE100 proved effective at controlling the fungal pathogens *Macrophomina phaseolina* or *F. oxysporum* in strawberry production, increasing yields by 387% to over 1,300% compared to untreated controls in infested soils (Hong et al., 2022). The use of several root dips in strawberry production, which included inocula for *Streptomyces lydicus* strain WYEC 108, *Bacillus amyloliquefaciens* strain D747, *Gliocladium virens* strain GL-21, and other complex cosortia, found that *S. lydicus* treatment significantly increased yield compared to the grower standard, but the effect was only observed for the first month of harvest, and there were no yield improvements thereafter (Bolda and Sheehan, 2013). When the same *S. lydicus* inoculum was tested alongside products containing *Glomus intraradices, G. aggregatum, G. mosseae,* and *G. etunicatum* or *Saccharomyces cerevisiae* and *Bacillus subtilis*, none of the biocontrol agents showed significant strawberry marketable yield increases compared to untreated control soil (Dara and Peck, 2017). These results are consistent with a broader review showing a lack of consistent performance for biocontrol agent products in strawberry production (Holmes et al., 2020).

Costs associated

There is a lack of published studies describing the costs associated with biologically derived pesticides and biocontrol agents when used for soil pest and pathogen control. However, recent reviews highlight the general high cost of producing these products, which are often manufactured through fermentation (Hamrouni et al., 2024; Marrone, 2024). Nevertheless, there are a number of established and start-up companies in the biopesticide market, and many are investigating avenues to decrease production costs through changes to bioreactor design and fermentation feedstocks as well as by engineering microorganisms that produce biologically derived pesticides more efficiently (Marrone, 2024).

Additional requirements for use

Biologically derived pesticides and biocontrol agents can be introduced to the soil via spraying, **broadcasting** and discing or tillage, or **chemigation**. Spraying entails the use of sprayers carried by workers or mounted on tractor booms or aerial crop dusters, which are not used during conventional fumigation. Broadcasting and discing or tillage partially overlap with fumigation processes, as tillage or discing are often performed ahead of fumigation to disrupt soil clumps. Chemigation application, where a solution of the active ingredient is delivered through a drip irrigation system, shares common materials and installation methods with drip application systems for fumigants.

Availability, ease, and reliability

Essential oils and other extracts (e.g., neem oil, saponins) from plants are currently available as commercial formulations (e.g., AzaGuard, Nema-Q) . Additionally, there are formulations of the bacteria *Streptomyces lydicus* and *Bacillus subtilis* as well as *Trichoderma* spp. fungi on the market that claim to provide control of multiple fungal pathogens. These products can be applied to the soil through spraying, drip, or furrow systems using equipment that are commonly used for pesticide application or irrigation, and some allow for treatment of seeds prior to planting using a mixing tank.

48. **FINDING:** There are biologically derived pesticide and biocontrol agent products on the market that contain active ingredients shown in laboratory, potted plant, or field studies to inhibit major pathogens and nematodes typically controlled through fumigation. However, there is little evidence that they are currently used for soil pest control in commercial agriculture.

49. **CONCLUSION:** Inactivation of fungal pathogens and phytoparasitic nematodes via biologically derived pesticides or biocontrol agents, and associated disease reduction and yield effects in treated crops, is variable and may be highly transient. The costs of using biologically derived pesticides and biocontrol agents at a scale for soil pest control are not well characterized.

50. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to determine the types of biologically derived pesticides and biocontrol agents, and their application practices, that maximize broad spectrum soil pest control with the aim of achieving parity with fumigation in California agriculture. If such conditions are identified, DPR and/or other relevant California state agencies should consider supporting analyses to determine the costs and net returns for growers.

Section 2.7: Non-chemical and biological method: Cover cropping

Overview

Cover or catch cropping involves planting certain crops between cultivation of cash crops to maintain or improve soil health, including soil pest control. In addition to disrupting host availability for certain pests and outcompeting weeds, cover and catch crops help prevent erosion and improve tilth, enhance soil organic matter, capture nutrients in the root zone, improve the water holding capacity of soil, and recruit pollinators. Moreover, incorporating cover crop biomass into soil can lead to biologically derived pesticide production (e.g., isothiocyanate compounds from *Brassica* crops) to promote soil disinfestation (Dutta et al., 2019). A wide variety of cover crops are used in California agriculture, such as legumes (e.g., varieties of vetch, clover, cowpea), cereals (e.g., rye, barley, wheat), grasses (e.g., ryegrass, Sudangrass), and cruciferous plants (e.g., mustard, rapeseed) (Miller et al., 1989; UC SAREP, 2024). The choice of cover crops depends on planting schedule, cost of seed, water availability, and the nutrient and pest control needs of the cash crop (Miller et al., 1989; UC SAREP, 2024). For example, rye has pest-suppressing properties and grows well during the cooler periods in California when many fields are fallow (UC SAREP, 2024).

Broadly, grass cover crops are associated with greater weed suppression than broadleaf cover crops due to their rapid growth and ability to dominate the canopy before weeds can establish (Osipitan et al., 2019). Cover crops in the *Brassica* genus (e.g., radish, mustard, turnip, rapeseed) contain glucosinolate compounds. Once the cover crop biomass is disrupted and incorporated into soil, the glucosinolate compounds degrade into isothiocyanate compounds via enzymes in the plant tissue (Gimsing and Kirkegaard, 2006). The isothiocyanates are volatile, biologically derived pesticides that diffuse through the soil and create a biofumigation effect that can inactivate phytoparasitic nematodes (Dutta et al., 2019) and fungal pathogens (Smolinska et al., 2003; Neubauer et al., 2014). In this way, cover crops employ similar chemistries to fumigants like metam sodium, metam potassium, and dazomet, which also rely on degradation of the active ingredient to promote formation of volatile isothiocyanates in the soil. The formation of isothiocyanates can occur within hours of cover crop incorporation into the soil, with the accumulation rate and maximum concentration depending on the concentration of isothiocyanate precursors in the cover crop biomass, as well as soil texture, soil depth, moisture, and temperature (Gimsing and Kirkegaard, 2006; Gimsing et al., 2007; Omirou et al., 2013; Wang and Mazzola, 2019).

Crop-pest combinations and scale of use

The use of *Brassica* cover crops to control soil pests and pathogens, such as *Meloidogyne* spp., *Fusarium oxysporum*, and *Verticillium dahliae* (Smolinska et al., 2003; Neubauer et al., 2014; Dutta et al., 2019), has been described for some specialty crops, including strawberries, lettuce, broccoli, and tomatoes (Clark, 2008; Rahman et al., 2023). Additionally, cover crops may be used in perennial crops such as grapes or almonds, where the cover crop occupies the alleys between the rows of vines or trees (Wauters et al., 2023). Cover crops such as rye and sorghum sudangrass hybrid can outcompete weeds; however, such cover crops can sometimes act as hosts for plant-parasitic nematodes (UC SAREP, 2024). The 2022 Census of Agriculture conducted by the USDA Economic Research Service reported a 17% increase in cover crop use in the U.S. between 2017 and 2022. This accounts for 4.2% of total national cropland, or approximately 18 million acres using cover cropping, with the highest adoption rates on the East Coast (Wallander et al., 2021; USDA ERS, 2024). In California, growers in most counties enacted cover cropping on 1 to 5% of cropland based on the 2022 data; however, Sonoma, Napa, and El Dorado Counties showed more than 15% of cropland used cover cropping (USDA ERS, 2024).

Efficacy and duration of pest control

Because cover cropping spans many possible combinations of crops (e.g., legume, root, grain, leaf, and fruit crops), it is difficult to make broad claims about its effectiveness. However, studies summarized in ***Appendix B*** show that cover cropping (particularly when combined with crop rotations) can suppress a broad spectrum of plant parasitic nematodes and fungal pathogens. At the same time, these studies also highlight variability in effectiveness against parasites, pathogens, and diseases compared to monoculture systems or fumigation with 1,3-D or chloropicrin. In some cases, near complete eradication was observed with rotation and cover cropping, while in others only partial suppression occurred, and, in some studies, the abundance of certain fungal pathogens actually increased. Within individual studies, these effects could differ based on the time of analysis. These results emphasize the importance of selecting crop rotations and cover crops that are tailored to the pest profile of a given field, as well as the need for additional research to identify crop-pest, crop-crop, and crop-environment interactions that influence suppression of specific soil pests.

Beyond disruption of the soil pest host cycle, cover crops that induce a biofumigation effect after incorporation into the soil have been studied for suppression of various pests and pathogens. In a study of black root rot disease in strawberry, which is caused by a complex of pathogen and environmental factors, the use of mustard cover cropping (a *Brassica* crop that contains glucosinolates) provided significant, but partial, reduction in disease (Rahman et al., 2023). In contrast, strawberries rotated with non-*Brassica* cover crops, such as wheat and sorghum-sudangrass, showed no decrease in fungal pathogen viability (Shrestha et al., 2024). A broad review of cover crop studies that have employed this biofumigation effect for control of plant parasitic nematodes found that >90% reduction in the pests or pest-associated diseases could be achieved, and that this was comparable to fumigation with 1,3-D and chloropicrin (Dutta et al., 2019).

The duration of pest control effects from cover cropping and rotation varies. One study found that two years of *Brassica* vegetation incorporation in soil were required to maximize the *Meloidogyne javanica* nematode suppression effect during grape cultivation (L. Rahman et al., 2011). Another multiyear study showed that maintaining cover cropping or rotations each year was necessary for continued nematode control (Kratochvil et al., 2004). Similarly, when crop rotation was used to suppress *Verticillium dahliae*, the control effect diminished after four years without continued rotation (Wheeler et al., 2019).

Production yield effects

A review of studies spanning 23 countries and various crops summarized yield responses to cover cropping with *Brassica* and non-*Brassica* crops that produce a biofumigation effect (Dutta et al., 2019). This review and select studies, which are summarized in ***Appendix B***, demonstrated varying yield effects, including possible yield improvements for several diverse crops. For instance, cover cropping with mustard, oilseed radish, or winter rapeseed with subsequent tarping to trap volatile compounds in the soil after cover crop incorporation increased yield in pepper by 48 to 54% on average compared to fallow control plots in a field infested with the fungal pathogen *Sclerotium rolfsii* (Hansen and Keinath, 2013).

Positive yield effects may depend on specific combinations of cover crops and cash crops. Studies have shown that cover cropping with multiple species can provide greater yield benefits compared to cover cropping with just one or two species. For example, cover cropping with a mixture of cereal rye, whole oats, purple top turnips, daikon radish, and crimson clover improved soybean yield by approximately 13% compared to controls without cover cropping (Chu et al., 2017). However, this effect was not consistently achieved over multiple soybean crop cycles (maximum 15% yield increase) and was not observed at all with corn (Chu et al., 2017). Additional studies highlight the inconsistent performance of cover cropping on cash crop yields. A comparison of various cover crops (sorghum-sudangrass, castor bean, grain sorghum) in cucumber production under root-knot and root lesion nematode stress did not show a yield benefit compared to nematode-susceptible plants (Kratochvil et al., 2004). An examination of various cover crops (brown mustard, turnip rape, fodder radish, purple vetch) interspersed with sunflower cultivation found that only purple vetch provided a significant yield benefit to sunflowers, and the effect was not consistently achieved year-to-year (Ait Kaci Ahmed et al., 2022). Turnip rape and a mixture of turnip rape and purple vetch led to significant reductions in sunflower yield in one trial year (Ait Kaci Ahmed et al., 2022). And finally, mustard cover cropping reduced plant mortality in a strawberry field with black root rot disease but failed to demonstrate significant increases in yield compared to untreated control plots for surviving plants (M. Rahman et al., 2023).

Costs associated

An investigation of costs associated with California winter cover crops in two cropping systems (tomatoes and almonds) found the direct costs, which represent the costs of establishing and terminating the cover crop, to be $53 per acre to $148 per acre for tomatoes and $38 per acre to $155 per acre for almonds (DeVincentis et al., 2020). The variability in cost stems from the different types of cover crops and planting densities used in these cropping systems. In tomatoes, purchasing cover crop seeds represented the greatest and most variable direct cost, with labor for cover crop termination and planting being the second and third most costly aspects, respectively. For almonds, purchasing seeds and labor for crop termination had similar costs, and labor for planting was the third most costly element. A recent cost study for organic rotated production of strawberries and vegetables estimated the annual cost of cover cropping at $150 per acre, although it did not specify the type of cover crop used (Bolda et al., 2024a).

Additional requirements for use

Cover cropping involves planting specific crops between cash crop cycles with the aim of disrupting host availability for pests and pathogens and delivering biologically derived pesticides to the soil via cover crop biomass. Crop rotation uses cycling of cash or cover crops to capitalize on these same soil pest control mechanisms. For these reasons, cover crops require additional field preparation, inputs and operations (e.g., application of seed and fertilizer, termination and incorporation of cover crop biomass), and grower knowledge that may otherwise not be required if fumigation is the primary soil pest control strategy.

Availability, ease, and reliability

Seed for common cover crops can be readily purchased from multiple suppliers. Cover cropping requires growers to identify crops that are compatible with their field conditions (soil chemistry and texture, rainfall, weather and climate) that also have the appropriate biologically derived pesticide or host disruption properties for the pest profiles in their fields. Additionally, growers must have the knowledge and ability to establish, maintain, and terminate or harvest a wider array of crops, which may also require more inputs, such as fertilizer and energy, compared to a monoculture system. As a result, there are temporal, logistical, training, and economic factors that growers must consider before implementing cover crops.

51. **FINDING:** Strategic selection of cover crops can contribute to soil pest control by disrupting pest lifecycles—which depends on the host range of the pathogens and phytoparasitic nematodes in the soil—and by outcompeting weeds. Termination and soil incorporation (i.e., mixing) of certain cover crops can release biologically derived pesticides into soil, such as isothiocyanate compounds, which inhibit pests sensitive to these compounds. Cover crops can also provide multiple soil health benefits, including nutrient capture and retention and improved soil texture.

52. **CONCLUSION:** Cover crops alone are unlikely to be an effective fumigation substitute. However, they can contribute to an integrated pest management strategy that uses multiple approaches to control soil pests.

Section 2.8: Non-chemical and biological method: Crop rotations

Overview

Rotating different crops within a field is a proven method for disrupting pest life cycles, especially for pests with a narrow host range. The effectiveness of crop rotation relies on profiling pests at the target site to identify those with limited hosts and select nonhost crops suited to the climate, soil, and management practices the site. Effective management of weeds is also required to avoid inadvertently maintaining hosts at the site. Rotations typically span two to four years before there is a repeat planting of a given crop or a crop within the same family, and may incorporate a fallow period into the rotation cycle.

Crop-pest combinations and scale of use

The University of California Division of Agriculture and Natural Resources (UC ANR) provides guidance on suitable crops to rotate for control of specific pests. Plant parasitic nematodes (such as *Meloidogyne* spp. and *Heterodera* spp.) can have host ranges that limit their growth to specific types or species of plants. In the case of *Heterodera* spp., possible host crops differ by species. For example, *Heterodera schachtii* can infest beets, spinach, cruciferous vegetables (e.g., broccoli, cauliflower, brussels sprouts), and related weeds (UC ANR, 2010). Rotations that include crops outside of the *Brassica* and cruciferous species (and others) that fall outside the host range for each *Heterodera* species can disrupt the nematode's life cycle by removing suitable hosts (UC ANR, 2010; UC ANR, 2020). In contrast, root-knot nematodes (*Meloidogyne* spp.) have a broad host range that encompasses many major specialty crops (e.g., tomatoes, lettuce, corn, carrots, almonds, and many others). As a result, control options through rotation are more limited. However, strawberry is not a host for *Meloidogyne incognita* and most populations of *Meloidogyne javanica*, but is a host for for *Meloidogyne hapla*, so it may be an effective rotation option against *M. incognita* and *M. Javanica* where environmental conditions are compatible with strawberries (UC ANR, 2020).

For fungal pathogens such as *Fusarium* spp. and *Verticillium* spp., which also have broad host ranges, crop rotation can mitigate disease to varying degrees. Rotating a cruciferous crop like broccoli with crops such as strawberries or eggplant can be effective for decreasing Verticillium wilt (Njoroge et al., 2009; Ikeda et al., 2015). Rotation between cruciferous vegetables such as cauliflower and broccoli can also antagonize *Verticillium* spp. (Xiao et al., 1998). Fusarium wilt occurs in many crops, such as tomatoes, lettuce, melons, and peppers, but different host-specific versions of *Fusarium oxysporum* (referred to as *formae speciales*) are responsible for disease in each crop (Paugh and Swett, 2021). As a result, rotation between these and other crops can mitigate Fusarium wilt even if soil *Fusarium* levels remain unchanged (Paugh and Swett, 2021). Published data concerning crop rotation use is limited and largely focus on crops that are not major drivers of fumigant use in California. A 1997 USDA assessment of crop rotation practices in corn, soybean, cotton, potato, and wheat gauged acreage with rotations as a percentage of total cropland (Padgitt et al., 2000). Although the survey did not cover all regions or crops, it found high levels of grower adoption, with 99% of potato, 92% of soybean, 85% of corn, 75% of wheat, and 40% of cotton acreage using rotation. These figures remained steady through 2009–2010 for corn and soybean and increased to 86% for spring wheat (USDA ERS, 2013).

Efficacy and duration of pest control

For fungal pathogens such as *Fusarium* spp. and *Verticillium* spp., and the fungus-like pathogen *Pythium* spp., which have broad host ranges, crop rotation can help reduce disease, but the effects are often temporary or limited. Rotating broccoli and eggplant reduced Verticillium wilt disease incidence in eggplant by 53% (Ikeda et al., 2015). Similarly, a 50% decrease in Verticillium wilt incidence in cauliflower was obtained by rotating with broccoli and incorporating the broccoli residues into the soil after harvest (Xiao et al., 1998). In strawberries, although Fusarium wilt was not completely eliminated, disease severity was reduced through rotation with tomato (Fang et al., 2012). Specifically, in monoculture disease severity ratings for strawberry shoots and roots decreased from 5.00 and 4.38, respectively, indicating wilt and death for the majority or all of the plant, to 3.12 and 2.25, respectively, indicating moderate to severe stunting and wilting, when monoculture was shifted to rotation (Fang et al., 2012). Milder disease control was obtained by rotating strawberries with pepper (Fang et al., 2012). Similarly, rotating strawberry with broccoli showed a 12 to 24% decrease in Verticillium wilt incidence compared to rotation with lettuce (Njoroge et al., 2009). For *Pythium* spp., there was no consistent effect on soil inoculum levels in response to rotation with broccoli or lettuce (Njoroge et al., 2009). A study rotating cotton and grain crops observed that Verticillium wilt decreased in cotton for the first four years, but rotations had no effect on disease incidence by nine years (Wheeler et al., 2019). Although disease incidence for Fusarium wilt or Verticillium wilt may decrease in response to crop rotation, the soil reservoir of *Fusarium* spp. may not be affected (Marburger et al., 2015). Additionally, pathogens may persist on rotation crops and cause asymptomatic infections that could eventually lead to the reemergence of disease (Wheeler et al., 2016; Henry et al., 2019).

Production yield effects

There are many ways to rotate crops, including different combinations of crops, the order in which they are planted, how often they are rotated, and where they are grown in a field. Although the possibilities for crop rotation strategies are vast, existing research provides useful examples of achievable yield effects for several crops. For corn and wheat rotated with each other and alfalfa, corn grain yield increased approximately 14 to 33% compared to a monoculture system, while wheat grain yield increased roughly 11 to 30% over monoculture (Berzsenyi et al., 2000). Greater wheat yield benefits were obtained when rotations included spring barley and peas (approximately 60% increase over monoculture) (Berzsenyi et al., 2000). A multi-year, multi-national review of crop rotation studies confirmed the general positive yield effects of the practice for corn production in North America (Bowles et al., 2020). A broad review of crop rotation effects in China determined that yield improvements ranged from 6% for cereals to 34% for root crops (Zhao et al., 2020). The review also found yield increases over non-rotated fields were greater when less nitrogen fertilizer was applied, suggesting crop rotations that include nitrogen-capturing crops (e.g., legumes) can compensate for low fertilizer use (Zhao et al., 2020). Moreover, crop rotations have produced yield benefits (compared to monoculture) for several specialty crops that currently employ soil fumigation in California. For example, strawberries showed variable yield effects using broccoli rotation, but matched the benefits of fumigation with methyl bromide in one trial despite not achieving the same reductions in Verticillium wilt (Njoroge et al., 2009). Although the ability to match fumigation was inconsistent and weed suppression was variable, strawberry yield benefits over monoculture were consistently observed with rotations of *Rudbeckia hirta, Sorghum bicolor, Tagetes erecta, Andropogon gerardii, Panicum virgatum*, or *Sorghastrum nutans* (Portz and Nonnecke, 2011). When pepper was rotated with beans and cotton, weed pressure decreased but yield improvements varied by year and were generally less than yields obtained in monoculture with synthetic fertilizer (Arpaci et al., 2016). Intercropping melon and cowpea resulted in a 12 to 74% increase in melon yield compared to monoculture (Marcos-Pérez et al., 2023). Yellow squash yield improved by 47% and eggplant yield increased by 71% in a castor rotation compared to using a fallow period with weed coverage despite no significant reduction in *Meloidogyne* spp. root galling (McSorley et al., 1994).

Costs associated

Since there are many possible crop rotation strategies, each with its own inputs and practices, the costs associated with crop rotation can vary widely. This was highlighted by a three-crop rotation (soybean, corn, and wheat) cost study conducted in Italy for conservation and organic production systems. The analysis found that different production costs for each of the three crops, with soybean, corn, and wheat requiring \$274 to \$360 per acre, \$51 to \$546 per acre, and \$390 per acre, respectively (all values were converted from their original units of euros (€) per hectare to dollars per acre according to the exchange rate contemporary to the study, \$1.24 per € , and then adjusting to 2024 dollars) (Sartori et al., 2005). An assessment of crop rotation strategies in California rice production found that rotations involving cover crops were less costly than rotations using only cash crops. However, the researchers emphasized that the net returns associated with each crop must also be considered when choosing a rotation (Rosenberg et al., 2022). It should be noted that there are few published cost analyses that focus on crop rotation systems. While the studies discussed here illustrate that costs for individual crops in a rotation can differ, the crops represented in these studies do not commonly use fumigation in California. Conversely, there are many cost studies available for individual crops in California agriculture (UC ANR, 2024a). Growers can calculate the costs for individual crops to get a general understanding of the total cost of a crop rotation.

Additional requirements for use

Rotating multiple cash crops requires growers to be familiar with the cultivation practices for several crops. This increases operational complexity and the variety of inputs needed (e.g., fertilizers, irrigation infrastructure, fuel for field operations). In some cases, landowners may need to lease their land to several growers, each with expertise in one or more of the crops in rotation. Growers must also ensure there is a market for each of the crops in the rotation, which could involve contracts with a larger number of buyers than is necessary with monoculture.

Availability, ease, and reliability

Crop rotations typically use combinations of established crops. As a result, seeds or transplants for these crops are generally commercially available. As with cover cropping, using crop rotations in lieu of monoculture introduces operational complexity for the grower since they must identify several crops that agree with their soil properties, weather, and climate, in addition to possessing the equipment and knowledge required to grow, harvest, and sell multiple crop types. Land availability may limit growers' ability to rotate crops. For instance, in California strawberry production, where back-to-back planting is an option, sustaining a given strawberry production level with a two-year rotation requires double the land of back-to-back planting (Ramos et al., 2024). Accordingly, in areas where land availability is low, the use of crop rotations in strawberry production has been observed to decrease (Ramos et al., 2024).

> 53. **FINDING:** Crop rotations can help control soil pests that have a narrow host range by selecting crops that disrupt the pest's life cycle. Crop rotations are less effective at controlling soil pests with a broad host range.

> 54. **CONCLUSION:** The use of crop rotations requires growers to be skilled in cultivating multiple crops. For effective soil pest control, growers must select rotated crops that can disrupt the host cycle of pests in their fields while also being compatible with their local soil, climate, land availability, and market conditions. These factors create hurdles to adoption. In cases where soil is infested with pests or pathogens with broad host ranges, or if multiple pests and pathogens are present with differing disease mechanisms, crop rotations may have more limited effectiveness as a fumigation alternative.

Section 2.9: Non-chemical and biological method: Resistant varieties and rootstock

Overview

Various cultivars and species within a given plant genus can have different resistances to soil pests and pathogens. Resistance can be enhanced through breeding or genetic modification. Additionally, certain annual and perennial crops can be grafted to a pest-resistant plant (generally a closely related variety or species with similar wound response), in which a shoot (or **scion**) of a more pest-sensitive plant is fused to pest-resistant rootstock. Several techniques are used to create grafts, but all rely on placing cut surfaces from the scion and rootstock in direct contact and allowing the stem cell-rich (cambium) plant tissues to grow and fuse (Wang, 2011) .

When selecting pest resistant varieties or rootstocks, susceptibility to other stresses, such as salt, pH, lime content, poor soil drainage, or other non-target pests must be considered. Additionally, when assessing potential rootstocks, the ability of the rootstock to properly anchor the plant and tolerate the planned planting density should be factored into the selection. These properties must be balanced with any differences in yield, post-harvest shelf life, and traits that could affect marketability (e.g., color, flavor) (Ficiciyan et al., 2018).

Breeding can be used to improve the pest resistance of whole plants or plants used for rootstock. Conventional breeding involves identifying plants with some degree of resistance to a given pest, using these plants to produce seed, and then selecting the progeny that show increased pest resistance. This process is repeated by crossing the progeny with themselves, each other, or the parent plants to further enhance resistance and potentially produce a new resistant variety. This type of classical breeding has focused on trait selection with less emphasis on identifying the underlying mechanisms of pest resistance. However, recent advances in DNA and mRNA sequencing and bioinformatics have enabled the identification of genes associated with pest resistance, creating opportunities for genetic engineering to add these traits to crops that do not naturally harbor these genes (Lilley et al., 2011; Ali et al., 2017).

Crop-pest combinations and scale of use

Many pest-resistant varieties and rootstocks (including resistance to phytoparastic nematodes and fungal pathogens) are either commercially available or described in the scientific literature. These span tomato (Grieneisen et al., 2018; Chitwood-Brown et al., 2021; Volesky et al., 2022), sweet potato (Martin and Jones, 1986), potato (Volesky et al., 2022), watermelon (Volesky et al., 2022), other melons (Volesky et al., 2022), peas (Volesky et al., 2022), almond (Duncan et al., 2023; Duncan, n.d.), strawberry (Holmes et al., 2020; Holmes, 2024), walnut (Arnold, 2020), grape (Sope, 2022; UC ANR, 2003), and peppers (Ploeg, 2016), among other specialty crops. Currently, there is no systematic reporting of the use of specific varieties or rootstocks resistant to soil pests.

Efficacy and duration of pest control

There are many pest-resistant varieties and rootstocks available for California crops that currently use soil fumigation. Several varieties of commercially available grape rootstock have robust resistance to several plant parasitic nematodes, including *Xiphinema* spp. and *Meloidogyne* spp., as indicated by absence of nematode eggs on roots and galls on root tips after three months of exposure to infested soil (Ferris et al., 2012). Commercially available peach and nectarine varieties similarly showed complete absence of galling and soil infestation after four months of exposure to *Meloidogyne* spp. (Yağcı et al., 2019). As almonds are closely related to peaches and nectarines, almond rootstocks are also available with immunity to *Meloidogyne* spp. (Wani et al., 2012). Breeding efforts have produced several varieties of strawberries with varying levels of resistance to fungal infection by *Fusarium oxysporum* f. sp. *fragariae race 1, Verticillium dahliae, Macrophomina phaseolina*, and *Phytophthora cactorum* that range from near total resistance under typical cultivation conditions to partial resistance (UC Davis, 2024b). Likewise, there is an assortment of carrot, tomato, and melon varieties available with resistance to various nematode and fungal pests, although quantitative data on disease resistance is not always readily available (Cornell University, 2024a; Utah State University, 2022).

It should be noted that the resistance results cited above apply within a single cropping cycle, and it is possible that soil pests and pathogens may adapt over time to overcome the resistance (Qiu et al., 2021) or that environmental conditions (such as temperature) may weaken plant resistance (Abd-Elgawad, 2022). Furthermore, while data show effectiveness in guarding against specific pests or pathogens, each variety or rootstock also has susceptibilities to other relevant nematode, fungal, and bacterial pathogens and pests, which are typically noted in the descriptions for each variety (e.g., UC Davis, 2024b).

Within a given crop there can be dozens of available varieties that each have resistance to specific soil pests, susceptibilities to non-target pests, tolerance to certain soil characteristics, differing anchorage in the soil, and, for certain crops, differing pollination compatibility with other varieties. As a result, it is challenging to make broad claims about the effectiveness of resistant varieties and rootstocks as a whole.

Production yield effects

Major California cash crops that currently rely on soil fumigation have undergone breeding or grafting to develop resistance to specific soil pests and diseases. Many *Prunus* (stone fruit) rootstocks are available, which are compatible with a range of almonds, peaches, plums, cherries, nectarines, and apricots. Several major rootstocks are resistant to parasitic nematodes such as *Meloidogyne* spp. For instance, a comparison of two such rootstocks, Nemaguard and Okinawa, showed that Nemaguard consistently delivered yields 4 to 16% higher than Okinawa when grafted to peach trees (Ahmed et al., 2017). Similarly, Nemaguard rootstock grafted to apricot resulted in higher yields compared to the Real Fino rootstock variety (91 to 110% increase) (Pérez Romero et al., 2014). For bell peppers, the Crusader variety maintained yields under increasing *Meloidogyne incognita* pressure that were similar to growth in uninfested soils (Aguiar et al., 2014). Melons grafted to a particular rootstock (RS 841, resistant to *Fusarium* spp. and *Didymella bryoniae*) had 36% more yield than ungrafted plants (Crino et al., 2007). Resistance to parasitic nematodes has been identified in a Brazilian variety of carrot, where yields improved over 1,900% compared to susceptible varieties grown in soils infested with *Meloidogyne javanica* (Huang et al., 1986). Note that the resistant varieties still benefitted markedly from nematicide application. Efforts are underway to breed these traits into carrot varieties suitable for California (Theisman, 2021). Similarly, there is ongoing work to develop squash varieties resistant to *Phytophthora capsici.* While recent varieties show disease resistance, this has yet to translate to significant yield improvements over existing squash varieties (LaPlant et al., 2020). Research on several combinations of pepper scion (upper portion of plant) and rootstock varieties in *Fusarium oxysporum*-infested soils found that specific pairings influenced yield, plant stature, and fruit quality (Attia et al., 2003). A comparison of pepper varieties that were either susceptible or resistant (Resistant Line 89422) to *M. incognita* showed that yield differences were only apparent once a critical density of nematodes were present in the soil, at which point the resistant variety showed up to 150% greater yield than the susceptible variety (however, this represented a 50% reduction in yield compared to growth in non-infested soil) (Di Vito et al., 1992). Strawberries have been the focus of rigorous breeding efforts to improve resistance to Fusarium wilt while maintaining or exceeding the yields seen with existing varieties. A recently developed resistant variety, UC Eclipse, has shown up to 54% improved yield compared to existing varieties. It has been bred for compatiblity with multiple growing regions in California (along with other new and fungal disease-resistant varieties such as UC Monarch, UC Surfline, UC Keystone, and UC Golden Gate) (Dooley, 2023).

Costs associated

Plant costs should be weighed against the possible net returns for using grafted plants. An analysis of grafted and non-grafted heirloom tomato transplants in soils infested with root-knot nematodes (*Meloidogyne* spp.) showed that grafted transplants were more than four times more costly than the nongrafted transplants ($0.78 versus $0.17 per plant). As a result, they could only be justified under intense nematode pressure in the soil (Barrett et al., 2012). A comparison of grafted and non-grafted tomatoes grown in North Carolina and Pennsylvania similarly found that grafted plants were 2.5 to 4.5 times more expensive than non-grafted plants (Rivard et al., 2010). No published cost studies could be found that compared crop varieties resistant to soil pests to corresponding susceptible varieties.

Research has shown that net returns can be highly dependent on the level of **pest pressure**. For instance, when non-grafted, susceptible tomato plants were compared to those grafted to root-knot-nematode-resistant rootstock in soils with low nematode pressure, the grafted plants underperformed and yielded lower net returns than the non-grafted plants (Barrett et al., 2012). However, under high nematode pressure the grafted plants yielded mean net returns roughly two to four times greater than non-grafted plants (Barrett et al., 2012). This emphasizes the economic importance of selecting resistant plants that match the pest type and magnitude of pest pressure at a given site.

Additional requirements for use

Use of pest-resistant varieties or grafted plants with pest-resistant rootstock is a matter of seed or transplant selection and sourcing rather than a soil disinfestation technique. As a result, this strategy represents a minor change to crop establishment procedures rather than affecting land preparation, labor, consumables, or equipment needed for soil disinfestation.

Availability, ease, and reliability

There are many soil pest-resistant varieties or rootstocks available for several of the major fumigant-reliant crops in California, including almonds, carrots, grapes, peppers, strawberries, sweet potatoes, and tomatoes, among others (Cornell University, 2024b; UC Davis, 2022, 2024b). Many of these varieties can be purchased from commercial nurseries. However, varieties within a given crop can differ in their growth behavior, product characteristics, resistance to specific soil pests, tolerance for other soil conditions (e.g., pH, drought, lime content, nutrient content), and, in some cases, pollination compatibility with other varieties. As a result, growers must select the appropriate varieties for their site and cropping system that also have commercial demand. Additionally, resistant varieties and rootstocks are usually only effective against a subset of soil pests, so other control strategies may be needed when multiple soil pest and pathogen stresses are present.

> 55. **FINDING:** There are commercially available resistant varieties or rootstocks for many of the crops in California that currently use soil fumigation. However, these varieties and rootstocks do not cover the full range of soil pests that are controlled through fumigation with 1,3-D and chloropicrin. Yield effects relative to non-resistant varieties may vary positively or negatively depending on the type and level of pest pressure in the soil.

> 56. **CONCLUSION:** Resistant varieties and rootstocks can be effective in controlling certain classes of soil pests, such as specific nematode and fungal pathogen species. They are less likely to be effective fumigation alternatives in fields with multiple pest stresses unless other complementary pest control strategies are used.

Section 2.10: Non-chemical and biological method: Steam treatment

Overview

Steam treatment of soil uses saturated steam as a heating medium to raise the soil temperature in the root zone, with the goal of pasteurizing the soil to eliminate pests and pathogens. (Saturated steam is steam that is at the boiling point temperature for water and rapidly condenses to hot liquid water as it loses heat.) Specialized equipment is necessary to apply steam to the soil. Several applicator designs have been described in the scientific literature;

all generally consist of a mobile steam generator coupled with a surface and/or injection apparatus to transfer the steam to the soil in a continuous or incremental fashion (Fennimore and Goodhue, 2016) (***Figure 2.2***). The technique aims for soil temperatures ranging between 60 to 80˚C (140 to 176˚F) for durations of 20 to 30 minutes in order to inactivate a broad spectrum of soil pests and pathogens (Fennimore and Goodhue, 2016). However, the rate of heat conduction in the soil, and thus the time to achieve target soil temperatures, depends on the soil texture and moisture content (Minuto et al., 2004) along with the temperature and flow rate of the steam (Yang et al., 2019). Presently, the heating requirements for the soil and effectiveness of steam delivery systems on applicator equipment can require less than 10 minutes to bring the upper 15 cm (~6 in) of soil to the critical temperature range, equating to a treatment rate of approximately 14.6 hours per acre (Fennimore and Goodhue, 2016). Soil temperatures can remain elevated for at least 30 minutes, and potentially hours, after the applicator has passed, providing the necessary dwell time for pest inactivation (Fennimore et al., 2014; Guerra et al., 2022). Current research aims to improve both the efficiency of steam generation and the infusion of steam into soil to decrease the fuel requirements and the time to heat the soil to the desired depth. This includes new steam injector and applicator designs, such as combining surface sheet application with shank injection or "just enough" treatment on beds to treat planting holes (Fennimore, 2023; Gay et al., 2010).

Figure 2.2. Mobile steam applicator used for soil disinfestation treatment, designed to deliver high-temperature steam (65 - 70°C or 149 - 158°F) for pest and pathogen control in agricultural fields. Photo: Jenny Broome.

Crop-pest combinations and scale of use

Research on steam treatment effectiveness has concentrated on strawberry production (Samtani et al., 2012; Fennimore and Goodhue, 2016, Kim et al., 2021). In strawberry field and nursery studies, steam treatment has proven effective in controlling weeds such as common chickweed, little mallow, yellow nutsedge, and common purslane along with the parasitic nematode *Tylenchulus semipenetrans*; control of the pathogens *Pythium ultimum* and *Verticllium* spp. was sometimes site- and depth-dependent (Samtani et al., 2012; Fennimore and Goodhue, 2016, Kim et al., 2022). Studies have explored steam treatment in cut-flower production, where steam treatment enhanced the control of several common weeds and pathogens and improved plant emergence (Rainbolt et al., 2013). Similarly, robust weed control and reduction of the pathogens *Sclerotinia sclerotiorum* and *Pythium* spp. were achieved with steam treatment in various lettuce, spinach, and carrot cropping systems (Guerra et al., 2022).

There are no published data describing the level of commercial adoption and acreage treated via steam. However, there are commercial providers of agricultural soil steam applicators that operate in containerized systems or directly in fields (Soil Steam International, Norway; Sioux Corporation, South Dakota). Other companies offer soil steaming as a service, but it is branded for remediation of soil contamination rather than disinfestation.

Efficacy and duration of pest control

Steam treatment field trials have demonstrated its effectiveness in suppressing fungal pathogens, weeds, and plant parasitic nematodes (e.g., *Pythium ultimum*, *Macrophomina phaseolina*, *Fusarium oxysporum*, *Verticillium dahliae*, *Meloidogyne arenaria*; see ***Appendix B*** for additional studied targets). Data from these studies consistently showed the ability of steam treatment to achieve complete or near complete suppression of the target pests within the treated depth. This often matched, and in some cases exceeded, the results achieved through fumigation with methyl bromide, chloropicrin, or 1,3-D. For one study that compared initial and final parasitic nematode levels across a growing season, pest suppression was maintained for at least seven weeks after steam application (the longest time point included in the study) (Kokalis-Burelle et al., 2016). No other data could be found regarding the duration of pest and pathogen inactivation following steam treatment.

Production yield effects

Steam treatment in strawberry production is well represented in the research literature. Field trials have shown benefits to strawberry marketable yield, achieving 18 to 214% increases over untreated control soils and matching the effectiveness of fumigation with 1,3-D and chloropicrin (Fennimore et al., 2014). Another study observed that steam treatment improved strawberry yield up to 59% over untreated soils under *Verticillium dahliae* stress, which was similar to the improvement obtained following fumigation with methyl bromide and chloropicrin (Samtani et al., 2012). Additional studies have reinforced this finding, showing that increased yield of strawberries in soils with fungal pathogens was comparable to fumigation with methyl bromide and chloropicrin (D. S. Kim et al., 2021, 2022). Yield benefits have also been achieved in ornamental flower production, where shoot weight and height increased by 25 and 9%, respectively, over plants grown in soils fumigated with methyl bromide (Kokalis-Burelle et al., 2016). However, results varied in a study using steam treatment for leafy greens and carrot production. Specifically, iceberg lettuce marketable yield increased relative to untreated controls in two of three trials (28 to 39% increase), but no significant improvements in marketable yield were observed for spinach or carrots (Guerra et al., 2022).

Costs associated

The economics of soil steam treatment have been most studied in California strawberry production. For strawberry fields in the Central Coast, an analysis of the fuel, labor, and annualized applicator costs for steam treatment determined the total treatment cost to be $3,720 per acre (Xu et al., 2017). Fuel costs (propane) accounted for over 80% of the total treatment cost, making fuel prices the primary factor influencing treatment cost for current steam applicators. The cost of steam treatment was more than twice the price of fumigation with 1,3-D and chloropicrin, resulting in higher net returns for fumigation (Xu et al., 2017). At the time of writing this report, prices to purchase commercially available steam applicators were not publicly available.

Additional requirements for use

Steam treatment of soil requires specialized equipment that can generate steam and infuse it into the soil, either through surface sheets or an injection apparatus. Currently, these devices are produced by a small number of manufacturers. Steam applicators require considerable time to treat one acre due to the time needed for steam to diffuse into the soil from the applicator. For example, one commercially available steam applicator is capable of treating a 1.6 m-wide area at a rate of 150 m per hour (Fennimore and Goodhue, 2016), equivalent to approximately 16.86 hours per acre. For comparison, DPR permits up to 80 acres to be fumigated with 1,3-D in a 24-hour period (DPR, 2024a). It would take the cited steam applicator over 56 days to treat the same acreage. Given this disparity, growers using steam treatment may be limited to small areas or need to deploy multiple steam applicators for larger fields.

Availability, ease, and reliability

Steam treatment of soil requires highly specialized equipment to generate and deliver steam to the soil. At the time of writing, there appears to be only a single manufacturer in the

United States for soil steam applicators that can operate on large fields (Sioux Corporation; Beresford, South Dakota). Other steam applicators described in the scientific literature are currently prototypes. It is unclear how readily growers can acquire this equipment or access external services that provide steam application. Furthermore, the relatively slow treatment time per acre (roughly 17 hours to treat one acre with one applicator) may lead to challenges for treating large fields.

Additionally , the maximum depth of steam penetration and heating kinetics across the entirety of the root zone for many crops remain uncharacterized. To date, studies have focused on tracking temperatures at shallow depths ranging 5 to 25 cm (2 to 5 in) (Miller et al., 2014; Yang et al., 2019), which comprise a fraction of the root zone for several crops that currently utilize fumigation (UCCE Los Angeles County, 2011). Even systems with steam injectors, where pipes are inserted into the soil with the intent to increase the depth of heating, have not measured soil temperature beyond 20 cm (7.9 in) depth (Yang et al., 2019). Heat transfer modeling of steam injectors placed at 20 cm (7.9 in) depth showed that the heating effect is expected to decrease substantially within 15 to 20 cm (~6 to 7.9 in) beyond the position of the steam emitter, and sub-lethal temperatures occur beyond this radius (Yang et al., 2019).

> 57. **FINDING:** There are a limited number of steam applicators available commercially or described in the research literature that can treat open fields in a way that would allow for displacement of fumigation. Design innovations have improved the delivery of steam to soil to better control the rate and depth of heating, but heating of soil beyond 20 cm depth is largely untested.

> 58. **CONCLUSION:** Steam treatment can deliver broad spectrum soil pest control, but the reliance on specialized equipment, limited knowledge of heating depth, and slow treatment times for a single applicator present barriers to adoption.

> 59. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting engineering and research efforts to characterize or enhance the depth of steam treatment along with work to improve steam treatment times for large fields. Additionally, given the fuel requirements to operate existing steam applicators, DPR and/or other relevant California state agencies should consider supporting life cycle assessments to understand the environmental impacts of using steam treatment in open field, greenhouse, and nursery settings and in response to different fuel types (e.g., natural gas, biogas, hydrogen).

Section 2.11: Non-chemical and biological method: Soilless cultivation

Overview

Soilless cultivation systems completely eliminate direct soil contact with crops and thus avoid exposure to soilborne pests. Soilless cultivation can be done entirely in nutrient-rich liquid (hydroponics), or by using a solid substrate combined with fertigation (delivering water and nutrients through irrigation). Some hydroponic systems use floating vessels or flow channel systems where roots are in continuous contact with a nutrient solution. Other hydroponic systems are designed for aeroponic operation, where plants are suspended in air and the roots are periodically sprayed with nutrient solution (Savvas and Gruda, 2018). Solid substrates for soilless systems include inorganic materials such as plastics, vermiculite, perlite, and other mineral particulates, and organic matter such as coir (fiber from the outer husk of coconut), bark, peat, or compost (Savvas and Gruda, 2018). Water holding capacity, pH and buffering capacity, salt content, nutrient retention capacity, stability, and porosity must be considered when selecting a substrate for a given crop. Pretreatment of the substrate, such as washing or composting, may be necessary to remove compounds from organic matter that would be toxic to plants. The interaction effects between the solid substrate and the crop are an active area of research. For instance, differing mixtures of inorganic and organic substrates affected photosynthesis, yield, and certain physical and chemical properties of strawberries grown under greenhouse conditions (Alsmairat et al., 2018). Similar research is needed to determine compatible substrates for other fumigant-reliant crops.

Soilless systems use substrates such as peat or coconut fiber (coir) in pots, bags, raised gutters, or lined trenches that are in open fields or greenhouses (***Figure 2.3***). However, there may be quality and yield differences between these formats, as has been seen in strawberries (Rahim Doust et al., 2023). Research is needed to identify and address the factors that lead to these differences for strawberries and potentially other fumigant-reliant crops so that the best-performing format can be compared against other fumigation alternatives.

Figure 2.3. A tabletop production system for strawberries. This cultivation system elevates plants off the ground, reducing soilborne disease risks by eliminating direct contact with soil. Photo: Gerald Holmes.

Crop-pest combinations and scale of use

As soilless cultivation seeks to avoid, rather than resist or inactivate, soil pests, it can be viewed as a method to mitigate all soil pathogens, parasitic nematodes, and weed propagules associated with a given crop. As most published production data is for conventional field cultivation, information is scarce regarding the magnitude of commercial crop production in soilless systems. However, an internet search revealed commercial hydroponic systems operating in California that produce leafy greens, strawberries, tomatoes, and fresh-cut flowers. Beyond hydroponic systems, trials in California have shown the potential for increased strawberry yield when plants are grown in troughs of coconut coir located in open fields rather than directly in field soil (Wang et al., 2019).

Efficacy and duration of pest control

Since soilless cultivation avoids crop contact with pests and pathogens rather than inactivating pests in the soil, soilless systems can potentially eliminate pest and pathogen exposure completely and indefinitely. To fully achieve this potential, it is essential to use sanitary substrates and practices that avoid contamination. This includes selecting substrates unlikely to harbor pests or pathogens, such as perlite and other mineral substrates, or biomass substrates that have been pasteurized via composting, heat treatment, or other methods. In hydroponic systems, **oomycete** pathogens (e.g. *Pythium* and *Phytophthora* spp.) can cause disease across multiple crops (Sutton et al., 2006; Postma et al., 2008). These pathogens readily grow in hydroponic nutrient solutions and can be introduced to these systems via air or contaminated plant material, tools, or workers (Sutton et al., 2006; Postma et al., 2008), requiring sanitation strategies at multiple levels of material sourcing, air handling, and worker practices.

Production yield effects

Research regarding soilless cultivation and yield effects has examined both solid substrate and hydroponic systems. A comparison of zucchini squash growth in soil and different soilless substrates indicated that increases of up to 33 and 40% for total and marketable yield, respectively, were possible relative to growth in soil (Rouphael et al., 2004). For hydroponic lettuce production, 41 to 43% increases in yield compared to conventional soil production were obtained across two cropping cycles (Majid et al., 2021). Likewise, strawberry yield increased 23% in a hydroponic system compared to soil cultivation (Treftz and Omaye, 2016), and hydroponic growth correlated with enhanced consumer preference for the fruit compared to that produced through soil cultivation (Treftz et al., 2015). Similarly, chrysanthemum flower number and dry weight both increased by 61% in a hydroponic system versus soil growth (Ai et al., 2021). Despite the benefits demonstrated in these individual studies, a meta-analysis of crop growth in hydroponic and conventional systems identified contrasting responses to each growth system based on crop type. While anise, fennel, coriander, peppers, and cucumbers saw greater yields in hydroponic systems, cabbage (and other *Brassica* crops), lettuce, spinach, tomatoes, and several other vegetable crops exhibited greater yield in conventional soil systems (Goh et al., 2023). These results indicated that the crops' nutrient needs, susceptibility to root disease, and root system expansiveness likely contribute to compatibility with hydroponic cultivation.

Costs associated

A comparison of production costs for cucumbers produced in a soilless greenhouse system versus soil-based greenhouse cultivation in Turkey determined that soilless production required more inputs, energy, and capital recovery (owing to initial investment in more complex systems to monitor and manage water and fertigation) compared to soil-based production (Engindeniz and Gül, 2009). This cost translated to \$3.70 per m^2 (\$0.34 per ft^2) for soilless production and \$1.91 per m^2 (\$0.18 per ft^2) for soil-based production (following conversion from euros (€) to dollars using an exchange rate contemporary to the study, \$0.72 per €, and then adjusting to 2024 dollars). For the soilless system, the initial investment for greenhouse construction and its interest represented 55.1% of the total cost. However, the soilless system resulted in greater yield such that the cost normalized to mass of product was \$0.036 per pound for the soilless system and \$0.038 per pound for the soil-based system (following conversion of values as described previously). A more recent study found the high costs of constructing a soilless cultivation system remains a barrier to adoption, and that additional development of an economy of scale and selection of low-cost growing substrates will be important for minimizing costs (Fussy and Papenbrock, 2022).

There are added energy costs for soilless production in greenhouses compared to field production, and implementing energy efficiency measures such as efficient LED lighting and on-site solar energy generation can further reduce energy costs (Gonnella and Renna, 2021). Available economic assessments of soilless systems cover a narrow range of crops and operating conditions (e.g., choice of planting substrate), and generally do not directly compare the costs of soilless systems (implemented in greenhouses or the field) to conventional soil-reliant field production. As a result, there is a need for additional comparative analyses where typical field production systems that rely on fumigation are compared against various soilless systems (e.g., soilless substrate contained in pots in greenhouses or in lined beds in the field) for any given crop.

Additional requirements for use

Soilless cultivation systems involve significant departures from conventional field production. For growers currently using conventional field cultivation, pivoting to soilless production would require shifting to greenhouse or in-field soilless production. For greenhouse production, significant capital investment is required to build the structure, including the water and fertigation management systems needed to support potted plants in soilless substrate. For in-field soilless systems, field preparation may involve shaping beds with lined trenches that contain soilless substrate, which is different from bed shaping processes used in conventional fields. Both options require the grower to adopt drip irrigation and fertigation systems, which may also be closed-loop and thus require treatment processes to support water and nutrient solution recycling. The grower must also select and source appropriate soilless substrates that are economical and have the appropriate physical and chemical properties for the target crop.

Availability, ease, and reliability

Soilless cultivation systems can be implemented within greenhouses or in open fields. Both formats rely on anchoring plants in a non-soil substate and use of drip, spray, or sprinkler systems for irrigation and fertigation. There are many potential substrates, and some are already widely used in potted plant and hydroponic systems, such as perlite, rock wool, peat moss, compost, wood chips, and coconut coir. These materials can be readily and reliably obtained commercially. Other fiber sources that may potentially be used as substrate, such as milled nut shells, may be collocated with the major agricultural regions of the Central Coast, but do not have the same industry precedent as conventional substrate.

For growers currently employing conventional soil-based crop production, switching to soilless cultivation would entail considerable capital investment to construct greenhouses or a radical retooling of their fields to accommodate lined trenches or growbags containing soilless substrate. Currently, a 371 m^2 (4,000 ft^2) greenhouse can cost \$30,000 to \$50,000 to construct and equip, depending on the design and materials used (Hochmuth et al., 2018). Moreover, growers must acquire new knowledge and training regarding the management of ventilation, light, temperature, and water in greenhouses. Similarly, open field soilless systems require new training and field operations for field preparation and management of irrigation and fertigation systems in soilless production.

> 60. **FINDING:** Soilless cultivation systems span a variety of hydroponic and solid substrate approaches. By their nature, soilless systems can avoid pests in soil commonly controlled through fumigation. However, these systems can be vulnerable to pathogenic growth in nutrient solutions.

> 61. **CONCLUSION:** Soilless cultivation systems represent a substantial departure from conventional agriculture in open fields, requiring infrastructure, nutrient and water management practices, and sanitation methods that are markedly different from those used in fields.

> 62. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting analyses to determine the feasibility and cost of transitioning various open field cropping systems to different hydroponic or solid substrate soilless systems, such as substrate bags in open fields or atop tables.

Section 2.12: Non-chemical and biological method: Sanitation

Overview

Sanitation practices do not disinfest soils or otherwise address existing soil infestations, and thus are not explored in depth here, but it is worth noting that they can complement fumigant alternatives to decrease the risk of creating new infestations. Sanitation practices prevent cross-contamination by thoroughly cleaning and sanitizing equipment that operate across multiple fields, promptly removing potentially infested plant debris, and using clean plant stocks to establish crops. Clean stocks come from nurseries that use a combination of sanitary practices, such as disinfesting planting substrates, regularly sanitizing plant and worker contact surfaces, and sanitizing any recycled irrigation water or nutrient solutions (Gullino et al., 2015). Controlled exposure to hot water or steam can also be used to directly disinfest seeds or transplants before introduction to the field (Grondeau et al., 1994; Crous et al., 2001; Turechek et al., 2021).

Section 2.13: Non-chemical and biological method: Diversified systems

Overview

Diversified farming Systems rely on the principle of functional biodiversity, which involves managing ecosystems that interface with agriculture to preserve and support critical agriculture processes such as plant nutrient availability and pest suppression (Kremen, 2012). Diversified farming systems employ many of the tactics outlined above but in combination, especially cover crops, crop rotations, organic amendments, and intercropping, with the goal of eliminating the need for pesticides (Kremen, 2012). Further research into the mechanisms of the functional biodiversity on diversified farms—and how it might relate to soil and plant health—could provide valuable insights into how these farms operate without fumigants. Additionally, going beyond traditional yield metrics, which correspond to single crops grown as a monoculture, and instead measuring overall yield across multiple crops grown in parallel may better reflect the productivity and crop health of diversified farming systems.

> 63. **FINDING:** Diversified farming systems employ many non-chemical and biological methods in combination, especially cover crops, crop rotations, organic amendments, and intercropping, as a substitute for pesticides.

> 64. **CONCLUSION:** Greater study of potential mechanisms of the functional biodiversity on diversified farms and how it might relate to soil and plant health, in addition to reporting the costs and returns of diversified farming systems, could provide insights into how these farms operate without using fumigants.

Section 2.14: Summary of key variables in the literature

Crop-pest combinations and scale of use

Presently, there is no comprehensive systematic tracking of fumigant alternative use across California or elsewhere. As a result, it is challenging to identify trends in the adoption of fumigation alternatives within the state or at the national and international levels. Research studies and reviews provide a cross-section of the differing scales, range of crops, regions, and pests targeted for major fumigant alternatives (***Appendix B***).

> 65. **FINDING:** There is no comprehensive systematic tracking of fumigant alternative use across California or elsewhere.

Efficacy and duration of pest control

Efficacy studies range from small lab-scale experiments to greenhouse and field trials. These studies often examine a subset of the spectrum of pests that may be controlled through fumigation with 1,3-D and chloropicrin. Studies quantify effectiveness through direct measurement of the abundance of viable pests in soil or associated with roots or by measurement of disease frequency and severity in crops. ***Appendix B*** provides a sampling of the scientific literature to demonstrate the diversity of effectiveness research approaches and outcomes.

> 66. **FINDING:** Research is inconsistent in the use of controls; some studies compared effectiveness against fumigation while others only compared against untreated soils.

> 67. **FINDING:** Overall, fumigant alternatives demonstrate varying levels of effectiveness compared to fumigation. Some alternatives show partial effectiveness, others are effective only under specific conditions, a few offer comparable effectiveness to fumigation for certain pest and crop targets, while others remain understudied or uncharacterized.

Production yield effects

Yield effect data demonstrate how different farming practices impact the productivity of crops. The data are highly contextual, depending on conditions such as crop type, local climate, soil health, and management processes.

> 68. **FINDING:** Yield effects for each fumigant alternative may differ based on the crop studied, type of pest pressure, and process variables unique to each alternative. Moreover, yield effects must be qualified based on comparisons to untreated soils (negative controls) or soils fumigated with 1,3-D and chloropicrin (positive controls), and the data are inconsistent in the types of controls used.

> 69. **FINDING:** For all alternatives, there is evidence of yield benefits when compared against untreated soils for at least some crops that currently use fumigation. For alternatives that have been directly tested against fumigation, such as anaerobic soil disinfestation, biosolarization, solarization, and steam treatment, similar or greater yield enhancement has been achieved in certain crop and regional use cases relative to fumigation.

> 70. **FINDING:** There are major gaps in the types of crops and regions studied, as well as the use of fumigated positive controls, that challenge direct yield comparisons across fumigant alternatives and between alternatives and fumigation with 1,3-D and chloropicrin.

Costs associated

There is inconsistency in the availability and representativeness of cost data for fumigant alternatives in the context of California agriculture. Alternative fumigants, non-fumigant pesticides, cover crop seeds, and pest resistant varieties for several crops are commercially available and use familiar farm operations for implementation. For these approaches, cost studies can draw from market prices and defined methods to inform quantification of process costs. In contrast, techniques such as anaerobic soil disinfestation and biosolarization are largely not commercialized and involve use of a variety of organic matter soil amendments that can potentially vary widely in cost; cost studies have not systematically examined these differences.

> 71. **FINDING:** Cost studies for fumigant alternatives capture only a small fraction of the use scenarios and crop systems that currently use fumigation with 1,3-D and chloropicrin.

Cost studies performed beyond California may have less relevance to California agriculture due to differences in labor costs. Moreover, less established fumigant alternatives may require more labor during adoption compared to later on when workers are more familiar with the process. Cost studies rarely acknowledge this, and none have attempted to quantify the cost implications over time.

> 72. **FINDING:** Even when cost information is available, it is often not tied to specific levels of pest inactivation or yield improvement (both of which directly impact net returns), making it difficult to compare costs between alternatives based on their relative effectiveness.

Section 2.15: Human health, environmental, and ecological concerns

Since all fumigation alternatives alter the soil's chemical environment or ecology to some degree, their potential negative effects on environmental, ecological, and human health must be considered. Negative environmental effects include pollution of the soil, water (both surface and ground), or atmosphere with harmful substances (toxicants), as well as compounds that contribute to broader environmental issues such as climate change. Ecological impacts can stem from toxicity to non-target organisms and environmental changes that perturb the existing biological diversity and activity (e.g., changes to the soil microbiota). Direct human health impacts relate to exposure to toxic compounds and associated disease risk.

Biosolarization and anaerobic soil disinfestation, which deliberately generate anaerobic (oxygen-free) conditions in the soil, can potentially produce methane, carbon dioxide, and nitrous oxide (Achmon et al., 2016; Prescott et al., 2023; Sanabria-Velazquez et al., 2020). As a greenhouse gas with approximately 30 times more **global warming potential** than carbon dioxide (over a 100-year period), methane emissions from agricultural soils could contribute to climate change. Nitrous oxide gas is also associated with climate change and ozone layer depletion.

> 73. **FINDING:** Data have shown that methane production can occur during biosolarization and anaerobic soil disinfestation.

Specific approaches to biosolarization and anaerobic soil disinfestation can mitigate or entirely prevent methane emissions. For instance, a study comparing biosolarization using residues from tomato and wine processing found that only residues from red wine production led to detectable methane emissions (Achmon et al., 2016). This was the least labile (least easily degradable) amendment tested, suggesting that selecting more rapidly degradable amendments may allow other microorganisms to outcompete methane-producing microorganisms (methanogens) or create soil conditions that inhibit methanogens. Supporting this, methane emissions were uniquely avoided during anaerobic soil disinfestation with wheat bran amendment (as opposed to mustard greens or molasses) (Sanabria-Velazquez et al., 2020).

Additionally, methane emissions are likely to be minimal if soils do not naturally harbor active methanogenic microorganisms, and these microorganisms are not introduced through the soil amendments used in biosolarization and anaerobic soil disinfestation. Granted, there is a dearth of data regarding the prevalence of methanogenic microorganisms in agricultural soils, underscoring the need for microbial profiling of soils and amendments to identify sites and conditions with low methane potential. In particular, manure-based amendments may increase the risk of methane emissions since manure can introduce methanogenic microorganisms to the soil (Wang et al., 2020). This risk is consistent with observed methane emissions during anaerobic soil disinfestation using manure amendment (Zhao et al., 2021).

Nitrous oxide emissions have also been detected during anaerobic soil disinfestation, although the emissions varied with site location, amendment type, and time, suggesting the background soil microbiota, duration of oxygen exclusion, amendment nutrient profile, or other environmental variables, such as temperature, play a role in determining emission potential (Di Gioia et al., 2017). Di Gioia et al. (2017) found that for the first 3 days of fumigation with 1,3-D and chloropicrin or anaerobic soil disinfestation, nitrous oxide emissions from the soil were similar, but by 21 days of treatment, emissions were significantly greater in the soils treated with anaerobic soil disinfestation. Studies do not use consistent units to express nitrous oxide emissions in agriculture, but the maximum emission value of roughly 1,400 µg m^2 per hour observed by Di Gioia et al. (2017) exceeded the maximum average seasonal emission rate observed for California rice production—a crop system that can also produce anaerobic soil conditions of 15.1 µg m^2 per hour (following conversion from units of kg per hectare per season assuming approximately six months (4,368 hours) from rice planting to harvest) (Linquist et al., 2018). As an emission mitigation measure, the study showed that use of totally impermeable film during anaerobic soil disinfestation was effective at decreasing nitrous oxide emissions during treatment (Di Gioia et al., 2017).

The incorporation of nitrogen-rich organic matter into soil, as may occur during biosolarization and anaerobic soil disinfestation, presents a risk of nitrogen leaching, which could contaminate groundwater. A study examining anaerobic soil disinfestation using straw and manure amendments found that nitrate leaching occurred but was reduced through co-amendment of manure with straw (Zhao et al., 2021). This result suggests that adjusting the amendment's carbon-to-nitrogen ratio can enhance nitrogen immobilization by soil microorganisms, thereby decreasing leaching. These results emphasize the need for carefully defined amendment types, application rates, and irrigation strategies—both during and after treatment—to minimize nitrogen leaching in soils treated with biosolarization or anaerobic soil disinfestation. Additionally, livestock manure and litter amendments, which have been used in some biosolarization and anaerobic soil disinfestation research (e.g., Di Gioia et al., 2017) pose risks of heavy metal accumulation, human pathogen contamination, or antibiotic contamination in soils (Han et al., 2000; Goldan et al., 2023). These findings highlight the importance of carefully selecting amendments to avoid introducing contaminants into the soil.

Fumigant alternatives that use fermentation or heat to disinfest soils may affect the abundance or diversity of soil microbial communities. Soil microbial communities play key roles in soil nutrient cycling, pest suppression, and crop protection, and it is important to preserve these functions. Research has shown that both anaerobic soil disinfestation and biosolarization can increase the overall microbial biomass in the soil, although there are shifts in community structure (Fernández-Bayo et al., 2017; Guo et al., 2018). Some of these changes may benefit crop production. For instance, one study of biosolarization observed enrichment of the bacterium *Azotobacter beijerinckii*, which can capture nitrogen for plants and produce compounds that promote crop growth (Hindersah et al., 2020; Simmons et al., 2014).

Similarly, steam treatment of soil has been shown to release labile carbon from soil organic matter, promoting an increase in microbial soil biomass and activity (Richardson et al., 2002; Roux-Michollet et al., 2010). This effect may be driven by the proliferation of bacteria (rather than fungi) in the soil (Elsgaard et al., 2010). Compared to fumigation with chloropicrin, steam-treated soils show more rapid recovery of soil microbial community richness (Tanaka et al., 2003). However, disruption of specific soil microbial functions, such as nitrification (a key part of nitrogen cycling), has been observed in steam-treated soils (as with chloropicrin fumigation), although this did not negatively affect tomato crop growth (Tanaka et al., 2003).

Solarization employs elevated temperatures to inactivate pests. However, solarization does reach the high temperatures achieved with steam treatment and thus may not produce the same level of carbon breakdown that supports microbial growth. Additionally, solarization lacks the soil amendments used in biosolarization and anaerobic soil disinfestation, which supply nutrients for microbial growth and activity. Field studies have shown that beneficial mycorrhizal fungi are capable of persisting after solarization (Camprubí et al., 2007). However, solarization may also decrease soil microbial biomass and activity, including respiration (Díaz-López et al., 2019; Yokoe et al., 2015). As with steam treatment, solarization particularly affects fungi and nitrifying bacteria, which convert ammonia into nitrite (Yokoe et al., 2015). Research has also shown that solarization may increase disease caused by heat-tolerant pests and pathogens (Gamliel and Katan, 2009). This effect is likely due to eliminating competition for these pests when soil temperatures do not reach levels necessary for pasteurization.

Some non-chemical fumigation alternatives, such as solarization, steam treatment, resistant varieties, crop rotations, and cover cropping (when used for host disruption rather than biofumigation), inherently avoid inputs of known toxicants. Therefore, they lack a known mechanistic basis for directly affecting human health and have not been the target of risk assessment research. Cover cropping, anaerobic soil disinfestation, and biosolarization may generate **volatile organic compound** in soil—which is part of the biofumigation effect that controls soil pests—potentially leading to human exposure. For example, the isothiocyanate compounds produced from degradation of *Brassica* cover crops in the soil lead to detectable air emissions. Trott et al. (2012) found concentrations of various isothiocyanate compounds 1 m (3.2 ft) above the soil can range 0.7 to 188 µg per m^3 (0.000541 to 0.145 to ppm) in fields with *Brassica* cover crops. As with any volatile compounds, there is the possibility of escape and drift from the soil. Based on available toxicity information, the risk to human health appears to be minimal for people near fields that receive such treatments (Trott et al., 2012).

An analysis of volatile compounds produced by biosolarization with almond hull and shell soil amendment found that the majority of volatile compounds produced were volatile fatty acids (such as acetic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid, and hexanoic acid) and ketones (such as acetoin, 2-butanone, 2-pentanone, and 2,3-butanedione) (Shea et al., 2021a; Fernandez-Bayo et al., 2021). The concentrations of these compounds under tarps (where levels are expected to be highest) did not exceed human exposure limits (Shea et al., 2021a; Fernandez-Bayo et al., 2021). A study using anaerobic soil disinfestation with rice bran and broccoli crop residue soil amendments identified over 50 gaseous compounds emitted from treated soils (Prescott et al., 2023). These compounds spanned alcohols, alkenes, aromatic hydrocarbons, ketones, and amines, among other volatile organic compounds.

> 74. **FINDING:** The volatile compounds generated during biosolarization or ASD can differ based on the organic matter soil amendments and implementation method.

> 75. **CONCLUSION:** Additional research is necessary to define the biosolarization and anaerobic soil disinfestation process conditions (e.g., amendment nutrient profiles, duration of tarp coverage) that avoid methane and nitrous oxide emissions.

> 76. **CONCLUSION:** A full health risk assessment is required for the complete array of volatile compounds commonly produced during biosolarization and anaerobic soil disinfestation.

The human toxicity of fumigant and non-fumigant alternatives to 1,3-D and chloropicrin can be compared based on exposure limits and carcinogenicity determinations set by the National Institute for Occupational Safety and Health (NIOSH) (NIOSH, 2024) (***Table 2.6***). NIOSH-recommended exposure limits (REL) represent time-weighted average values that assume work up to 10 hours in a day as part of a 40-hour work week. The NIOSH immediately dangerous to life and health (IDLH) limits represent critical levels to avoid **acute** toxicity. The IDLH limits are informed by human toxicity or animal toxicity data and represent the maximum airborne concentration from which a worker lacking respiratory protection could escape without irreversible health effects (NIOSH, 2024). Although NIOSH does not list metam sodium and metam potassium (fumigants that produce methyl isothiocyanate as a degradation product), it should be noted that the California Office of

Environmental Health Hazard Assessment (operating under California Proposition 65), citing the U.S. EPA, lists these fumigants as cancer-causing (OEHHA, 2024a and 2024b).

NIOSH has not published REL or IDHL values for dimethyl disulfide, methyl isothiocyanate, or allyl isothiocyanate. Risk assessments of allyl isothiocyanate and methyl isothiocyanate by DPR found that existing data provide some evidence of oral carcinogenicity but no evidence of carcinogenicity via inhalation (DPR, 2003; DPR, 2022). Overall, DPR did not deem the evidence strong enough to warrant a quantitative cancer risk assessment (see ***Table 2.6***; DPR, 2003; DPR, 2022). However, methyl isothiocyanate is identified as likely to be carcinogenic to humans by the U.S. EPA (U.S. EPA, 2023b). Similarly, metam sodium and metam potassium, which rely on methyl isothiocyanate generation in the soil, are listed as likely carcinogens by the U.S. EPA and as cancer-causing agents under California Proposition 65.

Table 2.6. NIOSH recommended exposure limits (REL) and immediately dangerous to life and health (IDLH) limits for 1,3-D, chloropicrin, and alternative fumigants.

Name	Potential occupational carcinogen	REL	IDLH
1,3-D	Yes	1 ppm	Not determined
Chloropicrin	No	0.1 ppm	2 ppm
Dimethyl disulfide	Not defined	Not defined	Not defined
Allyl isothiocyanate	Not defined	Not defined	Not defined
Methyl isothiocyanate	Not defined	Not defined	Not defined

DPR risk assessments provide exposure limits for allyl isothiocyanate and methyl isothiocyanate, referred to as reference concentrations or reference exposure limits, which represent concentrations that are unlikely to cause deleterious effects over a given period of exposure. The assessment for allyl isothiocyanate calculated acute inhalation exposure limits (i.e., reference concentrations) of 0.014 to 0.042 ppm, a sub-chronic inhalation exposure limit of 0.125 ppm, and a chronic inhalation exposure limit of 0.0125 ppm (i.e., human equivalent exposure concentrations extrapolated from animal studies that determined lowest observed effect levels for allyl isothiocyanate) (DPR, 2022). The assessment for methyl isothiocyanate calculated an acute inhalation exposure limit (i.e., reference exposure level) of 0.022 ppm (DPR, 2003) and sub-chronic or chronic inhalation exposure limits ranging 0.0001 to 0.004 ppm (depending on the seasonality and hours of daily exposure) (DPR, 2016). Comparing the NIOSH REL values and DPR sub-chronic and chronic exposure limits, there is not a clear reduction in toxicity for allyl isothiocyanate or methyl isothiocyanate compared to 1,3-D or chloropicrin. However, the allyl isothiocyanate assessment notes that it is difficult to calculate exposures due to lack of fumigant use, air monitoring data, and sub-chronic/chronic exposure data for allyl isothiocyanate. Additionally, individual risk assessments may use differing methodologies and data to identify critical exposure concentrations in animal studies and extrapolate them to humans. This confounds comparisons across risk assessments to identify the relative safety of different fumigants.

NIOSH has not issued REL or IDLH values for the non-fumigant pesticides discussed in ***Section 2.3***. However, the LD50 and LC50 values can be compared to examine relative toxicity. These values represent the dosage (LD50) or respiratory concentration (LC50) that is expected to be lethal 50% of the time. The PubChem database maintained by the National Institutes of Health aggregates LD50 and LC50 values for various chemicals (S. Kim et al., 2023). A summary of these values is provided in ***Table 2.7***.

Table 2.7. LD50 and LC50 values for 1,3-D, chloropicrin, and non-fumigant pesticides that target common soil pests.

Name	LD50*	LC50*	PubChem citation
1,3-D	94–2,100 mg/kg bodyweight (rat, oral)	3,041.8–5,402.6 mg/cubic m (rat, inhalation over four hours)	National Center for Biotechnology Information (NCBI) (2024a)
Chloropicrin	37.5–250 mg/kg bodyweight (rat, oral)	6.6 (rat, inhalation, nose-only exposure over four hours) to14.4 ppm (rat, inhalation, whole-body exposure over 4 hours)	NCBI (2024c)
Oxamyl	2.3 mg/kg bodyweight (mouse, oral)	170 mg/cubic m (rat, inhalation over 1 hour)	NCBI (2024g)
Ethoprop	3 (chicken, skin)–60 (rat, skin) mg/kg bodyweight	123 mg/cubic m (rat, inhalation)	NCBI (2024b)
Fenamiphos	1 (quail, oral)–178 (rabbit, skin) mg/kg bodyweight	91 mg/cubic m (rat, inhalation over 4 hours)	NCBI (2024f)
Fluazaindolizine	1,187 (oral, rat)–>5,000 (rabbit, skin) mg/kg bodyweight	>5,300 mg/cubic m (rat, inhalation)	U.S. EPA (2021)
Fluensulfone	Not listed	Not listed	NCBI (2024h)
Terbufos	1.1 (rabbit, skin)–15 (quail, oral) mg/kg bodyweight	Not listed	NCBI (2024e)

*Values indicate the lowest and highest figures in the PubChem database across all tested animals and exposure routes (specified in parentheses). Only a single value is given when PubChem contains only cited measurement.

Toxicological gaps in the data for fluensulfone and terbufos prevent meaningful comparisons with other pesticides. For the data given for oxamyl, ethoprop fanamiphos, and terbufos, while there is some overlap in the ranges for LD50 and LC50, the non-fumigant pesticides generally have lower LD50 and/or LC50 values than 1,3-D and chloropicrin. This indicates that these compounds may pose a greater acute toxicity risk compared to 1,3-D or chloropicrin. Of the listed non-fumigant pesticides, fluazaindolizine exhibited the lowest acute toxicity via oral, dermal, and inhalation exposures, and LD50 and LC50 values were comparable to the upper ranges for 1,3-D. However, not all animal models may equally simulate human responses to these compounds, and certain exposure types (oral and skin) or exposure durations may not represent the most likely exposure conditions for agricultural workers and communities proximal to fumigation sites. As a result, additional human acute toxicity risk assessments are necessary for expected or possible occupational and community exposures. Furthermore, there is a need for studies that gauge the **chronic** exposure risk for these compounds, particularly for the concentrations, exposure routes, and exposure durations that are relevant to pesticide applicators, proximal agricultural workers, and adjacent communities. As non-fumigant pesticides may be used on actively growing crops, it is possible that residues could persist on crops through harvest and lead to exposures for agricultural workers and post-harvest handlers. As a result, strict adherence to the application rates and pre-harvest application intervals described on product labels is required to mitigate this risk. Non-fumigant pesticides are also susceptible to run-off (Rohde et al., 1979; Wilson et al., 2007), and research is also needed to determine the fate and exposure risk in watersheds associated with their use.

77. **FINDING:** The lack of an IDLH value for 1,3-D and absence of any NIOSH guidance for dimethyl disulfide, allyl isothiocyanate, or methyl isothiocyanate highlight gaps that require health risk assessments to enable comparisons against other fumigants.

78. **CONCLUSION:** Calculated exposure limits from DPR risk assessments for methyl isothiocyanate and allyl isothiocyanate do not indicate a clear reduction in exposure risk associated with adoption of these fumigants over 1,3-D and chloropicrin. However, a deeper analysis of the underlying data and methods used to determine acute, sub-chronic, and chronic exposure limits for each fumigant is needed to ensure valid comparisons of toxicity and exposure risk.

Section 2.16: Additional plant back restrictions

Methods such as cover cropping, biosolarization, solarization, anaerobic soil disinfestation, steam treatment, biologically derived pesticides, biocontrol agents, and fumigant and non-fumigant pesticide alternatives to 1,3-D and chloropicrin can modify the soil chemical environment through the addition of toxicants, modification of soil pH, or release of compounds from organic matter in the soil. While this is often deliberate and part of the disinfestation process, persistence of these conditions can negatively impact subsequent crops, which is termed **phytotoxicity**. Plant-back restrictions define the time required to remediate phytotoxicity and make the soil safe for crops. ***Table 2.8*** describes plant-back periods that have been successfully used with each technique. For context, fumigation with 1,3-D and mixtures containing this chemical also have restrictions on how quickly crops can be established after fumigation is complete. When totally impermeable films are used to cover the soil, the tarp cannot be removed for at least 10 days after the beginning of treatment (DPR, 2024b). However, this period is intended to allow degradation of the fumigant and reduce human exposure risk rather than protect crops from phytotoxicity.

Table 2.8. Plant-back periods used with fumigant alternatives.

Method	Plant-back period	References
Biosolarization/anaerobic soil disinfestation	0 to 3 weeks	Muramoto et al. (2016)
Cover cropping	0 to 2 weeks	Brennan and Smith (2018); Haring and Hanson (2022); Jani et al. (2016)
Solarization	0 days (immediate planting post-treatment)	Elmore et al. (1997)
Steam treatment	0 days (immediate planting post-treatment)	Holmes et al. (2020)
Non-fumigant pesticides (ethoprop, fenamiphos, fluazaindolizine, fluensulfone, oxamyl, terbufos)	0 days (can be applied while crops are present or applied at the time of planting)	AMVAC Chemical Corporation (2017b, 2021); Bayer CropScience (2003, 2016); DuPont (2008); Makhteshim Agan of North America (ADAMA) (2016)
Alternative fumigants (dazomet, dimethyl disulfide, metam sodium, methyl isothiocyanate, allyl isothiocyanate)	1 to 3.5 weeks (depending on fumigant, application rate, and temperature)	Carlock and Dotson (2010); NCBI (2024d); Triky-Dotan et al. (2007); U.S. EPA, 2024; Wang et al. (2021)
Biologically derived pesticides and biocontrol agents	0 days for most currently used active ingredients, but some may be immediately phytotoxic if applied above critical levels	Daraban et al. (2023); Werrie et al. (2020)

Biosolarization and anaerobic soil disinfestation can produce phytotoxic compounds in the soil, such as organic acids, through fermentation. The plant-back time allows these compounds to dissipate through volatilization, aerobic microbial degradation, or leaching. However, the persistence of phytotoxic compounds can be influenced by the initial amendment level and the amendment particle size (Shea et al., 2021b). Specifically, identifying the minimum amendment rate needed for pest inactivation and milling the amendment to less than 2 mm diameter can minimize the plant-back time (Shea et al., 2021b).

For cover cropping, the plant-back period can depend on whether the cover crop is grown concurrent with and adjacent to the cash crop or is established and terminated on the soil that is subsequently used for the cash crop. Additionally, the plant-back period may be influenced by the time required to release nutrients from the cover crop biomass rather than the need to remediate phytotoxicity (Wayman et al., 2015).

> 79. **FINDING:** There is evidence that biosolarization, anaerobic soil disinfestation, cover cropping, and alternative fumigants can require a plant-back time. Alternatives such as solarization, steam treatment, non-fumigant pesticides, and biologically derived pesticides and biocontrol agents do not require plant-back times.

Section 2.17: Negative and unintended consequences of fumigant alternatives

Some possible negative or unintended effects of fumigant alternatives have been explored in other sections. For instance, in the discussion of plant-back time, the potential for phytotoxicity was noted following soil treatment with biosolarization, anaerobic soil disinfestation, or cover crop incorporation. While part of the weed inactivation process of biosolarization and anaerobic soil disinfestation, persistent phytotoxicity after treatment can negatively impact subsequent crops. As discussed, tuning the amendment type, incorporation rate, and particle size can help to avoid excessive phytotoxicity after treatment (Shea et al., 2021b).

Other consequences may arise due to shifting from broad spectrum pest control methods to those with narrower effectiveness. For instance, fumigation with 1,3-D and chloropicrin is broadly biocidal, promoting inactivation of nematodes, microorganisms, and weed propagules. This also applies to the alternative fumigants discussed previously. Similarly, broad spectrum pest control can be achieved through solarization, steam treatment, biosolarization, and anaerobic soil disinfestation due to broad pest susceptibility to thermal and biotic stresses induced in the soil. Non-fumigant nematicides or fungicides, crop rotation, and resistant cultivars are more targeted strategies and may result in lesser inactivation of the entire soil pest profile. For example, unlike broad-spectrum approaches, these strategies would not be expected to impact weed propagules (seeds, roots, and other plant parts that can sprout) in the soil. This can have major cost implications for growers. For instance, in California strawberry production, hand weeding costs for organic fields that do not use fumigation total $5,372 per acre (Bolda et al., 2024a) whereas fields using conventional production with broad spectrum fumigation only cost $1,832 per acre (Bolda et al., 2024b).

80. **FINDING:** Broad spectrum fumigant alternatives can decrease the weed propagule load in the soil, resistant cultivars and crop rotations generally guard against pathogen and parasite infection, and nematicides and fungicides may not affect weed propagules.

81. **CONCLUSION:** There may be a need to supplement the more targeted fumigant alternative methods with additional weed control measures, such as with post-emergence herbicides or hand weeding.

Section 2.18: Potential benefits of wide-scale use of alternatives

Widespread use of fumigation alternatives presents the direct benefit of mitigating or eliminating the human exposure and toxicity risks of 1,3-D and chloropicrin. However, certain fumigation alternatives may deliver secondary benefits to environmental sustainability and the health of soil or crops to further incentivize adoption. For instance, anaerobic soil disinfestation, biosolarization, biofumigation, and cover cropping involve incorporation of organic matter into the soil. Cover crop research has shown multiple benefits associated with such organic matter enrichment in the soil (Sharma et al., 2018). Cover crops are associated with reduced soil erosion (Chen et al., 2022), and the effect is greatest for those with dense, fibrous root systems (De Baets et al., 2011). Cover crop roots can also penetrate and loosen compacted soil (Chen and Weil, 2010). Fixation of nitrogen and uptake of mineral nitrogen, including nitrate, keeps these nutrients in the root zone for future crops and decreases the human health and environmental risks associated with nitrate leaching into groundwater (Thapa et al., 2018).In light of this, cover cropping is seen as a key enabling strategy for California's Sustainable Groundwater Management Act (Borum et al., 2024). Cover cropping can increase soil porosity, and residual organic matter from roots and incorporated vegetation have high water holding capacity, which can increase soil field capacity and plant availability water capacity (Basche et al., 2016; Gabriel et al., 2019), although these effects can be variable (Irmak et al., 2018). Beyond providing nutrients to crops, this organic matter can also support the growth of microorganisms and earthworms to maintain soil biodiversity, with effects on individual organisms depending on the cover crop used (Euteneuer et al., 2020; Nair and Ngouajio, 2012; Roarty et al., 2017; Vukicevich et al., 2016). Presumably, many of these soil chemical, physical, and biological benefits extend to biosolarization and anaerobic soil disinfestation given typical levels of labile organic matter added to the soil (often nine tons per acre or more).

An anaerobic soil disinfestation study using *Brassica* seed meal amendment observed that restructuring of the soil microbiota could lead to a suppressive soil that resisted reinfestation by the fungal pathogen *Macrophomina phaseolina* and root lesion nematodes (*Pratylenchus* spp.), and this corresponded to enrichment of known nematode-parasitizing and other pest-inhibiting microorganisms (Mazzola et al., 2016). Another anaerobic soil disinfestation study using rice bran amendment observed that beneficial bacteria from the Firmicutes and Proteobacteria phyla were enriched by the treatment (Pan et al., 2024). Bacteria from these phyla were also enriched following biosolarization using almond hull and shell amendments (Shea et al., 2022). Soil field capacity and plant available water increased after biosolarization with food digestate amendments (Fernández-Bayo et al., 2017). Soils treated with anaerobic soil disinfestation using composted poultry litter amendments exhibited increased levels of the major plant nutrients potassium and phosphorus (Di Gioia et al., 2017).

> 82. **FINDING:** Certain fumigant alternatives deliver secondary benefits to environmental sustainability and the health of soil or crops, which may include greenhouse gas reductions under specific conditions.

> 83. **CONCLUSION:** Additional research is needed to quantify the full range of soil physical, chemical, and biological effects for the many possible soil amendments and field conditions that are relevant to anaerobic soil disinfestation and biosolarization. Conducting life cycle assessments to compare fumigant alternative use scenarios that increase or decrease greenhouse gas emissions (relative to fumigation) could help incentivize their adoption.

Certain fumigation alternatives may deliver sustainability benefits in terms of greenhouse gas reductions. When cover crop biomass is incorporated into soil, the organic carbon content of the soil is increased, and a fraction of that carbon remains stable and sequestered in the soil (Poeplau and Don, 2015). Additionally, the nutrients from the cover crop can offset a fraction of crop fertilizer demand. Cover crop vegetation generally has a greater albedo than bare soil, meaning that more solar radiation is reflected rather than absorbed by the soil during cover cropping. A review of these effects on climate change determined that carbon sequestration and increased albedo could potentially decrease warming potential in cover cropped areas by the equivalent of 100–150 and 12–46 g CO_2 e/m^2/year, respectively, over a 100-year time horizon (Kaye and Quemada, 2017). Additionally, a life cycle assessment of solarization and biosolarization using tomato pomace amendments in the San Joaquin Valley indicated that global warming potential could be reduced by 20 to 35% relative to fumigation with 1,3-D and chloropicrin by avoiding the emissions associated with producing and transporting the fumigants to California (Oldfield et al., 2017). This conclusion is specific to the conditions and assumptions used in the analysis; different biosolarization or fumigation conditions (e.g., amendment or fumigant type and application rate, sourcing and transportation distance, deployment region, allocation of environmental impacts to byproducts used as soil amendments versus the primary processes that produce the byproducts) could affect the estimated relative global warming potential with respect to fumigation.

It is challenging to make sustainability claims about transitioning fumigant-reliant crops from the field to a soilless greenhouse or tunnel setting, and more research in this area is warranted. A review of soilless cultivation system life cycle assessments found that hydroponic growth in perlite is the most studied method (Licastro et al., 2024), but other media such as sand, biochar, and woody biomass may provide a lower carbon footprint (Fussy and Papenbrock, 2022). Life cycle assessments to compare soilless systems against other methods have typically focused on greenhouse or tunnel production. While comparing strawberry cultivation in mulched tunnels using soil or a mixture of coconut fiber and peat, only a small difference in global warming potential was predicted (Ilari et al., 2021). An assessment of tomato production in an agriponic system highlighted the potential to reduce several impact indicators, such as greenhouse gas emissions, by recirculating the nutrient solution, which in turn decreases in fertilizer demand (Pedalà et al., 2023). A life cycle assessment of tomato production in seven soilless substrates found that global warming potential for all substrates fell within the range determined for conventional field production (Litskas et al., 2021). However, in addition to screening multiple substrates, there is a need for studies that examine the possibility of repeatedly pasteurizing (e.g., via steam treatment) soilless substrates to permit recycling in multiple crop cycles. Such recycling strategies may be useful for substrates that would otherwise require importation (e.g., coconut coir). In addition, there is an overall lack of studies that directly compare conventional field production of a given crop to production in a soilless system.

Life cycle assessments are highly contextual, and the assumptions and conclusions associated with one study may not translate to other locations, cropping systems, or soil treatment conditions. Moreover, sustainability is multifaceted, as represented in the broad array of impact indicators that may be used in a life cycle assessment. While global warming potential is commonly used as a mid-point indicator of sustainability, other indicators such as ecotoxicity, eutrophication (nutrient overenrichment in bodies of water), and water use, among others, are potentially relevant to the comparison of fumigation alternatives against fumigation with 1,3-D and/or chloropicrin.

> 84. **FINDING:** Life cycle assessments for fumigant alternatives are sparse in the peer-reviewed literature.

> 85. **FINDING:** There is a need for additional research to quantify sustainability claims across the full spectrum of fumigant alternatives.

Fumigant alternatives that capitalize on **agroecology** to achieve soil disinfestation, such as crop rotations, cover cropping, anaerobic soil disinfestation, biosolarization, and biocontrol agents, can be more labor intensive compared to existing agricultural practices, which have shifted over time to be more input- than labor-intensive (Smith et al., 2015; Shi et al., 2019; Rachel et al., 2022). To the extent that this could translate to increased supply of well-paid agriculture worker positions, local economies could benefit through a multiplier effect, wherein more local spending by workers and their households leads to a cascading effect of local re-spending that promotes greater local wealth (Hughes, 2018).

Section 2.19: Support and subsidies in other countries

There is limited published literature describing support and incentive programs for the development and adoption of fumigation alternatives abroad. Grant programs to enable applied science appear to be the most common mechanism for promoting fumigation alternatives internationally. These grant programs include joint funds between the U.S. and other countries to advance agricultural technologies of common interest. For instance, the United States-Israel Binational Agricultural Research and Development Fund (BARD, 2024) fosters collaborations between researchers in each country and has supported research involving biopesticides, solarization, and biosolarization. The United States-Egypt Science, Technology & Innovation Funding Authority (US-Egypt STDF, 2024) has funded work to advance nematode control using biocontrol agents, biosolarization, and resistant crops. The Egyptian Ministry for Scientific Research has also supported similar work through its internal Science, Technology & Innovation Funding Authority as well as joint funds with other countries beyond the United States.

In the European Union, the European Commission's “A Soil Deal for Europe” mission was launched in 2021 to address multiple aspects of soil health improvement and protection. Among the nine topics described in the mission, “harnessing the multifunctional potential of soil biodiversity for healthy cropping systems” (European Food Safety Authority, 2024) encompasses informed manipulation of microbial ecology in soils, promoting beneficial plant-soil interactions to decrease the need for external inputs, and increasing viable integrated pest management strategies with the aim to advance the EU Farm to Fork objective of reducing pesticide use by 50% (compared to 2015–2017 levels) by 2030. Although the proposal solicitation for this program is still open and no awards have been granted (in fact, a recent proposal was withdrawn due to lack of consensus by the European Parliament (European Commission, 2024)), the Sustainable Use of Pesticides directive remains in place, and the stated aims suggest that fumigation alternatives such as pest-resistant cultivars and rootstocks, cover cropping, biocontrol agents, biofumigation, biosolarization, and anaerobic soil disinfestation would align with this initiative since they leverage soil ecology to create pest-inactivating conditions.

Section 2.20: Fumigant alternatives with the best trade-offs

A nuanced perspective is needed when comparing the effectiveness and potential risks of fumigant alternatives. This is due to the known variability and differing requisite conditions for various fumigant alternatives and the fact that knowledge gaps exist in the published effectiveness and risk assessment data. Pest inactivation effectiveness can be highly dependent on the specific pest targets (e.g., species of phytoparasitic nematode, species of fungal or bacterial pathogens), as seen in the studies summarized in ***Appendix B***. Additionally, pest control effectiveness can depend on environmental and logistical variables. For instance, solarization may be an ideal solution in areas with persistent high summer temperatures, such as the Central Valley, but may be less effective in regions with more moderate temperatures, such as the coastal and Sierra Nevada foothill areas of the state (Stapleton et al., 2008). Logistically, steam treatment may be an effective and reasonable technique when small areas require treatment, but it may prove challenging for large fields. There are also crop-specific factors that affect the availability and effectiveness of certain fumigant alternatives. For instance, resistant varieties or rootstocks may not exist for all fumigant-reliant crops or may only resist a subset of the pests controlled through fumigation. Similarly, crop rotations and cover cropping are most effective against soil pests with narrow host ranges. However, there may not be suitable rotations or cover crops that are both well-suited to the soil and weather of a particular site and sufficiently different from one another to disrupt pest host cycles.

It is also challenging to make broad claims regarding the relative health and environmental risks between fumigant alternatives. Techniques such as solarization, soilless cultivation, resistant crops, steam treatment, and crop rotation do not involve the addition of known toxicants to the soil and, by extension, avoid the exposure risks of such additives. Conversely, use of alternative fumigants or non-fumigant pesticides requires application of known toxicants (as discussed in ***Section 2.15***). Even so, application rate and method, along with emission controls, may affect the risk of acute human exposure, although the impact that these methodological variables might have on chronic exposure is extremely difficult to ascertain.

> 86. **FINDING:** Pest inactivation efficacy can be highly dependent on the specific pest targets (e.g., species of phytoparasitic nematode, species of fungal or bacterial pathogens). Additionally, pest control efficacy can depend on environmental and logistical variables.

> 87. **CONCLUSION:** Based on the current state of knowledge, each cropping system and region in California may have one or more fumigant alternatives that provide partial or complete control of major pests for a span of months to years with less apparent risk to humans or the environment compared to 1,3-D or chloropicrin.

> 88. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting basic science research to further explore the pest inactivation mechanisms of fumigant alternatives, as well as field demonstration studies that directly compare feasibility, cost, and pest inactivation effectiveness between multiple fumigant alternatives and fumigation in a given cropping system and environmental context. Such work may involve experimentation or meta-analysis of existing published data. Additionally, DPR and/or other relevant California state agencies should consider supporting appropriate risk assessments for each fumigant alternative.

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Chapter 3: Research on Fumigant Alternatives

Section 3.1: Chapter overview

Since the late 1980s, fumigant alternative research has been driven by expanded regulation on conventional fumigants and their subsequent reduced availability, aimed at reducing environmental and human health effects (UC Division of Agriculture and Natural Resources (UC ANR), 2019). The implementation of the USDA National Organic Standards in 1990, reflecting rising public interest in organic agriculture, also motivated research into alternative methods for soil pest control because organic production prohibits the use of conventional fumigants.

Across the range of fumigant alternatives, some have been studied for nearly a century while others are relatively new. Generally, early research into any fumigant alternative begins with validating pest control effectiveness and assessing crop effects. This research often begins in smaller laboratory or greenhouse environments before progressing to full field trials. Research remains ongoing across all fumigant alternatives due to their variable effectiveness compared to conventional fumigants (see ***Appendix B*** for examples of the variability in both observed pest control effectiveness and how effectiveness is gauged and compared to conventional fumigants).

Section 3.2 provides a brief overview of the past 20 years of research in each fumigant alternative category, focusing on efforts to validate and enhance pest control effectiveness and crop benefits, either as stand-alone methods or in combination. Although not an exhaustive review, the cited studies illustrate key research themes for each fumigant alternative during this period. ***Section 3.3*** highlights which fumigant alternatives have been investigated in California within the last 15 years; and ***Section 3.4*** addresses the scale of research for these alternatives. ***Section 3.5*** examines the environmental conditions where research was conducted and its applicability to agricultural conditions in California. ***Section 3.6*** evaluates the suitability of research for identifying a fumigant alternative to implement in California. Finally, ***Section 3.7*** discusses promising fumigant alternatives currently undergoing research.

Chapter 3 contains 6 Findings, 3 Conclusions, and 1 Recommendation.*

***Finding**. Fact(s) the study team finds that can be documented or referenced and that have importance to the study. **Conclusion**. A reasoned statement the study team makes based on findings. **Recommendation**. A statement that suggests an action or consideration as a result of the report findings and conclusions.

Section 3.2: Research into fumigant alternatives

Non-biological chemical methods: Alternative fumigants

Research with alternative fumigants such as metam sodium, metam potassium, methyl isothiocyanate, dimethyl disulfide, and dazomet has demonstrated their effectiveness in various cropping systems for **nematode**, fungal, insects, and weed targets (Devkota et al., 2013; Gilardi et al., 2017; Mao et al., 2014; Santos, 2009; Tsror et al., 2005; J. Yu et al., 2019).* Additionally, to minimize cost and maximize safety, research has sought to reduce the application rates needed for effective pest control by investigating improved application methods and strategies to limit fumigant escape from the soil (Taylor et al., 2005). Since fumigants can be broadly **biocidal**, research has also explored the broader impact of alternative fumigants on the soil microbiome, with a focus on impacts to microbial functions that can affect crop nutrient availability (Li et al., 2017; Toyota et al., 1999).

Regarding novel fumigants , ethanedinitrile (EDN) was first identified as a potential soil fumigant in the early 2000s (Mattner et al., 2003; Mattner et al., 2004; Waterford et al., 2004). However, research to characterize and maximize its efficacy for broad spectrum pest and pathogen control in agricultural soils has occurred primarily in the last five years. For instance, a microcosm study in Australia demonstrated broad spectrum inactivation in acidic sand and alkaline sandy loam (Thalavaiasundaram et al., 2023). When applied at 14 to 78 mg per kg sand (acidic sand) and 58 to 180 mg per kg soil (alkaline sandy loam) in microcosms, at least 90% inactivation of several pathogens (*Fusarium oxysporum*, *Macrophomina phaseolina*, *Verticillium dahlia*, and *Pythium ultimum*) and nematodes (*Tylenchulus semipenetrans* and *Globodera rostochiensis*) was achieved within 24 hours (Thalavaiasundaram et al., 2023). Similar concentrations were required for at least 90% inactivation of seeds or tubers from sever common weeds (*Cyperus rotundus*, *Portulaca oleracea*, and *Stellaria media*): 56 and 318 mg per kg sand (acidic sand) and 81 and 103 mg per kg soil (alkaline sandy loam) (Thalavaiasundaram et al., 2023). In contrast, the weeds *Malva parviflora* and *Cyperus esculentus* were resistant to EDN, and 90% inactivation was not achieved even when EDN concentrations exceeded 1,000 mg per kg soil (Thalavaiasundaram et al., 2023). Florida field trials showed that both purple and yellow nutsedge (*Cyperus rotundus* and *Cyperus esculentus*) densities were reduced by 75 to 100% following fumigation with EDN (336 to 672 kg per hectare) via shank or vapor application through buried drip lines, which was comparable to fumigation with 1,3-D or chloropicrin (Stevens et al., 2019). These trials also indicated that EDN applied via shank at rates spanning 336 to 672 kg per hectare did not reduce tomato root galling due to root knot nematodes (*Meloidogyne* spp.) compared to untreated controls (a similar result was obtained with fumigation with 1,3-D and chloropicrin) (Stevens et al., 2019). Notably, when EDN

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*Bolded terms can be found in the glossary.

was applied as a vapor through buried drip lines, it led to significant elevations in tomato root galling 90 days post-treatment compared to untreated or fumigated controls (Stevens et al., 2019). Another series of Florida trials found that EDN applied at 448 to 560 kg per hectare most consistently delivered similar levels of purple nutsedge (*Cyperus rotundus*), broadleaf weed, and grass weed control to fumigation with 1,3-D and chloropicrin (Yu et al., 2020). Application of 560 kg EDN per hectare also consistently matched or outperformed 1,3-D and chloropicrin for reduction of the fungal pathogen *Macrophomina phaseolina* in strawberry production (Yu et al., 2020). A field trial in the Czech Republic observed that EDN applied at rates of 30 to 50 g per m^2 to soils infested with the nematode *Meloidogyne hapla* resulted in significantly reduced carrot root galling compared to untreated control soils (89 to >98% reduction) (Douda et al., 2021).

Yield effects in recent studies have shown varying results based on crop system. Carrot yields of 17.35 to 50.78 g per plant (fresh weight) were achieved in soils treated with 50 to 50 g EDN per m^2, an increase of 35 to 191% increase over untreated controls (Douda et al., 2021). Application of EDN at rates ranging 224 to 560 kg EDN per hectare showed no significant difference in strawberry yield compared to untreated controls (which was also true for fumigation with 1,3-D and chloropicrin), suggesting that the study potentially had low pest pressure but confirming that there were no phytotoxic effects for EDN 8 weeks after fumigation (when strawberries were transplanted to the plots) (Yu et al., 2020). However, other studies have noted that higher application rates of EDN (>560 kg per hectare via shank injection or vapor application through buried drip tape) have reduced tomato crop vigor, but the effect is transient and disappears within six weeks of fumigation (Stevens et al., 2019). The mechanism for short-term crop inhibition following doses of EDN is not thought to be due to lingering EDN in soil since it dissipates quickly after application (Stevens et al., 2019). The same study observed that EDN fumigation via shank application at rates of 336 to 448 kg per hectare improved yield of extra-large tomatoes compared to non-treatment (matching the performance of 1,3-D and chloropicrin), but this effect could not be replicated in a second trial at another site (Stevens et al., 2019).

As a nitrogenous compound, EDN degrades in the soil to produce ammonium (NH_4^+), a plant fertilizer. Additionally, EDN inhibited nitrification for at least 7 weeks after fumigation (Stevens et al., 2020). The accumulation of ammonium and inhibition of nitrate production could offset a fraction of fertilizer demand and retain plant-available nitrogen in the root zone, since ammonium does not leach as readily as nitrate (Stevens et al., 2020). While this could be a beneficial agricultural effect, the overall human and environmental toxicity of EDN in the context of California (or United States) agriculture has not been evaluated. For instance, the risk of EDN runoff to non-target environments has not been studied despite the chemical being designated as highly toxic to aquatic organisms by the

World Health Organization (World Health Organization, 2001). Risk assessments conducted in Australia and New Zealand for EDN use in tarped log pile fumigation deemed the risk to aquatic life to be negligible due to lack of contact in this highly localized application, and occupational exposures were deemed acceptable with the use of access restrictions, buffer zones, tarps, and personal protective equipment (New Zealand Environmental Protection Authority, 2018). However, while this use case may have some overlap with containerized fumigation of soil for greenhouses or nurseries, it is quite different from pre-plant use in fields. Although the U.S. Occupational Safety and Health Administration recognizes EDN as a "highly hazardous chemical, toxic, or reactive" (U.S. Occupational Safety and Health Administration, 2024), and the National Institutes of Health PubChem database defines Acute Exposure Guideline Levels for transient, irreversible, or life-threatening health effects (National Center for Biotechnology Information, 2024), comprehensive exposure and risk assessments for agricultural EDN use do not exist for any locations in the United States.

> 89. **FINDING:** Ethanedinitrile (EDN) has primarily been studied as a soil fumigant in the last 5 years. Published studies describe work conducted outside of California, although crops such as carrots, tomatoes, and strawberries overlap with those that currently use 1,3-D and chloropicrin fumigation in California.

> 90. **CONCLUSION:** Based on current data, ethanedinitrile (EDN) is inconsistent in its ability to control weeds, pathogens, and phytoparasitic nematodes while benefitting the health and productivity of crops. Additionally, there are poorly understood phenomena that affect transient inhibition and plantback times following EDN fumigation with higher application rates. There are no environmental or human health risk assessments for the use of EDN in California agriculture.

> 91. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to determine the efficacy and safety of ethanedinitrile (EDN) use in the context of California agriculture. This could include field trials to study use in crops and regions that currently employ 1,3-D and chloropicrin fumigation in California. Additionally, the work should include measurement of EDN escape and risk of exposure and disease for agricultural workers, adjacent communities, and non-target organisms.

Non-biological chemical methods: Non-fumigant pesticides

Major commercial non-fumigant pesticides were developed decades ago. Research in the last 20 years has focused on expanding knowledge of the crop systems, pest targets, and application strategies to optimize pest control and yield benefits. For example, research has examined non-fumigant nematicide delivery via drip irrigation in a rotation crop system (Morris et al., 2015); soil drenching, dips, and foliar spraying (Oka, 2010; Blauer and Holmes, 2020; Blauer and Holmes, 2024); furrow **chemigation** (Charlton et al., 2010); granular delivery (Radwan et al., 2012); and shank injection (Ingham et al., 2007)

These studies have also assessed different schedules and concentrations for pesticide application to maximize pest suppression (Desaeger et al., 2011; Zasada and Walters, 2017). Beyond pest inactivation, research has explored the biodegradation of these pesticides in soil to better understand and control their persistence and transport in the environment (Gallego et al., 2019; Haydock et al., 2012; Osborn et al., 2010; Osman et al., 2009).

Non-chemical and biological chemical methods: Anaerobic soil disinfestation and biosolarization

In the late 1990s and early 2000s, researchers increasingly experimented with combining organic matter soil amendments with practices like tarping and **solarization** (Blok et al., 2000). Soil amendments used in research through the early 2010s were primarily *Brassica* biomass, ethanol, rice bran, and wheat bran (Molendijk et al., 2009; Shennan et al., 2009; Strauss and Kluepfel, 2015). Later studies increasingly explored alternative amendments sourced from food processing byproduct streams (Achmon et al., 2016; Fernandez-Bayo et al., 2020; Serrano-Pérez et al., 2017) or composts and digestates (nutrient-rich byproducts) derived from food system residues (Fernández-Bayo et al., 2017, 2018; Hestmark et al., 2019). Research to validate the effectiveness of **biosolarization** and **anaerobic soil disinfestation** (ASD) in a variety of crop systems against plant parasitic nematodes, pathogens, and weed propagules has largely occurred in the past decade (Achmon et al., 2018; Butler et al., 2012; Domínguez et al., 2014; Guerrero et al., 2019; S. Koike et al., 2014; Paudel et al., 2020; Ros et al., 2008; Serrano-Pérez et al., 2017; E. A. Shea et al., 2022; Shennan et al., 2018). Studies have also identified the risk of lingering **phytotoxicity** following biosolarization or anaerobic soil disinfestation. Research has sought to understand the factors that contribute to this issue and develop strategies to remediate soils after treatment (Hewavitharana et al., 2014; E. Shea et al., 2021; van Agtmaal et al., 2015).

Non-chemical and biological chemical methods: Solarization

Invented in the 1970s, and building upon centuries-old practices of using sun and heat exposure to treat agricultural soils, solarization gained traction through foundational research in the 1980s and 1990s (Gamliel and Katan, 2005). These early studies established the general methodology and evaluated effectiveness in different seasonal, regional, and soil infestation conditions. Over the past 20 years, research has continued to explore the compatibility of solarization with various crops and its effectiveness against specific soil pests in both open field and greenhouse systems (e.g., Candido et al., 2008; Hasing et al., 2004; Mauromicale et al., 2010; Talavera-Rubia et al., 2022; Travlos et al., 2009).

Research has also focused on assessing different tarps for their ability to enhance solar heating of the soil, including conventional plastics, novel wavelength-selective films, and bioplastics (Candido et al., 2011; Di Mola et al., 2021; Gill et al., 2009; Mormile et al., 2012; Russo et al., 2004). Additional research has investigated how environmental factors such as soil moisture (Marshall et al., 2013; Shlevin et al., 2004) and soil depth (El-Keblawy and Al-Hamadi, 2009; Marshall et al., 2013; Scopa et al., 2008; Tamietti and Valentino, 2006) impact soil heating or pest inactivation. To optimize treatment, research has modeled the relationship between temperature and exposure time for specific pest targets, providing guidance on solarization treatment durations (Dahlquist et al., 2007; K.-H. Wang and McSorley, 2008).

Similarly, studies have explored strategies to adapt solarization to areas or seasons with cooler weather by adjusting treatment timing and soil moisture levels (Johnson III et al., 2007; Lambrecht and D'Amore, 2010). In the early and mid-2000s, research began augmenting solarization with organic matter amendments to improve pest control consistency by combining solar heating with additional pesticidal stresses. This led to the development of biosolarization, which is covered in the preceding subsection.

Non-chemical and biological methods: Biologically derived pesticides and biocontrol agents

Research has screened numerous plants for biochemicals with pesticidal activity. This process typically involves creating extracts from plant materials (including essential oils) and testing their ability to inactivate pests in a laboratory setting. This approach has yielded dozens of potential biologically derived pesticides (Faria et al., 2021; Seepe et al., 2021) and, for some, research has determined how quickly they act on target pests and the amount needed to be effective (Ullah et al., 2015). Research has also examined several **biopesticides** in the environment, determining that biopesticides are generally less broadly biocidal (less harmful to a wide range of species) and break down more quickly (their persistence) compared to conventional pesticides (Kokalis-Burelle and Rodríguez-Kabana, 2006).

Much of the research on biocontrol agents for soil pests has focused on species from groups including *Streptomyces* (Bubici, 2018), *Beauveria* (Karabörklü et al., 2022; Prabhukarthikeyan et al., 2014), *Trichoderma* (Matarese et al., 2012; Sahebani and Hadavi, 2008), *Paecilomyces* (Kiewnick and Sikora, 2006), and *Bacillus* (Sebayang et al., 2021; Z. Yu et al., 2015). Rigorous testing over the last 20 years has evaluated the effectiveness of several of these biocontrol agents against key soil pests in various cropping systems (Bubici, 2018; Bubici et al., 2019; Roopa and Gadag, 2020).

Non-chemical and biological methods: Cover cropping

Cover crop research as a named field started in the 1990s. Research over the last 20 years has defined the effects of several cover crop types, such as *Brassica*, rye, wheat, radish, oats, canola, and hairy vetch, and their effects on soil populations of fungal pathogens, plant parasitic nematodes, and overall nematode communities in several cropping systems (e.g., carrot, corn, tomato) (Bakker et al., 2016; DuPont et al., 2009; Grabau et al., 2017; Gruver et al., 2010; Hooks et al., 2010; Roberts et al., 2005; Steele, 2023; K.-H. Wang et al., 2006). These studies have shown that both suppression and growth of nematodes and pathogens can be promoted by cover crops (or there may be no detectable effect on soil pests) and that these phenomena may take years to fully develop. Research has found that the time needed between terminating a cover crop and planting a cash crop, called the plant-back time, can affect plant health (phytotoxicity) and disease risk differently depending on the cover crop, pest target, cash crop, and year-to-year conditions (Acharya et al., 2017; Adler and Chase, 2007). However, some studies also found that temporary harmful effects (temporary phytotoxicity) following cover cropping can help control weeds (Kunz et al., 2016). Similarly, researchers have explored how the biocidal properties of specific cover crop-derived chemicals can help manage or eliminate soil pests. Certain crops, such as those in the *Brassica* genus, contain glucosinolate compounds that biodegrade (break down) in soil to form isothiocyanates—the same active ingredients found in some fumigants—creating to a biofumigation effect. Research has identified the glucosinolate content and nematode resistance of various cover crops, studied the conditions that promote conversion of glucosinolates into isothiocyanates (e.g., incorporation methods, moisture, temperature), and measured their impacts on nematode control and crop yields (Dutta et al., 2019; Hanschen and Winkelmann, 2020; Kruger et al., 2013).

Non-chemical and biological methods: Crop rotations

Crop rotation research for soil pest management has focused on testing variables such as the number and types of crops put into rotation, the sequence and length of rotations, and the resulting effects on soil pest levels and crop health. Studies on plant parasitic nematodes in various cash crops typically test three to five rotation treatments over multiple years, incorporating two to 10 resistant and susceptible crops. The studies have identified rotations of fallowing, root crops, grains, ornamental flowers, legumes, and other resistant or susceptible cash crops (e.g., strawberries, tomatoes, peppers) that effectively reduce soil parasitic nematode levels and improve yields (Chen and Tsay, 2006; Govaerts et al., 2007; Kimpinski and Sanderson, 2004; Talavera et al., 2009). Research has focused on rotation for controlling plant parasitic nematodes due to their vulnerability to life cycle disruption by non-host crops. However, studies that investigated rotation effects on fungal pathogens found mixed results, with some reporting no reduction in soil pathogen levels (Marburger et al., 2015), an increase in disease risk after crop rotation (Tillmann et al., 2017), propagation of pathogens on crop roots (Scott et al., 2014), or partial disease reduction (Fang et al., 2012). Recently, the scale of research to monitor the regional use of rotations and their effect on crop health and yield has expanded though the use of satellite imagery paired with direct field measurements. For example, this approach was used to monitor rotation trends in strawberry-producing regions of California over a five-year period, identifying relationships between distance from the coastline, soil pathogen profiles, and rotation duration (Ramos et al., 2024).

Non-chemical and biological methods: Resistant varieties and rootstocks

Research to develop resistant varieties typically involves screening existing varieties, their parents, or wild relatives for traits that resist one or more soilborne pests, followed by breeding to enhance resistance (Buerstmayr et al., 2020; Mesterházy et al., 2012; Paynter et al., 2014; Shaw et al., 2010; Smith et al., 2017). Similar screening and breeding methods are used to identify and develop resistant rootstocks (Gainza et al., 2015; Leslie and McGranahan, 2013; Ollat et al., 2014). In some cases, researchers evaluate a resistant rootstock that works well for one crop by testing its compatibility for grafting onto a different crop, along with the pest resistance, growth, and yield performance in the new grafted plants (Guan et al., 2014). Beyond breeding new resistant varieties and rootstocks, studies have also explored wild plant species related to cash crops to find nematode and fungal pathogen resistant rootstocks suitable for grafting (Huang et al., 1986; Liu et al., 2015).

In some cases, research on resistant varieties and rootstocks has leveraged known resistance genes. For example, the *Mi* gene in tomato, discovered in 1998, confers resistance to root-knot nematodes (*Meloidogyne* spp.) (Jesse et al., 1998). Subsequent research has evaluated the nematode resistance of tomato varieties or rootstocks containing this gene (Jacquet et al., 2005; López-Pérez et al., 2006). Similar resistance genes have been found in other crops, including peppers, strawberries, and peaches (Gillen and Bliss, 2005; Kiewnick et al., 2009; Pincot et al., 2018).

The discovery of resistance genes and genetic markers for soil pest resistance traits, along with use of these markers to guide breeding efforts, has advanced due to genome sequencing and bioinformatics to screen, which enables researchers to screen for DNA sequences associated with pest resistance (Barbary et al., 2015; Bertrand and Anthony, 2008; Caromel and Gebhardt, 2011; KS. Kim et al., 2016). For instance, breeding strawberries for resistance to *Phytophthora cactorum* has been challenging due to moderate heritability and complex genetic features spread across the strawberry genome. Genome sequencing of a strawberry population with high genetic diversity, combined with computational screening, has helped identify genetic markers predicting resistance to *P. cactorum* (Jiménez et al., 2023). A similar approach was used to identify markers for strawberry resistance to *Verticillium dahliae* (Feldmann et al., 2024).

High-throughput genotyping has uncovered several additional Fusarium resistance genes in strawberry beyond the traditional FW1 gene, including genes that confer resistance to the emerging *Fusarium oxysporum* race 2, which can overcome resistance associated with FW1 (Pincot et al., 2022). Resistance may be enhanced by combining multiple genetic traits, each providing partial resistance, as seen in strawberry resistance to *Macrophomina phaseolina* (Nelson et al., 2021). A genome-wide association study identified specific alleles (versions of genes) for genes that must be present to confer strawberry resistance to the fungal pathogen *Macrophomina phaseolina* (Knapp et al., 2024). Since no single allele provided significant resistance on its own, these resistance trait assemblages can only be identified through this type of "multilocus" analysis. Identifying resistance genes has also led to opportunities to genetically engineer pest-resistant crops (El-Sappah et al, 2019). However, challenges remain regarding consumer acceptance because genetically engineered foods can sometimes be viewed as unnatural (Siegrist and Hartmann, 2020).

Recently, research has focused on identifying and characterizing emerging pathogen strains that can overcome traditionally resistant crop varieties. For instance, strawberries with the FW1 resistance gene were previously resistant to all strains of *Fusarium oxysporum* f. sp. *fragariae* in California. However, a new strain of *Fusarium oxysporum* f. sp. *fragariae* known as race 2 was recently detected in California and is capable of infecting strawberry cultivars with the FW1 resistance gene (Dilla-Ermita et al., 2023). Similarly, studies have found multiple *Meloidogyne* nematode isolates from a field growing tomato varieties with the *Mi* resistance gene, which are capable of breaking through this resistance (Ploeg et al., 2023). Current research seeks to better understand the extent of these resistance-breaking traits, as the *Mi* resistance-breaking *Meloidogyne* isolates from tomato show varying impacts on other *Mi*-containing crops (Ploeg et al., 2023).

Non-chemical and biological methods: Steam treatment

The use of steam to disinfest soil (i.e., inactivate pests) has been known for over a century (Hansen et al., 2011). In the past 20 years, researchers have demonstrated the effectiveness of steam treatment in several cropping systems and effectiveness and against major microbial and nematode pests (Kokalis-Burelle et al., 2016; McSorley et al., 2006; Melander and Jørgensen, 2005; Rainbolt et al., 2013; Samtani et al., 2012). Studies have also focused on optimizing steam injection into soil to achieve the desired temperature, heating duration, and treatment depth (Miller et al., 2014; Minuto et al., 2004). More recently, research has prioritized testing new steam applicator designs that can maintain consistent pest control, reduce fuel use and increase efficiency. These advancements have shown great promise for controlling several pathogens and weeds (Fennimore et al., 2014; Gay et al., 2010a, 2010b; Miller et al., 2014; Samtani et al., 2012).

Non-chemical and biological methods: Microwave treatment

Research to investigate using microwave radiation to heat soil and inactivate soil pests began in the 1970s. By the mid-1990s, this approach was considered impractical due to incomplete pest control and its sensitivity to soil moisture and texture (Nelson, 1996). Microwave treatment to disinfest soils has since remained a relatively niche field of research compared to other fumigant alternatives. There have been a few studies using lab-scale or containerized systems to continue exploring the control of pathogens, plant parasitic nematodes, and weed propagules with microwave treatment. However, pest inactivation remains inconsistent and often incomplete, with limited effectiveness at soil depths below 10 cm (4 in) (Brodie et al., 2007; Cicatelli et al., 2015; Rahi and Rich, 2007; Riga et al., 2020). A recent field trial using a novel trailer-mounted microwave unit demonstrated strong control of multiple plant pathogens, but these effects were limited to the upper 5 cm (2 in) of soil and took 40 minutes to treat 4 m^2 of soil (approximately 43 ft^2) (Brodie et al., 2022).

Non-chemical and biological method: Ozone treatment

Ozone is a molecule composed of three oxygen atoms. This configuration is chemically unstable, making ozone highly reactive. When it interacts with living organisms, ozone can oxidize and disrupt many of the essential molecules for life, such as DNA, enzymes, and lipids. Ozone can be produced by passing oxygen gas between a pair of electrodes under high voltage in the presence of a dielectric material, which helps distribute electricity evenly. The electrical discharge through the gas converts oxygen to ozone. Ozone can be applied to soil as a gas or dissolved in water. Research in the past 20 years has examined ozone's ability to control soil pests and pathogens. Studies have shown that gaseous delivery of ozone can achieve partial (19 to >90% mortality) or complete inactivation of plant parasitic nematodes depending on the ozone concentration, exposure time, and temperature (Qiu et al., 2009; Mitsugi et al., 2017; Msayleb et al., 2017; Msayleb and Ibrahim, 2011).

For fungal pathogens, the effectiveness of gaseous ozone varies by species. In one study, inactivation levels for *Fusarium graminearum*, *Penicillium citrium*, *Fusarium verticilliodes*, *Aspergillus flavus*, and *Aspergillus parasiticus* were 97, 96, 77, 51, and 49%, respectively (Savi and Scussel, 2014). Ozonated water delivery has also been effective against nematodes, ranging from 77 to 91% mortality (Veronico et al., 2017; Zheng et al., 2020). It has shown similar success against plant pathogens, with 80 to 100% inactivation of the fungal pathogen *Fusarium oxysporum* (Kobayashi et al., 2011; Msayleb et al., 2022) and the bacterial pathogen *Pectobacterium carotovorum* (Kobayashi et al., 2011), with effectiveness linked to ozone temperature, concentration, and exposure time.

Compared to other disinfestation methods, ozone treatment is less studied, particularly in field trials. Most commercially available ozone generators are designed for research or water treatment, not large-scale field applications. As a result, most disinfestation studies have been conducted using small containers of soil (Qiu et al., 2009; Kobayashi et al., 2011; Msayleb and Ibrahim, 2011; Mitsugi et al., 2017; Msayleb et al., 2017), and the largest studies to examine soil ecology or pesticide remediation effects have been at the scale of greenhouses (Martínez et al., 2022; Díaz-López et al., 2022) or lysimeters (specialized plant containers that allow measurement of accumulation and loss of water and other soil inputs) (Schloter et al., 2005).

Non-chemical and biological methods: Soilless cultivation

Over the past 20 years, research into soilless cultivation systems—including both hydroponic and solid substrate systems in greenhouses, under macrotunnels, or in open fields—has focused on optimizing cultivation conditions (e.g., plant spacing, coverings, lighting, temperature, plant nutrition, and irrigation) to achieve yield and product quality comparable to or better than growth in soil (Balliu et al., 2021; Kittas et al., 2006; Maboko et al., 2008; Maboko and Du Plooy, 2009; Nadalini et al., 2017; Rouphael et al., 2004; Saha et al., 2016). Research has focused on selecting non-soil growing substrates that are compatible with crops (Alu'datt et al., 2019; Maršić and Jakše, 2010; Tzortzakis and Economakis, 2008) and developing water and nutrient management strategies. These studies aim to ensure effective water and nutrient delivery along with potential recycling of nutrient solutions, and include investigation of nutrient formulations and the frequency and placement of water delivery systems (Ahmed et al., 2014; Dufour and Guérin, 2005; Giuffrida et al., 2014; Luna et al., 2013; Meric et al., 2011; Preciado-Rangel et al., 2020; Putra and Yuliando, 2015; Santamaria et al., 2003; Sezen et al., 2010). Pathogen management has also been an important area of research, as soilless production systems can become contaminated through infected planting stock, equipment, or irrigation water, as well as from airborne pathogens (Vallance et al., 2011).

Non-chemical and biological methods: Combination approaches

Recognizing that individual fumigant alternatives may have variable or partial effectiveness on their own (either by targeting a limited range of pests or providing incomplete inactivation), research has increasingly supported combination approaches that use multiple fumigant alternatives. These strategies aim to address the limitations of individual methods by:

1. **Using complementary methods in parallel** to broaden the range of pest control, such as applying a non-fumigant fungicide at the same time as a nematicidal biologically derived pesticide;
2. **Creating synergistic effects** to improve the magnitude or kinetics of pest control, such as combining solarization with subsurface steam treatment to maximize soil heating and pest inactivation; or
3. **Applying methods sequentially** to extend the duration of pest control or provide broad spectrum control over time such as using pre-plant anaerobic soil disinfestation with disease resistant crops and crop rotation.

Table 3.1 provides examples of research evaluating the performance of combined fumigant alternative strategies.

Table 3.1. Examples of research that has examined combined fumigant alternative approaches.

Strategy	**Outcome**	**Reference**
Alternative fumigant plus biocontrol agent	Enhanced bell pepper yield and *Verticillium* wilt control compared to either method alone.	Ślusarski and Pietr (2009)
Alternative fumigant plus non-fumigant pesticide	More consistent *Meloidogyne* spp. control compared to fumigant alone.	Desaeger et al. (2004), Ingham et al. (2007)
Solarization with biocontrol agent	Enhanced *Meloidogyne* spp. control compared to either method alone.	Giannakou et al. (2007)
Solarization with biologically derived pesticide	Enhanced *Meloidogyne* spp. root disease control in tomatoes compared to either method alone.	Hajji-Hedfi et al. (2018)
Subsurface steam treatment with solarization	Steam can compensate for suboptimal heating during solarization to achieve complete *Meloidogyne* spp. inactivation.	Samtani et al. (2012), Kokalis-Burelle et al. (2016)
Anaerobic soil disinfestation plus rotation with cover crops	Enhanced strawberry yield and *Fusarium* control compared to crop rotation alone.	Shrestha et al. (2024)
Anaerobic soil disinfestation with cover crop soil amendment	Certain cover crops were compatible soil amendments for anaerobic soil disinfestation and promoted high-level *Meloidogyne* spp. reduction.	Kokalis-Burelle et al. (2013)

Diversified farming systems—which focus on the preserving and utilizing **functional biodiversity** to benefit crop and ecological health—offer a combination approach to managing soil pests (Kremen et al., 2012). These systems often incorporate fumigant alternatives such as crop rotations and cover crops, but diversified cropping systems may also employ these methods in unique ways, such as intercropping multiple crops, varieties, and cover crops in the same field at the same time (Vialatte et al., 2021). Additionally, cover or catch crops may be planted at field edges, or the surrounding natural environment may be integrated into the mosaic of cropped areas (Vialatte et al., 2021). However, for diversified systems to succeed, sufficient ecological knowledge and careful coordination of natural and cultivated environments is essential. This ensures the enrichment and persistence of beneficial, pest-suppressing organisms while minimizing the risk of inadvertently creating niches for pests and pathogens (Vialatte et al., 2021). A review of studies using various intercropping strategies found that soilborne diseases decreased in 74.5% of cases compared to monoculture systems. The key factors included spacing, the combinations of crop and non-crop plants, and how the plants were managed both during simultaneous planting and when rotated over time. However, disease control was often incomplete and there was no clear benefit to yields (Hiddink et al., 2010). Nevertheless, complete disease control was achieved in some cases (Zewde et al., 2007). Achieving consistent results for most crop and pest combinations in California remains a challenge, underscoring the need for further research to define the variables that influence the success of mixed cropping strategies and allow for reliable control of the pathogens and nematodes commonly targeted by 1,3-D and chloropicrin.

For individual or combined fumigant alternatives that do not offer broad spectrum soil pest and pathogen control and may require post-emergence weed removal to compensate, emerging weeding options should be considered. For instance, there are a growing number of automatic robotic weeding devices that use mechanical disruption, precision herbicide spraying, or laser treatment to destroy weeds. Several economic analyses have indicated that the savings from displacement of manual weeding can offset the capital recovery costs for a robotic weeder or the costs to use a robotic weeding contract service (Lowenberg-DeBoer et al., 2020). However, most of these studies were conducted outside of California or in cropping systems that do not use 1,3-D and chloropicrin fumigation. Accordingly, additional research would be useful to quantify the economic implications of using robotic weeders as part of a combination fumigant alternative approach in the context of California agriculture.

> 92. **FINDING:** Research has increasingly validated combination approaches that utilize multiple fumigant alternatives.

> 93. **CONCLUSION:** Additional targeted research would be useful to determine the most effective combination methods for major fumigant-reliant crops.

Section 3.3: Fumigant alternatives investigated in California

All fumigant alternatives listed in ***Table 2.1*** (***Section 2.1***) are actively being researched in California. ***Table 3.2*** highlights examples of studies conducted within the past 15 years in California. To our knowledge, no fumigant alternative has been researched in other countries or U.S. states without also being investigated in California.

While each fumigant alternative strategy is represented in California research, ***Appendix B*** provides additional examples of national and international studies that may focus on different crops, environmental conditions, or process variables.

> 94. **FINDING:** All major fumigant alternatives are being actively researched in California.

Table 3.2. Examples of research studies to develop alternatives to 1,3-D and chloropicrin conducted in California.

Technique	Crop	Location (region)	Reference
Alternative fumigants	No target crop	Oxnard, Salinas, and Watsonville (Central Coast and South Coast)	Triky-Dotan and Ajwa (2014)
Alternative fumigants	Cut flowers and strawberry	Carlsbad and Oceanside (South Coast)	Hoffmann et al. (2020)
Alternative fumigants	No target crop	Parlier (Central Valley)	Nelson et al. (2013)
Anaerobic soil disinfestation	Strawberry	Santa Cruz County (Central Coast)	Mazzola et al. (2018)
Anaerobic soil disinfestation	Strawberry	Oxnard (South Coast)	Muramoto et al. (2016)
Anaerobic soil disinfestation	Strawberry	Watsonville (Central Coast)	Mazzola et al. (2016)
Biologically derived pesticides and biocontrol agents	Walnut	Davis (Central Valley)	Strauss et al. (2015)
Biologically derived pesticides and biocontrol agents	Strawberry	San Luis Obispo (Central Coast)	Blauer and Holmes (2020 and 2024)
Biopesticides and non-fumigant pesticides	Tomato	Riverside (South Coast)	Loffredo et al. (2024)
Biopesticides and non-fumigant pesticides	Strawberry	San Luis Obispo (Central Coast)	Blauer and Holmes (2020 and 2024)

Technique	Crop	Location (region)	Reference
Biosolarization	Almond	Chico (Central Valley)	Shea et al. (2022)
Biosolarization	Tomato	Davis (Central Valley)	Achmon et al. (2018)
Cover cropping	Grape	San Luis Obispo County (Central Coast)	Lazcano et al. (2021)
Cover cropping	No crop target	Davis (Central Valley)	DuPont et al. (2009)
Cover cropping	Tomato and cotton	Five Points (Central Valley)	Kelly et al. (2021)
Cover cropping	Tomato	Irvine (South Coast)	López-Pérez et al. (2010)
Crop rotation	Strawberry	Moss Landing (Central Coast)	Muramoto et al. (2014)
Crop rotation	Lettuce	Davis (Central Valley)	Scott et al. (2014)
Non-fumigant pesticides	Tomato	Riverside (South Coast)	Silva et al. (2019)
Non-fumigant pesticides	Carrot	Irvine (South Coast)	Becker et al. (2019)
Resistant varieties and rootstocks	Grape	Amador County, Sacramento County, Mendocino County, Napa County, and Sonoma County (North Coast and Central Valley)	Dodson Peterson et al. (2019)
Resistant varieties and rootstocks	Grape	Davis (Central Valley)	Ferris et al. (2012)
Resistant varieties and rootstocks	Almond, Apricot, Cherry, Nectarine, Peach, Plum	Davis (Central Valley)	Browne (2017)
Resistant varieties and rootstocks	Strawberry	Oxnard and Ventura	Koike et al. (2013)
Resistant varieties and rootstocks	Strawberry	La Selva Beach and San Luis Obispo	Holmes et al. (2017), Ramirez et al. (2024a), Ramirez et al. (2024b)
Resistant varieties and rootstocks	Strawberry	Davis	Feldmann et al. (2024)
Soilless cultivation	Lettuce	Davis (Central Valley)	Albornoz and Lieth (2016)
Soilless cultivation	Ornamentals	Davis (Central Valley)	Pitton et al. (2021)
Solarization	No crop target	Davis and Parlier (Central Valley)	Marshall et al. (2013)
Solarization	Broccoli, Cantaloupe, Sweet Corn, Wheat	Thermal (Low Desert)	G. Wang et al. (2009)
Solarization and steam treatment	Strawberry	Salinas (Central Coast)	Samtani et al. (2012)
Steam treatment	Strawberry	Salinas and Watsonville (Central Coast)	Fennimore et al. (2014)
Steam treatment	Strawberry	Salinas (Central Coast)	D. S. Kim et al. (2020)
Steam treatment	Cut flowers	Prunedale and Nipomo (Central Coast)	Rainbolt et al. (2013)

Section 3.4: Scale of fumigant alternative research

The studies summarized in ***Appendix B*** demonstrate the different scales and formats used for fumigant alternative research. At the smallest scale, research may use a microcosm (a vessel housed in a lab containing soil that is meant to replicate certain field conditions) or other containerized format. This scale is typically employed for early-stage research to screen potentially pesticidal compounds or conditions for effectiveness against target soil pests and pathogens. This scale may also be used to identify lethal dosages (e.g., doses required for 50% or 90% pest inactivation within a set timeframe) and explore interactions between process variables such as temperature and exposure time in relation to pest inactivation. Mesocosm studies are the middle-ground between laboratory and field trials, in which vessels of soil with known physical, chemical, or biological properties are embedded in field soil. Mesocosm studies balance the variability of genuine exposure to the environment with the ability to target and control specific soil variables within the mesocosms. Greenhouse studies may also be used to assess pest inactivation and crop effects for fumigant alternatives. Research may focus on pest management strategies specifically for greenhouse production systems, or use potted plants in a greenhouse to generate predictive data before field deployment. Field trials are the most common experimental format for validating the effectiveness and crop health effects of fumigant alternatives. Field trials generally mimic commercial agricultural conditions by using similar agricultural fields, farm operations, and material inputs as growers.

Field trials represent the largest scale of fumigant alternatives research. The size of a field trial is determined by several factors, including the number of treatments to be tested, the spacing requirements of any crops that will be grown in treated soils, the variability of the soil, pest, and crop responses to be measured, and the desired sensitivity for detecting differences between treatments. Practical considerations, such as land availability, research budget, and research team size, also play a role in determining trial scale. As a result, research field trials are often considerably smaller than commercial farms. Field trials conducted in the last decade for various fumigant alternatives commonly used plots that are well below one acre (examples are provided in ***Table 3.3***).

> 95. **FINDING:** Fumigant alternative research currently occurs at a scale far below that of commercial agriculture.

Table 3.3. Examples of plot or container sizes used in fumigant alternative trials.

Crop (cultivation system)	Alternative to 1,3-D and chloropicrin	Size of one experimental unit (i.e., one replicate within one treatment)	Reference
Tomatoes (greenhouse)	Fumigation with dimethyl disulfide	5 x 5 m plot	Gómez-Tenorio et al. (2018)
Sweet potato (field)	Non-fumigant nematicides and biopesticides	9.14 x 2.04 m plot	Watson et al. (2023)
Pepper and squash (field)	Non-fumigant nematicides	51.82 x 0.91 m plot	Nnamdi et al. (2022)
Strawberry (greenhouse and field)	Soilless cultivation	0.75 x 0.15 x 0.25 m grow bag	Rahim Doust et al. (2023)
Wheat (field)	Crop rotation	36 x 80 m	Flower et al. (2019)
Almond (field)	Solarization and biosolarization	3 x 295 m	Shea et al. (2022)
Strawberry (field)	Steam treatment	1.32 x 59 m	Fennimore et al. (2014)
Strawberry (field)	Anaerobic soil disinfestation	1.2 x 12 m	Shennan et al. (2018)
Strawberry (field)	Resistant varieties and rootstocks	3 x 2 m	Ramirez et al. (2024a, 2024b)

Section 3.5: Environmental conditions of research

Research into fumigant alternatives has been conducted using crops and climate zones relevant to California agriculture. This is due to the considerable amount of research into fumigant alternatives directly undertaken within California, as discussed in ***Section 3.3***. ***Appendix B*** provides a sampling of fumigant alternative research studies that span the U.S. and other countries. Within the U.S., fumigant alternative research has been conducted in states like Florida, Georgia, and Oregon. Florida and Georgia have subtropical climates that differ from the Mediterranean climate of the California's Central Valley and Central Coast. Nevertheless, warm temperatures are common to both regions, and there is overlap in the crops grown in both states, such as tomatoes, strawberries, and peppers, although growing seasons and rainfall differ markedly. Oregon's Willamette Valley, which produces strawberries and other berries, shares the moderate spring and summer temperatures and cool, humid nights found in California's coastal farm regions.

International research into fumigant alternatives spans countries such as Spain, Australia, China, Japan, Iran, Jordan, Egypt, and France (see ***Appendix B***). Spain, China, Japan, and France occupy the same temperate, Mediterranean latitude band as California and produce major California crops like tomatoes, strawberries, melons, grapes, and peppers. Similarly, southern Australia, where much of the country's fruit and vegetable production is located, falls within a comparable latitude to California (Department of Agriculture, Fisheries and

Forestry, Australian Government, 2024). Northern Iran, where the bulk of the country's agriculture (mostly grains) is based, falls within the temperate latitude band (Mesgaran et al., 2017). Jordan and Iran have subtropical climates similar to Florida, with parallels to California in terms of crops produced, hot summers, and mild winters. Given the similarities in crop types and environmental conditions captured in this international research, the methods and results may be applicable to California. However, careful consideration must be given to aligning the specific climate zones and relevant soil properties (e.g., texture, pH) to ensure the applicability of data generated in these countries to California's agriculture.

Section 3.6: Suitability of research to identify an alternative for California

Existing research has demonstrated that all fumigant alternatives listed in ***Table 2.1*** (***Section 2.1***) can inactivate one or more soil pests commonly controlled with 1,3-D or chloropicrin, improving crop health or yields in at least one cropping system relevant to California. However, research has also revealed variable or conditional effectiveness for these alternatives depending on specific pest targets, cropping systems, or environmental factors. Where research has shown effective pest control and crop health benefits under conditions applicable to California—either because the research was conducted in California or in regions with a similar climate to California (see ***Section 3.3*** and ***Section 3.5***)—it is reasonable to consider these alternative viable for larger-scale use in California. Nevertheless, additional research is needed to define the process and environmental variables that optimize pest control effectiveness and crop benefits across the diverse range of fumigant-reliant crops, soil pests, soil types, and climate zones in California. This need is also present for combination methods that employ multiple fumigant alternatives in parallel or in series (see Section ***Section 3.2***). While many potential combinations exist, current research has only explored a narrow range for select crops. As a result, targeted studies are needed to identify robust and scalable combination methods for major fumigant-reliant California crops. These methods can overcome the shortcomings or inconsistencies of individual fumigant alternatives and consistently match the effectiveness of conventional fumigation (see ***Section 2.20*** and ***Section 3.7***).

To encourage grower adoption of fumigant alternatives, additional research is needed to directly compare multiple alternatives within the same context (i.e., specific crop systems, soil pest profiles, locations) and provide relative pest control and crop performance data to guide growers in selecting the most effective option. Similarly, comparative environmental and human health risk assessments are also essential for fumigant alternatives, considering California-specific factors such as the surrounding ecology, proximity of nearby communities, and potential worker exposure.

Currently, data for individual fumigant alternatives are spread across multiple studies and publications that often use varying deployment conditions. This fragmentation makes it challenging to directly compare alternatives for specific pests and crop systems and complicates identification of the most promising fumigant alternatives for a given site. In addition to direct empirical comparisons between various fumigant alternatives, **meta-analysis** of existing studies can provide valuable insights. By synthesizing data across multiple crops and pest targets, meta-analyses can identify consistently observed pest control and crop effects and help growers choose effective fumigant alternatives for their fields. For example, a meta-analysis of anaerobic soil disinfestation studies systematically identified average expected effects on individual pest categories and yield changes for individual crops, in addition to environmental and process factors that generally maximize these benefits (Shrestha et al., 2016). Similar analyses are needed for other fumigant alternatives.

Fumigant alternatives may also face logistical and technological challenges that limit their adoption. For instance, steam treatment uses specialized applicators that move slowly through fields and are not commonly available (see ***Section 2.10***). Soilless cultivation systems require significant investment in new infrastructure, such as greenhouses or recirculating irrigation systems, or extensive retooling of how fields are prepared and maintained to support soilless cultivation. While these techniques show promise for avoiding or mitigating soil pests, additional research could help address key engineering challenges (e.g., applicator speed, soil heating efficiency, and depth of heating for steam treatment) and operational challenges (e.g., transitioning open fields to soilless cultivation with minimal increases to cost and labor) to enable use at scale.

Research has been inconsistent in assessing the costs and expected net returns for growers transitioning from fumigation with 1,3-D and chloropicrin to an alternative approach. While steam treatment in California strawberry production has undergone rigorous techno-economic analysis (see ***Section 2.10***), similar studies are lacking for other crop systems and fumigant alternatives. This gap is particularly evident in research on combination pest control strategies using multiple fumigant alternatives, where the potential enhancement to pest control and yield must be weighed against the cost of additional inputs and labor, along with the greater management and skill needed. Without comprehensive technoeconomic analyses to expand the range of cost studies and net return projections for individual fumigant alternatives and combination methods, it is difficult for growers to make informed decisions about adopting these alternatives.

> 96. **FINDING:** Technoeconomic studies are sparse for the full range of fumigant alternatives currently available in California.

Section 3.7: Promising fumigant alternatives undergoing research

Each fumigant alternative offers promise for specific use cases. Fumigants other than 1,3-D and chloropicrin, cover cropping to induce biofumigation, anaerobic soil disinfestation, biosolarization, and steam treatment all use broad-spectrum inactivation mechanisms similar to the broad biocidal activity of conventional fumigants. For anaerobic soil disinfestation and biosolarization, multiple pesticidal stresses can be induced in the soil, including heat, low oxygen, microbial competition, and accumulation of fermentative biochemicals with pesticidal activity. These synergistic stresses can improve effectiveness and guard against failure if one mechanism is insufficiently effective. For example, while solarization relies on solar heating and soil temperature and is thus limited by seasonal and regional weather and climate conditions, the oxygen depletion and antagonistic microbial activity during biosolarization or anaerobic soil disinfestation may compensate when soil temperatures are sub-lethal. Moreover, cover cropping, anaerobic soil disinfestation, and biosolarization incorporate organic matter amendments in the soil. Enrichment of organic matter can lead to multiple soil health benefits beyond disinfestation, such as enhanced fertility and water holding (see ***Section 2.18***). This enrichment aligns with the California Department of Food and Agriculture's Healthy Soils Initiative (CDFA, 2024). However, care must be taken to avoid unintended outcomes such as nitrogen leaching, which could conflict with other state initiatives like the Salinity Alternatives for Long-Term Sustainability (SALTS) program (which addresses nitrate contamination of groundwater). Like 1,3-D and chloropicrin, these alternative methods are primarily used as pre-plant soil treatments, and reinfestation may occur after application.

Other fumigant alternatives with more persistent pest control potential (although the control may be narrower in scope), or the ability to be deployed post-planting, may be needed to complement pre-plant techniques. For instance, combining crop rotation, resistant crops or rootstocks, biologically derived pesticides, or biocontrol agents—which either continually resist pests or can be applied repeatedly to established crops—with pre-plant fumigant alternatives could deliver an initial broad spectrum reduction of soil pest reservoirs with sustained pest suppression that mitigates the risk of reinfestation.

> 97. **FINDING:** Each fumigant alternative is promising for particular use cases and constraints.

> 98. **CONCLUSION:** Combination approaches that integrate multiple fumigant alternatives, whether simultaneously or in series, are likely to offer the greatest versatility and duration for broad-spectrum soil pest control.

However, as outlined in ***Section 2.14***, ***Section 2.15***, and ***Section 3.6***, there are significant knowledge and guidance gaps regarding effectiveness, logistical feasibility, costs, sustainability, human health, and environmental effects for individual fumigant alternatives when used at commercial scale, compared to conventional fumigation, and these challenges compound when multiple fumigant alternatives are combined.

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Chapter 4: Addressing Barriers and Increasing Adoption of Fumigant Alternatives

Section 4.1: Chapter overview

Chapter 1 explored concerns about human health and environmental impacts of chloropicrin and 1,3-D, including the regulatory actions that the Department of Pesticide Regulation (DPR) has taken to mitigate the risks posed by the use of these pre-plant soil fumigants in California. Chapters 2 and 3 summarized available alternatives to these fumigants (including their suitability as fumigant alternatives for crops that currently rely on 1,3-D and chloropicrin) and the past 20 years of research developing both chemical and non-chemical alternatives.

We turn now to the barriers that inhibit the adoption of these alternatives (***Section 4.2***). ***Section 4.3*** discusses various approaches that could theoretically reduce those barriers. ***Section 4.4*** describes methods for how information about these alternatives could be disseminated to potential users.

We describe approaches to incentivize adoption so that should a regulatory agency decide to promote fumigant alternatives, they might better understand the variety of tools that exist. However, these are not necessarily recommendations of the Steering Committee, unless otherwise indicated as such.

Much of the research in this chapter is based in social sciences, including qualitative sociological studies. This is, in part, because these fields examine how individuals and groups behave and make decisions within broader social and economic systems. Qualitative social research, especially, aims to uncover deeper meanings and reveal underlying social and economic (i.e., structural) conditions that are not immediately observable and can only be ascertained through in-depth discussion and logical inference (Crouch and McKenzie, 2006; Sayer, 2010). To the best of the study team's knowledge, the discussion presented herein is consistent with the best available research and reflects the broader consensus of sociological research on these topics.

Chapter 4 contains 8 Findings and 3 Conclusions. The Steering Committee did not identify any Recommendations.*

***Finding**. Fact(s) the study team finds that can be documented or referenced and that have importance to the study. **Conclusion**. A reasoned statement the study team makes based on findings. **Recommendation**. A statement that suggests an action or consideration as a result of the report findings and conclusions.

Section 4.2: Barriers to adoption

A wealth of studies has examined the factors, variables, and considerations that shape grower decisions about pesticide use. Many of these studies focus on how growers' perceptions of pest virulence, treatment effectiveness, and chemical health and environmental risk influence their decisions (Hashemi and Damalas, 2010; Heong et al., 2002; Khan and Damalas, 2015; Parveen et al., 2003; Penrose et al., 1996), with some noting that the risk of economic losses from reducing pesticide use often outweighs other concerns (Damalas and Koutroubas, 2014; Kishi, 2002; Tucker and Napier, 2001). The limited adoption of alternatives even amidst pressure to move away from fumigating with 1,3-D and chloropicrin suggests that variable or insufficient pest control effectiveness for fumigant alternatives—and the complexity of implementing these alternatives—are together the most significant barrier to adoption. Practices such as solarization, biosolarization, anaerobic soil disinfestation (ASD), cover cropping, soilless cultivation, and steam treatment show promising data in controlling major soil pests and pathogens. However, further research is needed to define optimal conditions under different soil types, pest conditions, cropping systems, and other variables. Further, there are sometimes only short windows of time between crops, which disallows for fumigant alternatives that are more time intensive (e.g., pest inactivation via solarization can take between four to eight weeks).

> 99. **FINDING:** Variable or insufficient pest control effectiveness for fumigant alternatives—and the costs and complexity of implementing these alternatives—are significant barriers to adoption.

Regulatory barriers

The flip side of the previous obstacles is the continued allowability of fumigants. Growers are more likely to experiment with and adopt alternatives when specific agricultural chemicals are disallowed or there are signals that they may be in the future (Guthman, 2014). Growers are primarily concerned that alternate methods may lead to reduced productivity. In a survey to gauge strawberry growers' priorities related to variety selection and use of resistant varieties or fumigation to mitigate crop disease, growers cited the possibility of crop loss as the primary issue preventing transition away from fumigation (Guthman, 2020). For most growers, maximizing yield was the top concern for varietal choice (Guthman, 2020). Notably, yield outweighed marketability as a grower priority. Most growers indicated that only a 0 to 5% reduction in yield would be tolerable when shifting away from fumigation, setting a high bar for fumigant alternative effectiveness to gain grower acceptance. However, in follow-up interviews, when growers were asked why yield remains a priority despite concerns about low prices, it became clear that the desire for alternatives to produce equivalent yields as with fumigation reflects a collective action problem—a situation in which cooperating would be mutually beneficial, but individuals are also incentivized to act alone. Growers felt that choosing a lower-yielding variety would be folly individually, since they would be less productive than their competitors, but they acknowledged that reducing supply could benefit the industry as a whole. Industries such as strawberry, almond, grape, and walnut have routinely faced overproduction problems due to technology breakthroughs, including the use of fumigation, leading these industries to invest in finding new markets for their products (Baum, 2005; Reisman, 2020). In cases where growers routinely face overproduction, a modest reduction in yield from adopting fumigation alternatives may not be unwelcome. This suggests that government regulations to reduce fumigation could provide a consistent incentive for adopting alternatives. However, given global competition, such a policy could also drive agricultural production out of California to bypass this restriction. Currently, there is only limited competition for early season domestic producers because most imports from Mexico occur during the winter and early spring (Wu et al., 2021). If producers in Mexico expand production in temperate regions to compete with later-season strawberries, some protection of domestic producers may be needed.

Restrictions could be set up such that any produce sold in California—not just that grown in state—comply with fumigation regulations. An example of this approach is California's recent animal welfare restrictions on pork, veal, and eggs. Proposition 12, upheld by the Supreme Court (Sutton, 2024), amended California's Proposition 2, which required that only pork, veal, and eggs produced in California comply with animal welfare restrictions. As production moved out of state, Proposition 12 expanded the requirement, mandating that all such products sold in California comply with these standards. Lee et al. (2023) found that consumers might expect a 3.5% increase in the cost of pork, now that all producers must comply. A similar restriction regarding crops and fumigants could possibly impact food access to the most vulnerable consumers if food prices rise to make up for the potentially more costly use of the fumigant alternatives. That said, the causes of food insecurity are complex.

100. **FINDING:** At present, growers who choose to forego the pathogen, pest, and weed control as well as yield-enhancing benefits of fumigation in their fields face an economic disadvantage compared to those who do fumigate.

101. **FINDING:** As social science research has demonstrated, government regulations to reduce, phase out, or eliminate fumigation for produce sold in California would encourage adoption of fumigant alternatives.

102. **CONCLUSION:** As long as fumigation is allowed, there is a disincentive for growers to adopt alternatives because they risk lower yields relative to those who fumigate.

Land use challenges

Land values are also a structural obstacle to the adoption of fumigant alternatives. Land values are typically calibrated to the "highest and best" use for that land. In California, agricultural land values are unusually high, affected not only by the prevalence of high value specialty crops, but also the encroachment of urban/suburban development of that land. With land values tied to the high productivity allowed by fumigation—especially by eliminating the need for crop rotations—fumigation has become ingrained into the value of land, making it challenging to incorporate alternatives that rely on rotations of lower- or no-value crops (Guthman, 2019; Guthman and Jiménez-Soto, 2019). Land values are especially high along California's coast, where conditions are most suitable for long growing seasons, as is the case with strawberries (Guthman, 2019). Indeed, any long-term erosion of the profitability of strawberry operations puts them at risk of being replaced by competitors using traditional fumigation techniques, other crop producers, or urban development. Profitability depends on yields and cultural costs, both of which may be affected by using fumigant alternatives.

Lease agreements may also complicate the adoption of fumigant alternatives. Arrangements such as crop-share agreements require coordination and agreement between the landowner and the tenant(s) (i.e., the grower(s)) (UC ANR, 2024). It is not unusual for lease agreements to involve multiple growers rotating crops at the same site, and many such agreements stipulate the use of fumigation. Many strawberry growers, for instance, rotate with vegetable or lettuce growers who insist that strawberry growers fumigate, even when strawberry growers hold the master lease (Guthman, 2017a). As a result, even if grower-tenants want to use a fumigant alternative, they may not have the authority to change pest management practices.

Labor costs

Labor costs and availability may also pose obstacles to alternative methods, especially if the alternatives involve additional labor (Pfeffer, 1992). For strawberry harvesting, growers rely heavily on piece-rate wages to maximize worker productivity. Piece-rate payment ties worker income directly to the amount of product harvested. During labor shortages, growers can leverage the reliable yield benefits from fumigation to attract workers by maximizing the amount of product available to harvest, and thus increasing the potential earnings for workers per unit of worker time (Guthman, 2017b). In this way, piece-rate payment may further entrench fumigation and create resistance to adoption of alternatives. In addition to differences in harvest labor costs, significantly more hand labor for weeding may be required for certain fumigant alternatives (e.g., pathogen resistant varieties, ASD, cover crops, organic production systems), creating an economic barrier for growers (Bolda et al., 2024).

Outside pressures

Grower decisions about fumigation are often dictated by other stakeholders. **Shippers** hold tremendous economic power in California agriculture, a relic of crop specialization and the division of labor between growing and selling fruits, nuts, and vegetables (Stoll, 1998).* Although some growers ship their own crops, the shipping industry has become even more concentrated in crops like strawberries, giving shippers additional leverage in setting the terms of purchases from growers (Guthman, 2019). In strawberry production, some shippers hold growers to particularly high aesthetic standards, forcing growers to cull berries that are undersized, irregularly shaped, or off in color (Jansen and Vallema, 2004). To the extent that fumigation minimizes irregularity (e.g., by controlling soilborne pests that would otherwise damage or stunt crops), shipper quality standards also play a role in discouraging the use of alternatives (Guthman 2019). Moreover, since many growers are beholden to shippers for credit, land, and other materials, they must often abide by shipper wishes in other areas, which may steer them away from alternatives to fumigation (Guthman, 2019; Guthman and Jiménez-Soto, 2021). Growers have also reported that banks stipulate the use of fumigation as a condition for obtaining credit (Guthman, 2019).

While most of the structural barriers to adoption of fumigation alternatives discussed above have been identified for the California strawberry industry, many of these barriers may also affect the use of fumigant alternatives in other specialty crops.

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*Bolded terms can be found in the glossary.

103. **FINDING:** Land costs, labor costs, access to credit, and market pressures constrain growers' economic ability to adopt fumigant alternatives.

104. **CONCLUSION:** Given challenges of land costs, labor costs, access to credit, and market pressures, growers would benefit from economic supports for transitioning from fumigants to fumigant alternatives.

105. **FINDING:** Entrenched practices and existing business relationships may make it difficult for growers to adopt fumigant alternatives.

Additional barriers

Further challenges to the adoption of fumigant alternatives include those that affect access to economic resources, technical support, and information about alternatives (Chaves and Riley, 2001; Khan and Damalas, 2015; McNamara et al., 1991; Mumford, 1981; Robinson et al., 2007; Thiers, 1997; Thomas et al., 1990). For example, fumigant manufacturers provide readily available information about compatible crops, susceptible pests, and application methods, supported by a wealth of research on lethal dosages, performance under various soil and environmental conditions, and plant-back times. Fumigant alternatives do not have as much rigorous supporting research and straightforward guidance for growers. Additionally, studies have shown that the pesticide industry aggressively markets chemicals, which is not matched by extension support for non-chemical alternatives (Deguine et al., 2021; Barraza et al., 2011; Bellamy, 2011; Galt, 2014; Harrison, 2011). Public research funding and related extension of the results, such as through the U.S. Department of Agriculture (USDA) and public universities, are crucial for developing and promoting non-chemical alternatives to fumigation. These alternatives involve fewer commodifiable technologies and services, making them of less interest to private-sector industry. Broadly speaking, chemical-intensive monoculture still receives the majority of funding for agricultural research (DeLonge et al., 2016; Miles et al., 2017).

Growers also face unequal access to information about newer technologies. For instance, a study of environmental conservation in the Central Coast strawberry region showed that low-resource and Mexican-origin growers received less guidance on techniques to employ (Mountjoy, 1996). However, outreach to small farms and limited-resource growers has been an area of significant effort over the last two decades. Even in the best of circumstances, varying levels of awareness and familiarity with the full range of fumigant alternatives—including factors that may affect suitability for specific environments or cropping systems—represent barriers to their adoption and scaling. Currently, information regarding implementation methods and data on the effectiveness of each alternative are scattered across journal articles, books, digital and print extension materials, select farm advisors, extension specialists, and other academic and industry researchers. Some of these dispersed resources, like academic journals, are behind paywalls, creating additional accessibility challenges for growers.

Not only are there challenges for growers to access research-based and unbiased information on the use of 1,3-D and chloropicrin fumigants or their alternatives, economic interests can influence the information growers receive. Pest Control Advisors (PCAs) and Pest Control Operators (PCO) are key figures in pest management. Growers consult PCAs for pest control advice and pay PCOs to apply these restricted-use materials. Social science researchers have documented that some PCAs obtain income from commissions on the products and services they sell to their clients (Guthman, 2019; Harrison, 2011; Van den Bosch, 1978; Wolf, 1998). When this dynamic occurs in fumigation services or among providers of fumigant alternatives, it creates a conflict of interest.

There are also varying degrees of knowledge gaps across the spectrum of fumigant alternatives that impact their selection and adoption. While commercialized options like non-fumigant pesticides, biologically derived pesticides, biocontrol agents, resistant varieties, and resistant rootstocks often come with clear and accessible guidance from manufacturers, nurseries, or breeders, the less commercialized options—such as solarization, biosolarization, anaerobic soil disinfestation, or cover cropping—typically lack centralized, detailed guidance that addresses the full range of crops and soil pests associated with fumigation.

There is a hypothetical risk that knowledge gaps or misinterpretation of data could lead to ineffective pest control, **phytotoxicity**, non-target toxicity and ecological effects, or excessive cost. However, this risk has not been established in the research. Studies have found that negative personal experiences with pesticides or the fears of public concern have led to reduced pesticide use (Guthman, 2014; Guthman, 2016).

Logistical hurdles can also hamper adoption of certain fumigant alternatives. For example, methods such as solarization, biosolarization, anaerobic soil disinfestation, and cover cropping rely on specific climate and weather conditions, which may create scheduling challenges for growers and limit where these methods can be used. Similarly, the treatment duration and highly specialized equipment required for soil steam treatment may also pose barriers to grower adoption.

Finally, path dependency, wherein historical experiences and precedents create resistance to change—or even "lock-in"—can hinder adoption of new agricultural practices. Generally, scholars attribute lock-in to the widespread adoption of an agricultural technology, where increased usage leads to improved performance over time (Magrini et al., 2016). Pesticides are particularly prone to lock-in due to their ease of use and initial yield boosts for users, which drive early profitability. However, as adoption spreads, profit rates re-normalize with lower prices, reflecting the classic "technology treadmill" effect (Galt, 2013; Wilson and Tisdell, 2001). Additionally, uncertainties about the effectiveness and social acceptance of fumigant alternatives can stymie transitions to these methods (Cowan and Gunby, 1996; Wagner et al., 2016). The familiarity, ease of use, and broad toxicity of fumigants have reduced the need for growers to understand, capitalize on, and preserve the agro-ecosystem to achieve pest inactivation (Hu, 2020; Uekötter, 2014). Thus, those fumigant alternatives that are more complex to implement and require specialized knowledge face additional barriers. Factors such as age and general education may play a role, as several studies have found that younger and/or more educated growers are more likely to adopt techniques associated with "sustainable agriculture" (Comer et al., 1999; Damalas and Koutroubas, 2014; Lasley et al., 1990; Lighthall, 1995).

Loss of expertise (**deskilling**) in soil pest control—and growers' perceptions of the value of fumigation alternatives—can be reinforced by economic pressure and risk distribution factors. For instance, pesticides are affordable for many crops, and growers see a direct economic return on pesticide use through increased yields. In contrast, the broader risks that fumigants pose to environmental and human health are decentralized externalities, affecting communities at the local, regional, and even global scale (Hu, 2020). As explored in more detail in the next section, economic tools, like taxes or subsidies, could help mitigate these negative impacts of fumigant use.

Many of the structural barriers discussed above undermine the adoption of non-fumigant alternatives and reinforce reliance on chemical fumigants. Addressing these barriers requires higher-level organizational changes, including increased research, targeted incentives, and regulatory restrictions on fumigant use. California agriculture is vibrant and market-driven, and growers are likely to embrace new and profitable opportunities. The primary challenge, as noted earlier, is that many new alternatives may not be profitable.

Section 4.3: Promoting widespread acceptance and incentivizing use

Regulatory programs include setting standards, granting permissions, and enforcing prohibitions, all of which require monitoring and enforcement to ensure compliance (Goodhue et al., 2022). DPR, like most regulatory agencies, seeks input from all stakeholders to ensure buy-in and understand the concerns and interests of the wider community. For 1,3-D and chloropicrin, regulations have included outright bans (only temporarily in California); geographical restrictions of allowed pounds applied (township caps); buffer zones; regional restrictions (e.g., inland vs. coastal areas); seasonal restrictions; changes to rates; water content requirements for different types of soils; tarping methods for onsite containment; notifications; reporting requirements; and monitoring. As noted in the pesticide use analysis in Chapter 1, regulations play a significant role in shaping grower pesticide use and encouraging the adoption of alternative chemicals. Additionally, regulations have been shown to influence the adoption of entire farming systems, such as organically certified production (Guthman, 2014).

Alongside potential regulatory restrictions, more incentives could be introduced to influence grower behavior, particularly to help ameliorate potential economic impacts of transitioning to more complex alternatives to pre-plant fumigation with 1,3-D and chloropicrin. Goodhue et al. (2022) reviewed four ways to increase adoption of "**sustainable pest management** practices," most of which can equally apply to alternatives to these pre-plant soil fumigants. The practices included 1) direct financial benefits or economic incentives such as subsidies and cost-sharing; 2) insurance targeted to support the use of pest management practices; 3) taxes imposed based on certain characteristics and used to encourage particular fumigant alternatives; and 4) state procurement policies for certain commodities to encourage adoption of fumigant alternatives in producing these crops (e.g., Buy California and school lunches). Additionally, the market can be brought to bear through **organic certification**, product labeling, and various regional and statewide sustainability assessment and certification programs such as Lodi Rules (Lodi Rules Sustainable Winegrowing Program, 2024) and SIP certified (Sustainability in Practice) for winegrapes (SIP Certified, 2024). Many such certification programs would by definition prohibit the use of all fumigants and promote the use of various alternatives outlined in preceding chapters (Broome and Warner, 2008).

Economic incentives to adopt alternative fumigant practices could be voluntary, mandatory, or a combination of both (Goodhue et al., 2022). Most agri-environmental programs such as the Conservation Reserve Program (CRP) and Environmental Quality Incentive Program (EQIP) in the U.S. are voluntary (Garnache et al., 2016). For instance, **agricultural subsidies** could be used to encourage growers to adopt certain alternatives to fumigation best practices (Goodhue et al., 2022). Agricultural subsidies may include subsidized crop insurance, tax credits, cost-sharing, and/or environmental stewardship payments (Claassen et al., 2017; Wallander et al., 2019). These subsidies could fund practices already supported by federal USDA programs, such as the Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP), as well as state initiatives like the at the California Department of Food and Agriculture (CDFA) Climate Smart Incentives program. These programs include cover cropping, the purchase of macro tunnels and some parts of soilless substrate culture, and purchase of resistant rootstocks and varieties. Subsidies could be explicitly tied to use of the alternatives to specific fumigants. Payments may be withheld if growers fail to comply with contracted obligations and implement the required practices (Palm-Forster et al., 2019). Because these kinds of economic incentives programs are voluntary, regulators would benefit from a comprehensive understanding of each industry and the factors influencing the adoption of specific practices. Adoption decisions are likely to be influenced by variables such as weather conditions and drought; field characteristics such as soil type and quality; commodity prices; production costs; levels of financial assistance; stringency of program requirements (e.g., contract duration); current management status; and growers' beliefs, management skills, and risk attitudes (Goodhue et al., 2022).

Agriculture incentives

Federal incentive programs have seen less uptake in California compared to other regions due to the high cost of specialty crops production relative to the payments and support offered. This imbalance could be changed. The CDFA Climate Smart agriculture incentives program can serve as a model for how DPR might design, fund, and operate a sustainable pest management initiative. Such a program could subsidize the costs of pre-plant fumigant alternatives (and potentially alternatives to other priority pesticides) such as cover crops, purchasing of easily decomposed (labile) carbon sources for anaerobic soil disinfestation, steam soil disinfestation, and other practices that enable a farm to adopt and implement **sustainable pest management (SPM)** practices (DPR, 2023; Babin et al., 2024). Babin et al. (2024) studied the Climate Smart incentives program, which allocated more than $800 million in funding between 2014 and 2020. The researchers surveyed all 1,652 growers who received funding to adopt agricultural practices aimed at mitigating greenhouse gas (GHG) emissions, improving soil health, managing manure, promoting renewable energy, and enhancing water and energy use efficiency across California. Respondents reported an average practice persistence rate of 75% (ranging from 62% to 86%) across all 967 funded practices evaluated and felt their farms were more resilient post-project. The CDFA Climate Smart agriculture incentives program can serve as a model for the DPR to develop a similar program, which would provide funds in the early years to offset reasonable yield losses incurred as growers adopt and implement SPM practices, including alternatives to fumigants such as 1,3-D and chloropicrin (DPR, 2023).

Insurance programs

In the U.S., farm incomes—especially in the Midwest—are often stabilized through federal multiple peril crop insurance programs, which help protect farmers from risks due to reduced yields or revenues (Goodhue et al., 2022). Farmers are protected against losses from natural causes (e.g., drought and disease) with the premiums subsidized by the federal government. Growers with crop insurance have improved farm productivity (Kurdys-Kujawska et al., 2021) and increased resilience to adverse financial events (Glauber et al., 2021). The strength of these effects varies spatially (Hungerford and O'Donoghue, 2016), across farmer income levels (Farrin et al., 2016), and with farmer experience (Zhao et al., 2020). Goodhue's review of literature on the effects of crop insurance programs on producers' decisions suggests there is potential to develop an insurance program tied to pest management and related crop management practices (cover crops, **diversified farming** operations, longer rotations, etc.). Such a program could incentivize the adoption of alternative practices and products to replace certain pre-plant soil fumigants (Rosa-Schleich et al., 2019; Belasco and Schahczenski, 2021).

The USDA's Risk Management Agency (RMA) expanded its Production and Revenue History (PRH) Strawberry Pilot crop insurance program to California in 2022. Developed for specialty crop producers, PRH allows producers to secure coverage based on their individual production and revenue history. The PRH strawberry pilot policy offers producers a choice between yield or revenue protection. Crop insurance is sold and delivered through private crop insurance agents. RMA estimates potential insurance liability of $120 million in California (USDA RMA, 2021). A closer look at this program and how it could be linked to support adoption of 1,3-D and chloropicrin fumigant alternatives is warranted (USDA RMA, 2021). DPR noted the potential of this approach in their 2013 report on strawberry fumigant alternatives (DPR, 2013). Finally, land ownership, or lack thereof, does not have to hinder the use of crop insurance tied to pest management practices. Both landowners and lease holders can obtain insurance, agree to share the cost of premiums, and, if a payout is needed, divide it based on signed agreements.

A comprehensive review of the USDA's Risk Management Agency (RMA) insurance programs could identify opportunities to improve coverage for risks associated with adopting fumigant alternatives (USDA RMA, 2024). Insights from this review could inform future iterations of the federal farm bill, including modifications to the federal crop insurance program to cover risks related to transitioning away from fumigation with 1,3-D and chloropicrin.

Tax incentives

Taxes can be used to influence growers' pesticide purchases and usage decisions by targeting specific product attributes. Goodhue et al. (2022) illustrate this approach by referencing taxes on sugary beverages, which have been shown to reduce consumption of the target drinks (Cawley et al., 2020; Pereda and Garcia, 2020). In California, an analog can be found in the pesticide mill assessment, which is set at a flat rate of 2.45 cents per dollar of all pesticide sales revenue. This rate increased from 2.10 cents per dollar in July 2024 and is scheduled to rise yearly until it reaches 3.00 cents per dollar in 2027 to support expanded programmatic work by DPR; prior to this, the rate had remained unchanged for over 20 years (DPR, 2024).

Crowe LLC consultants recently completed a study (2023) for DPR regarding the mill assessment and how to fund future pesticide regulatory programs of DPR, County Agricultural Commissioners, and CDFA and encourage adoption of SPM as outlined in the SPM roadmap. In the Crowe report, they recommended a flat increase in the mill assessment with the potential to revisit "tiering" as a feasible option once "Priority Pesticides" are identified through the process outlined in the SPM Roadmap (Crowe, 2023; DPR, 2023). As per the SPM roadmap, a new workgroup will be formed by 2025 to develop a list of priority pesticides "that have been deemed to be of greatest concern and warrant heightened attention, planning, and support to expedite their replacement and eventual elimination" (DPR, 2023). These determinations will be based on the various ways that pesticides are currently characterized, such as by toxicity, **restricted use**, classification as a **toxic air contaminant** or carcinogen, potential as ground water contaminants, and availability of viable alternatives. This list will be used to prioritize a possible phaseout of the most hazardous pesticides to meet the SPM Roadmap's 2050 goals. A potential future tiering of the mill assessment could help to educate users and manufacturers while also serving as a policy signal to incentivize the development and use of safer pest management tools and practices (DPR, 2024). Assembly Bill 2113 (Garcia, 2024) sets new mill assessment rates; defines SPM as a holistic approach integrating environmental, social, and economic priorities; and encourages its adoption throughout California's agricultural and urban pest management systems.

Procurement policies

Public procurement—that is, the purchase of commodities with particular attributes by federal, state, or county governments or related agencies—represents another viable strategy for encouraging increased use of 1,3-D and chloropicrin fumigant alternatives. Originally implemented in school lunch programs, this approach has spread to colleges and universities, corporate campuses, government agencies, and hospitals (Warsaw and Morales, 2022). Motivated by concerns about the ecological and economic challenges impacting agriculture, these institutions are intentionally purchasing regional, ecologically sustainable, fresh, and healthy food items from suppliers to help drive systemic change in the food system (Thottathil, 2022). This strategy could similarly be applied to encourage adoption of alternatives to specific chemical fumigants. Some studies have examined the impact of public procurement policies on the adoption and expansion of organic production practices outside the U.S., providing insights for designing and implementing procurement policies to influence pesticide use domestically. For example, Altieri and Nicholls (2012) evaluated Brazil's Food Acquisition Program (PAA), aimed at increasing the number of family farms producing organically and scaling up of organic production in several municipalities in Brazil. They found that the program yielded mixed results due to the small scale of the purchasing entity. In contrast, Lindstrom et al. (2020) found that Sweden's Green Public Procurement (GPP) policy successfully increased the amount of land used for organic agriculture. The policy directed the public sector to increase the share of organic food procured to 25% by 2010, and 60% by 2030 (Goodhue et al., 2022).

In the U.S., successful procurement programs include the Farmers Market Nutrition Incentive (FMNI), part of the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC). Administered by state agencies, FMNI provides WIC participants with additional funds beyond their regular benefits to purchase food from farmers markets and roadside stands (Goodhue et al., 2022). Another notable U.S. program is Farm to School (F2S), which focuses on buying and serving locally sourced food in schools. F2S programs often incorporate creating and running a school garden for hands-on learning and providing gardening and nutrition education (Goodhue et al., 2022).

The University of California's five hospitals launched a farm-to-hospital sustainable food procurement program in 2009 with the goal of sourcing 20% of their food purchases by 2020 through sustainable programs. Their criteria recognize 21 different certification or specific attribute programs, including USDA Organic and Food Alliance Certified, which incorporate best practices that could include use of alternatives to 1,3-D and chloropicrin. By 2020, the hospitals had spent $7.7 million on food and beverages meeting these criteria, accounting for about 21% of their total food and beverage budget (Thottathil, 2022). They also committed to increase their sustainable food procurement goals for the UC Health Systems to 30% by 2030 (Thottathil, 2022).

According to Goodhue et al. (2022), the effectiveness of public procurement programs in achieving environmental goals depends on market characteristics. Programs may be more successful if the government entity is a relatively large buyer, the supply of the agricultural products is elastic, and private demand of the good is inelastic (Lundberg et al., 2016; Marron, 1997). Building on these examples and the SPM Roadmap, California could develop purchasing criteria to identify and validate agricultural products grown in accordance with the new SPM standards. These criteria could include the exclusion of certain fumigants, such as 1,3-D and chloropicrin, which may be designated as "Priority Pesticides" by a DPR-sponsored workgroup by 2025. According to the SPM Roadmap, the use of such pesticides should be reduced by 2050 (DPR, 2023). The state could then expand procurement efforts through state-owned or state-run institutions, including public universities and colleges, and incorporate programs such as school meal reimbursement and other initiatives. The Department of General Services would need to work together with the California Environmental Protection Agency (CalEPA), DPR, CDFA, and other relevant state agencies to institutionalize and incentivize the purchasing of what could be termed **SPM**-certified products within its own procurement processes. The state could mandate SPM and California-grown state procurement requirements by offering California growers enhanced bid preferences. For instance, the "California Grown" bid preference could be raised from the current 5%, while California growers practicing SPM could receive an even higher bid preference over non-California grown bids on institutional contracts (DPR, 2023).

Land use programs

In addition to leveraging procurement policies to promote increased adoption of alternatives to 1,3-D and chloropicrin fumigants, the state could use land it owns or leases—such as Caltrans-managed highways, UC and CSU lands, and state parks—to demonstrate the costs, benefits, and feasibility of these alternatives. The UC Agriculture and Natural Resources (UC ANR) research and extension system could support this initiative through its statewide programs or county-based advisors, or both. Other state agencies, such as the California Coastal Commission, could also play a role by promoting the use of fumigant alternatives, including encouraging organic farming as part of its commitment to sustaining agricultural operations within three miles of the coast.

As noted in ***Section 4.2***, high land prices and related land ownership challenges, along with urban and suburban development pressures, are structural barriers to adopting alternatives to pre-plant fumigants such as 1,3-D and chloropicrin. Various public and private agricultural easement programs could be deployed to protect farmland from development, reduce taxes, and provide financial support to continue farming while transitioning to fumigant alternatives. These legal tools establish perpetual land use agreements that preserve future agricultural viability by limiting incompatible activities. Since the 1990s, agricultural conservation easements have protected millions of acres of land. Many of these donations were supported by federal tax incentives under Section 170(h) of the Internal Revenue Code (Phelps, 2019). Between 2017 and 2022, California growers received $29 million for establishing agricultural easements, the fourth-highest amount in the nation. In addition to federal programs like the Agricultural Conservation Easement Program (ACEP), California has the Williamson Act, also known as the California Land Conservation Act of 1965. This program allows local governments to contract with private landowners to restrict specific parcels of land to agricultural or related open space use. In return, landowners receive significantly reduced property tax assessments, which may help growers offset the costs of fumigant alternatives.

Market incentives

Many market-based solutions could be expanded to encourage the adoption and use of alternatives to fumigating with 1,3-D and chloropicrin. For example, certified organic crop production offers growers a price premium, reflecting consumer demand for products that align with their personal environmental and health values. This premium provides an economic incentive to growers to adopt practices that exclude certain chemicals. Organic acreage and value have increased significantly year over year in recent history (CDFA 2022). While still a small percentage of total California farm acreage—9% or 2.13 million acres out of 24.2 million acres—organic acreage was valued at $14.0 billion in 2021, up 16.4% from $12 billion in 2020 (CDFA, 2022).

Organic certification is overseen by the USDA National Organic Standards Board in partnership with state agencies and non-profit certifiers. Organic certification includes a three-year transition period and imposes restrictions on chemical inputs related to fertility and pest management, including prohibition of any, and all, pre-plant chemical fumigants (USDA, 2024a). Certified organic production also requires creation of an **organic system plan (OSP)**, which outlines farming, handling, and processing practices to ensure compliance with organic standards. The OSP must include information on crops, animals, harvests, sales, records, soil-building practices, pest management, health care, pasture, and any other practices related to organic production (USDA, 2024b). Allowed farming practices include some of the fumigant alternatives discussed in the previous chapters, such as crop rotations, resistant varieties, cover crops and compost, and increasing on-farm biodiversity.

It is important to note that organic premiums can only be sustained while organic produce remains a relatively small share of the market. Additionally, the scarcity of land available for growing organic food leads to higher land values, thereby eroding the economic benefits of organic premiums for growers (Guthman, 2004). To address these challenges, the USDA recently allocated $100 million to the Transition to Organic Partnership Program (TOPP), administered by the Agricultural Marketing Services (AMS) (USDA AMS, 2024). This program provided $16 million to California nonprofits that support growers transitioning to organic production. These funds could be directed toward growers currently using fumigants, providing financial and technical support for their transition to organic production.

In addition to organic certification, there are sustainable certification programs, and more recently regenerative certification programs, some of which are already identified in the marketplace by labels. These programs can be evaluated for their treatment of pre-plant soil fumigation practices and whether they encourage use of alternative practices to 1,3-D and chloropicrin fumigant use (Broome and Warner, 2008; DPR, 2023).

Financial institutions and their lending mechanisms, such as agricultural loans, could be evaluated to determine whether they include alternatives to specific fumigants as eligible expenses under program rules. In addition, the USDA Farm Service Agency (FSA) offers a variety of loans for equipment purchases and farm inputs like cover crop seeds, and provides a Loan Assistance Tool to determine eligibility for FSA loans (USDA FSA, 2024).

Marketing cooperatives, companies, and handlers can promote sustainable farming practices through their contracts with growers. For example, they could offer higher prices to growers who use sustainable alternatives to fumigants. Companies like Driscoll's, Inc., Robert Mondavi, and GALLO Wineries or cooperatives like Blue Diamond Growers could take steps to reduce or eliminate pre-plant fumigation with certain chemicals by supporting their growers through research, extension services, demonstrations, and subsidizing non-fumigant production systems. Such initiatives could become more feasible if a growing number of consumers express a preference for food grown without the use of fumigants.

Driscoll's, Inc., drawing on more than 10 years of experience in the European Union and in the United Kingdom with substrate farming for cane berries (e.g., raspberries), blueberries, and tabletop strawberries, chose to subsidize an alternative production system in California that eliminates pre-plant fumigation. The company invested in 15–20 acres of substrate demonstration farms in the Pajaro Valley and Ventura County, providing infrastructure such as macro-tunnels, tabletops, pots, irrigation, substrate media, water recirculation systems, and trellis systems. Growers were invited to "learn by doing" by farming using these subsidized, fumigant-free systems (Broome, pers. observation). This investment was primarily driven by the documented 30% increase in farm labor efficiency and higher yields associated with these production systems, with the elimination of soil fumigation as a secondary benefit (Lieten, 2013).

Regulatory processes

DPR could speed up adoption of fumigant alternatives by improving the efficiency of its pesticide registration process. Currently, alternative products often face delays due to the slowness of the state regulatory process. In California, registering new products can take an additional 1–2 years after the U.S. EPA has granted registration (DPR, 2024). While DPR and the U.S. EPA try to conduct parallel reviews of pesticide safety and effectiveness data to streamline approvals, the delays persist. However, the newly implemented mill assessment funding presents an opportunity to allocate resources toward making the registration process faster and more efficient. While speeding up registration will be helpful, DPR's requirement that pest control effectiveness be shown for products remains an important priority, even if it slows the approval timeline. Unlike the U.S. EPA, which does not require effectiveness data for registration, DPR's approach helps growers to have confidence in new products, particularly those intended as 1,3-D and chloropicrin fumigant alternatives (Zhang et al., 2018).

Research and funding

As outlined in Chapter 3, further research is needed to develop new alternatives to the pre-plant soil chemical fumigants 1,3-D and chloropicrin; optimize existing alternatives;

and integrate multiple strategies such as the use of resistant varieties, disease-suppressive crop rotations, organic amendments, reduced rates or novel application methods for chemical fumigants, innovative fumigant emission control methods, and clean nursery stock to achieve effectiveness comparable to current fumigants (Chellemi et al., 2016; Shen et al., 2016).

In addition to researching the integration of multiple tactics to control soilborne pests within intensive monoculture production systems, some researchers have called for a greater focus on **agroecology** to guide development of alternative farming systems. These systems aim to mimic natural ecosystems and emphasize greater crop diversification over time—such as rotating pathogen-suppressive crops—and in space, through practices such as cover crops in furrows, intercropping, and field-edge plantings like hedgerows (Ewert et al., 2023). These diversification practices can follow pre-plant soil treatments (ASD, biosolarization, steam soil disinfestation) in fields with known pathogens issues, along with the use of resistant rootstocks.

These **integrated pest management** or **agroecological** systems will likely need to be tailored to specific commodities and regions (e.g., strawberries on the Central Coast and almonds in the Central Valley). Their development should include collaboration with the relevant commodity boards and their research programs, as well as federal USDA and National Institute of Food and Agriculture (NIFA) specialty crops and pest management grants, and grant programs for alternatives to methyl bromide. California state grant programs, including those from DPR, CDFA, and the California Air Resources Board (CARB), should also be engaged. DPR's SPM Roadmap recommends using the pesticide mill assessment to expand funding for pest management research and alliance grants by several million dollars each year (DPR, 2024).

Additional research will also be needed as global climate change-induced weather extremes—such as heat waves, drought, and flooding—are expected to increase the prevalence and impact of weeds, pests, and diseases (Yang et al., 2024).

However, research alone is not enough. Although substantial funding has been allocated for fumigant alternative research, such as $104 million across 131 projects through the USDA Methyl Bromide Transition Program as of 2024 (up from $47.3 million across 122 projects in 2020) (Holmes et al., 2020; USDA NIFA, 2024), broader efforts are needed. Supporting the agricultural community in adopting more sustainable practices will require high-level organizational changes, including research, incentives, and more stringent regulatory limits on fumigant use.

Section 4.4: Disseminating information to potential users

As mentioned earlier, the most effective approaches to controlling soilborne pathogens, pests, and weeds likely involve a combination of methods. This underscores the critical role of public technology transfer programs, as implementing multiple tactics will require public research and extension efforts to develop and demonstrate their value, in collaboration with private technology companies and consultants and other stakeholders.

Disseminating information on fumigant alternatives is best accomplished through a range of agricultural information exchange methods, including meetings, online guidelines and decision support tools, field days, manuals, peer-reviewed publications, farm visits, and social media (Lamichhane, 2017; Rosskopf et al., 2024; Warner, 2006). Outreach should include commodity boards, grower organizations, nonprofits, and University of California land-grant universities (UC Berkeley, UC Davis, UC Merced, UC Riverside, and UC Santa Cruz), as well as the statewide ANR programs, such as UC Integrated Pest Management (IPM) and UC Sustainable Agriculture Research and Education Program (SAREP), the Small Farms network, and farm advisors. Programs like UC Davis's strawberry breeding program serve as a model for developing and extending resistant crop varieties (Lamichhane, 2017; UC Davis, 2024). The CSU campuses—including Cal Poly San Luis Obispo, Cal Poly Pomona, Chico, and Fresno—and community colleges should also be engaged. Many of these institutions have agricultural technology transfer programs that can foster innovation in chemical, biological, and mechanical engineering alternatives to pre-plant soil fumigation with 1,3-D and chloropicrin.

There are online tools to help growers and consultants choose the best alternatives to pre-plant chemical fumigants, such as the UC IPM's pest management guidelines, as well as interactive decision-support tools. One such tool is being developed to help growers and consultants select best pre-plant chemical fumigant alternatives based on the crop, target pests, and region (J. Farrar, pers. comm, 10/2024). Modeled after the chloropyrifos insecticide decision-support tool (Regents of the University of California, 2015), it should be helpful in extending the information compiled in this report. There are also private software companies, such as Agrian (TELUS Agronomy, 2024), that provide platforms to assist with agricultural chemical use decisions.

Crop consultants affiliated with pesticide distributor organizations such as the California Association of Pesticide Advisers (CAPCA), Pesticide Applicators Professional Association (PAPA), and Certified Crop Adviser (CCA), along with independent pest control advisers such as the American Association of Applied Insect Ecologists (AAIE) and organic nonprofits such as the Ecological Farming Association (Ecofarm), California Certified Organic Farmers (CCOF), and Organic Farming Research Foundation (OFRF), regularly organize meetings to share updates on regulations, applied research results, and practical experiences with pest management and organic farming in California. These meetings often feature hands-on trade shows and product displays showcasing tools and services.

Many growers greatly value learning from other growers and consultants rather than websites, published manuals, or researchers (Warner, 2006). Programs like the Biologically Integrated Farming Systems (BIFS), now administered by CDFA, encourage "farmer-to-farmer" information exchange through on-farm demonstrations and innovative farmer leaders to increase adoption of pre-plant fumigant alternatives. Farmer leaders have successful agroecological operations from which other farmers could learn (Warner, 2006). These projects also include researchers who work closely with grower innovators to investigate and document pest management alternatives. Nonprofit grower organizations such as the Community Alliance with Family Farmers (CAFF) and California Certified Organic Farmers (CCOF) also have grower members who are likely interested in fumigant alternatives.

Researchers and extension agents could benefit from additional training in outreach and education strategies to help growers understand and adopt farming systems that do not rely on pre-plant fumigation. These efforts should include setting realistic expectations, emphasizing that alternatives are not direct, one-to-one replacements for fumigants. According to the 2023 SPM Roadmap, training pest control advisers in sustainable pest management strategies and ensuring they have access to relevant information are critical steps toward broader adoption of sustainable pest management practices.

> 106. **FINDING:** A variety of strategies could be deployed to increase the adoption of fumigant alternatives, including regulatory actions, incentive-based programs, additional research, and educational programs.

> 107. **FINDING:** Numerous policy tools could encourage growers to adopt alternatives to pre-plant soil fumigation with 1,3-D and chloropicrin. These include federal and state financial incentives programs; taxes such as the pesticide mill assessment; private and public loans; and public procurement of produce grown using fumigant alternatives. Support for transitioning to organics or other certification programs might further promote grower adoption of fumigant alternatives within market limits.

> 108. **FINDING:** The 2023 Sustainable Pest Management Roadmap may classify fumigants as “Priority Pesticides”—those containing active ingredients likely to cause or known to cause significant or widespread human and ecological impacts.

> 109. **CONCLUSION:** Building on the goals and priorities outlined in Assembly Bill 2113, along with guidance from the 2023 Sustainable Pest Management Roadmap and additional resources from the pesticide mill assessment, DPR could consider advancing a combination of these policies. Engaging a broad range of stakeholders would be essential to ensure alignment with these objectives, promote understanding, improve implementation, and maximize the impact of future programs.

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Appendix A. Glossary

70-year lifetime cancer risk: A measure used in toxicology and public health to estimate the additional probability of an individual developing cancer over a typical human lifetime, assumed to be 70 years, specifically due to exposure to a particular carcinogenic substance. This estimate is separate from the baseline risk of cancer from other causes, but instead focuses on the increased risk from exposure to a single chemical. In regulatory contexts, such as evaluating the safety of pesticides and fumigants, the 70-year lifetime cancer risk helps determine acceptable exposure limits to protect public health, aiming to keep the risk as low as reasonably achievable. ***20***

72-hour acute risk: A measure used in environmental and public health contexts to assess the potential acute risks of exposure to a toxic substance over a short period of time. The focus on acute exposure is potential health effects that might arise almost immediately or within a short time frame after exposure. ***20***

Acute: A human exposure to a compound or condition that occurs over a short period of time. ***20, 163***

Agricultural subsidies: Payments or other forms of support provided by the government to farmers and agribusinesses. Their purpose is to support and stabilize the agricultural sector, ensure food security, protect domestic producers, and maintain a thriving agricultural economy. ***240***

Agroecology: An approach to agriculture that integrates ecological principles and social considerations to create sustainable and resilient farming systems. It emphasizes biodiversity, soil health, and the use of natural processes to manage pests and improve crop production, often reducing the need for synthetic inputs like fumigants. ***169, 246***

Anaerobic soil disinfestation: A soil treatment method that combines the use of organic matter (such as plant residues, molasses, or wheat bran) with solar heat to improve soil health and manage soil-borne pests. The process involves incorporating organic matter into the soil, which is then covered with plastic tarps to trap heat from the sun. This increased temperature and moisture promote the decomposition of the organic material, releasing bioactive compounds that can suppress soil pathogens and weed seeds. “Biosolarization” and “anaerobic soil disinfestation” are often used interchangeably, although as originally conceptualized, biosolarization used clear tarps, while anaerobic soil disinfestation used opaque ones. ***41, 116, 200***

Biocidal: A substance or product that can kill or inhibit the growth of harmful organisms—including bacteria, fungi, insects, nematodes, and weeds—through chemical or biological action. Examples include disinfectants, pest control products, and preservatives. ***106, 197***

Biopesticide: A pest-inactivating compound obtained from biological material or produced through biological action, such as fermentation, or an organism that directly inhibits or antagonizes pests. ***98, 201***

Biosolarization: A soil treatment method that combines the use of organic matter (such as plant residues, molasses, or wheat bran) with solar heat to improve soil health and manage soil-borne pests. The process involves incorporating organic matter into the soil, which is then covered with plastic tarps to trap heat from the sun. This increased temperature and moisture promote the decomposition of the organic material, releasing bioactive compounds that can suppress soil pathogens and weed seeds. “Biosolarization” and “anaerobic soil disinfestation” are often used interchangeably, although as originally conceptualized, biosolarization used clear tarps, while anaerobic soil disinfestation used opaque ones. ***41, 116, 200***

Broadcast: A mode of soil pesticide delivery that treats the entire field as opposed to only treating rows or beds. ***31, 134***

Canker: A plant disease caused by various fungi and bacteria primarily affects woody species. Symptoms include sunken, swollen, flattened, cracked, discolored, or dead areas on the stems (canes), twigs, limbs, or trunk. ***28***

Chemigation: A method to deliver pesticides into soil by creating a water-based solution and distributing via an irrigation system. ***31, 134, 200***

Chlorotic: A plant with leaves that have yellowed or become pale due to insufficient chlorophyll. Chlorosis can result from various factors, including nutrient deficiencies, root damage, pest infestations, diseases, or environmental stress. ***26***

Chronic: A human exposure to a compound or condition that occurs over a sustained period of time. One way that the California Department of Pesticide Regulation assesses chronic exposure to nonoccupational bystanders is via long-term ambient air sampling. ***20, 166***

Critical Use Exemption (CUE): A mechanism to permit use of pesticides that would otherwise be prohibited by the Montreal Protocol. CUEs are issued when there are no technically or economically feasible alternatives available and when the lack of the product could lead to significant economic disruption or harm. ***43***

Deskilling: The process by which jobs or tasks that once required specialized skills and expertise are simplified or automated. In the context of agriculture, the ease with which fumigants are used could reduce the need for workers with more specialized knowledge in pest control or crop management. ***239***

Diversified farming: Agricultural practices and landscapes designed to incorporate functional biodiversity at multiple spatial and temporal scales. These systems aim to enhance ecosystem services—such as soil fertility, pest and disease regulation, water use efficiency, and pollination—thereby supporting sustainable and resilient food production. ***157, 242***

Edema: Swelling; occurs when fluid accumulates in the tissues. Edema can occur in various parts of the body, including the legs, ankles, feet, or lungs. ***57, 61***

Emphysema: a progressive chronic lung condition characterized by damage to the small air sacs in the lungs, known as alveoli. When these alveoli become damaged or destroyed, they can rupture, leading to the formation of larger air pockets instead of numerous small ones. This damage causes air to become trapped in the affected areas, impairing the lungs' ability to effectively move oxygen throughout the body. ***57***

Endoparasite: A parasite that lives inside its host organism. In agriculture, common endoparasites include nematodes and certain insect larvae. ***25***

Exposure science: A multidisciplinary field that brings together expertise from risk assessment, epidemiology, public health, toxicology, environmental chemistry, public policy, and engineering to determine how harmful agents in the environment impact people, communities, and public health. ***66***

Flash point: Flash points are one characteristic used to describe the flammability risk of chemical substances. Flash points are the lowest temperature at which a chemical can vaporize into an ignitable mixture in air. The lower the temperature, the lower the flammability risk. ***18***

Functional biodiversity: The range and abundance of organisms in an ecosystem that perform essential ecological roles, such as pollination, pest control, nutrient cycling, and soil formation. This concept emphasizes the functions and services that organisms provide to maintain ecosystem health and productivity, rather than focusing solely on species numbers or diversity. ***207***

Gall / galling: An abnormal growth on a plant caused by excessive cell proliferation, which can be caused by infection or colonization by certain pests. Galling is the process of gall formation. Root galling, in particular, refers to galls that form on plant roots, often due to nematode infestations, and can significantly affect nutrient and water absorption. ***28, 107***

Genotoxicity: The ability of a substance to damage genetic material inside a cell, leading to mutations, cancer, or other genetic defects. Genotoxic substances can cause changes to the DNA, which may result in chromosomal fragmentation, mutations, or the inhibition of DNA repair mechanisms. Not all genotoxic substances are carcinogenetic (i.e., cancer-causing). ***22***

Global warming potential (GWP): A measurement that compares how much heat a greenhouse gas traps in the atmosphere relative to carbon dioxide over a specific time period (typically 100 years). The GWP is used to assess the relative impact of different greenhouse gases on climate change. CO_2 has a GWP of 1, serving as the baseline, while other gases are rated based on their ability to trap heat. For example, methane (CH_4) has a GWP of 25, meaning it is 25 times more effective at trapping heat than CO_2 over 100 years. ***160***

Hazardous air pollutant (HAP): A toxic airborne substance that can harm human health or the environment. These pollutants can cause serious diseases including cancer, respiratory illness, and birth defects when people are exposed to them. HAPs are regulated by the U.S. Environmental Protection Agency under the Clean Air Act. HAPs are subject to regulations to limit their release into the air to protect public health and air quality. ***20***

Integrated pest management: A holistic approach to pest control that combines multiple strategies to manage pests effectively while minimizing environmental and human health risks. IPM integrates biological, cultural, physical, and chemical methods, such as crop rotation, biological predators, habitat manipulation, and selective pesticide use. ***17, 248***

Labile: The attribute of being readily transformed, often used to describe materials that can be chemically or biologically transformed into other compounds. Labile carbon sources are readily available for microbial activity and can rapidly release nutrients. ***69, 116***

Lacrimator: An agent that irritates the eyes, causing excessive secretion of tears. ***21***

Margins of exposure: A risk assessment metric used to evaluate the safety of chemical exposures, including fumigants. MOE is the ratio of the no-observed-adverse-effect level (NOAEL) obtained from animal toxicology studies to the predicted or estimated human exposure level or dose. ***60, 61***

Meta review: A type of review article that synthesizes and analyzes the findings from multiple existing systematic reviews or meta-analyses on a specific topic. Unlike traditional review articles that summarize individual studies, a meta-review focuses on aggregating the results of previous reviews, critically evaluating their methodologies, and identifying patterns or discrepancies across the reviewed evidence. ***118***

Meta-analysis: A statistical technique used to combine and synthesize data from multiple independent studies on the same research question. The goal of a meta-analysis is to provide a more precise and comprehensive estimate of the effect of a treatment, intervention, or relationship between variables by pooling the results of studies that have similar research designs and methodologies. ***118, 214***

Nematodes: Microscopic, worm-like organisms commonly found in soil. They are classified into feeding groups based on consumption of bacteria, fungi, plants, other nematodes, or a mixture of these or other materials. Plant-feeding nematodes, also known as phytoparasitic nematodes, can be harmful to crops. ***22, 23, 103, 197***

No Significant Risk Level (NSRL): A regulatory threshold established under California's Proposition 65. NSRLs are the maximum level of chemical exposure that poses no significant risk of causing cancer in humans (i.e., would cause no more than one case of cancer out of every 100,000 individuals exposed to the chemical over a 70-year period). ***40***

Oomycete: A fungus-like organisms belonging to the kingdom *Stramenopila*, often referred to as water molds. Though they resemble fungi, their evolutionary origins are closer to that of algae. Oomycetes are plant pathogens that can cause significant crop diseases. Common examples include Phytophthora species (e.g., *Phytophthora infestans,* which causes late blight in tomatoes and potatoes) and Pythium species, which cause root rot. ***21, 23, 118, 153***

Organic system plan (OSP): A detailed document that farmers and processors must submit to become certified organic. This plan outlines all aspects of their operation—from seed sources and soil management to pest control and product handling—demonstrating how they will meet organic standards. ***240, 246***

Ozone: A highly reactive gas made up of three oxygen atoms (O_3), occurring both naturally and as a result of human activities. Ozone exists in two layers in the atmosphere: in the stratosphere, ozone helps to absorb and protect organisms from ultraviolet rays; ground-level ozone is a harmful air pollutant that is created when volatile organic compounds interact with nitrogen oxides in the presence of sunlight. Ground level ozone is major component of smog. ***16, 20, 205***

Permissible exposure limits (PELs): PELs indicate the average concentration of a chemical that workers can be exposed to during an 8-hour workday, 5 days a week, throughout their lifetime without experiencing harmful effects. PELs are enforceable legal standards of exposure established by the Occupational Safety and Health Administration (OSHA). ***57***

Pest pressure: With regards to soil pests, pest pressure refers to the presence and abundance of specific deleterious organisms in the soil, which affect the level of crop disease or magnitude of competition with crops. ***146***

Phytotoxicity: The ability of a chemical substance, such as pesticide or fumigant, to cause damage to plants. Phytotoxicity in soils can occur immediately following certain treatments to control pests. Symptoms include leaf burn, chlorosis, stunted growth, and reduced yield. ***32, 115, 167, 200, 238***

Registrant: Registrants are those that submit a request to distribute their product to the California Department of Pesticide Regulation. Registrants are not necessarily the manufacturers of the products. ***22***

Restricted use pesticide: Restricted use pesticides (RUPs) are not available for purchase or use by the general public. These products can potentially cause significant harm to the environment and pose risks of injury to applicators or bystanders if used without additional precautions. The “Restricted Use” classification is designated by the U.S. Environmental Protection Agency and limits the use of a product to certified applicators or individuals working under the direct supervision of a certified applicator. ***19, 243***

Saprophytes: Organisms, such as fungi, bacteria, or certain plants, that obtain nutrients by decomposing dead and decaying organic matter, including plant and animal remains. ***70***

Scion: The upper part of a grafted plant, typically a stem or bud, that is attached to a rootstock to grow as a single plant. The scion determines the characteristics of the above-ground portion, including fruit quality, flower type, and overall growth habit, while the rootstock provides the root system and often imparts disease resistance, drought tolerance, or improved nutrient uptake. ***143***

Screening level: A health-based reference concentration to evaluate the safety of air quality. It represents a threshold below which no significant health risks are expected. The California Department of Pesticide Regulation sets screening levels for different exposure durations, including acute, sub-chronic, chronic, and lifetime. ***60***

Shippers: In the context of agriculture, shippers refer to individuals or companies responsible for transporting goods from farms or production facilities to markets, distributors, or retailers. Shippers play a critical role in the supply chain, ensuring that products reach their destinations safely and efficiently. ***236***

Solarization: A soil treatment method that uses the sun's heat to manage soil-borne pests, weeds, and pathogens. The process involves covering moist soil with clear plastic sheets for several weeks, typically during the hottest part of the year. The solar energy trapped under the plastic increases the soil temperature, effectively "cooking" the soil and killing pests, weed seeds, fungi, and bacteria. In contrast to biosolarization and anaerobic soil disinfestation, no organic amendments are added to the soil, and the primary inactivation mechanism is heat. ***125, 200***

Specific heat capacity: The amount of heat energy required to raise the temperature of a given quantity of a substance by one degree Celsius (typically expressed in joules per gram per degree Celsius). ***125***

Sustainable pest management (SPM): Builds upon principles of integrated pest management but with a broader focus on the three pillars of sustainability: human health and social equity, environmental protection, and economic vitality. SPM aims to reduce pesticide dependency as much as possible and emphasizes resilience against pest pressures in the context of climate change and other environmental stressors. ***240, 241, 244***

Threshold limit values (TLVs): TLVs represent the maximum average airborne concentration of a hazardous material to which healthy adult workers can be exposed during an 8-hour workday and a 40-hour workweek over a working lifetime without experiencing significant adverse health effects. TLVs are developed by the American Conference of Governmental Hygienists. ***57***

Tissue culture meristem shoot tip propagation: A laboratory technique used to produce virus-free plants by isolating and growing the tiny, actively dividing cells at the tip of a plant shoot (meristem). Since meristems are often free of viruses, this method allows for the cultivation of clean, disease-free plants under sterile conditions. It is commonly used in agriculture to maintain healthy stock for propagation. ***35***

Toxic air contaminant: An air pollutant that may increase mortality or serious illness, thus posing a potential hazard to human health. The state of California maintains a list of toxic air contaminants for which efforts must be made to mitigate or control emissions. ***20***

Toxicokinetics: The study of how the body processes a chemical over time in relation to the dosage. This involves understanding the processes of absorption, distribution, metabolism, and excretion. Essentially, it provides a mathematical description of how these processes unfold over time. ***58***

Volatile organic compound (VOC): Compounds made of carbon that easily vaporize at room temperature and standard atmospheric pressure. VOCs can be derived from either natural or anthropogenic sources. Under certain atmospheric conditions, they can lead to ground level ozone, a precursor to smog. ***18, 20, 67, 67, 69, 162***

Appendix B. Fumigant Alternative Studies

Table B.1. Select studies provided as examples of the breadth of tested conditions and efficacy results for various fumigant alternatives.

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Abamectin	Biological - biopesticide	*Meloidogyne* spp.	Alexandria, Egypt; cucumber	Laboratory and potted plant trials; abamectin reduced root galling by up to 75% and led to variable positive and negative effects on cucumber growth relative to untreated control.	Yes	Massoud et al., 2023
Root-knot nematode-resistant pepper cultivar (Carolina Wonder), *Burkholderia* spp. strain A396	Biological (resistant cultivar, bionematicide)	*Meloidogyne incognita*	Tifton, Goergia; pepper and squash rotations	Field trial; resistant pepper cultivar reduced nematode levels at harvest more than 1,3-D or chloropicrin but had positive and negative pepper yield effects relative to fumigation that depended on the trial year and fruit size class; bionematicide showed no difference in nematode levels or squash yield compared to 1,3-D and chloropicrin.	n/a	Nnamdi et al., 2022

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Dimethyl disulfide	Chemical (fumigant)	*Meloidogyne* spp., *Fusarium* spp., *Pythium* spp., *Alternaria* spp., *Rhizoctonia solani*, *Olpidium bornovanus*	Murcia, Spain; melons	Greenhouse trial; dimethyl disulfide matched the nematode and root galling reduction of 1,3-D. Effects on fungal pathogens were inconsistent and included both positive and negative changes in abundance.	No	Montiel-Rozas et al., 2019
Allyl isothiocyanate	Chemical (fumigant)	*Meloidogyne incognita*	Tifton, Goergia; pepper and squash rotations	Field trial; allyl isothiocyanate did not suppress nematodes and reduced squash yield compared to 1,3-D+Pic.	No	Nnamdi et al., 2022
Metam potassium	Chemical (fumigant)	*Cyperus rotundus, Fusarium oxysporum* f.sp. *lycopersici*	Wimauma, Florida; no crop tested	Field trial; up to 92% reduction in nutsedge and >90% reduction in *Fusarium* compared to untreated control soils.	Yes	Khatri et al., 2021
Metam potassium	Chemical (fumigant)	*Fusarium oxysporum, Macrophomina phaseolina, Meloidogyne javanica*, various weeds	Wimauma, Florida; no crop tested	Microcosm trial; fumigation showed activity against all pest targets with varying sensitivity. Fungal pathogens were less sensitive than *Meloidogyne javanica*, and complete weed control required the greatest fumigant concentrations.	Yes	Khatri et al., 2021

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Metam sodium	Chemical (fumigant)	*Rhizoctonia solani, Fusarium solani, Fusarium oxysporum, Meloidogyne incognita*	Kazanlı, Turkey; pepper	Greenhouse trial; fumigation reduced disease incidence by 96% and enhanced yield by approximately 250% compared to untreated control soils.	Yes	Yücel et al., 2017
Isothiocyanate compounds	Chemical (fumigant)	*Meloidogyne javanica*	Yangling, Shaanxi, China; no crop tested	Laboratory trial; certain isothiocyanates matched or exceeded the nematode inactivation obtained with metam sodium.	Yes for methylisothiocyanate; no for other isothiocyanates	Wu et al., 2011
Dazomet	Chemical (fumigant)	*Verticillium dahliae, Phytophthora cactorum, Phytophthora fragariae,* total nematodes	East Malling, United Kingdom; strawberry	Field trial; dazomet showed near complete suppression of Verticillium in only one of two trials; dazomet achieved 80 to 85% nematode reduction, which was not as suppressive as fumigation with Pic or MeBr; Phytophthora root rot was decreased with dazomet, Pic, and MeBr; yield increased 28 to 53% over untreated control soils.	Yes	Harris et al., 1991
Dazomet	Chemical (fumigant)	*Meloidogyne incognita*	La Habana, Cuba; cucumber	Field trial; fumigation significantly decreased nematode levels and enhance growth and fruit production compared to untreated control.	Yes	Cuadra et al., 2009

Name	**Control strategy**	**Pest target(s)**	**Location(s) and crop(s) studied**	**Format and efficacy**	**Registered in CA**	**Reference**
Dimethyl disulfide	Chemical (fumigant)	*Meloidogyne* spp., *Fusarium oxysporum* f. sp. *radicis-lycopersici*	Almería, Spain; tomato	Greenhouse trial; fumigation significantly decreased root galling and levels of fungi and nematodes compared to untreated control.	No	Gómez-Tenorio et al., 2018
Oxamyl and fenamiphos	Chemical (non-fumigant nematicides)	*Meloidogyne* spp., *Fusarium* spp., *Pythium* spp., *Alternaria* spp., *Rhizoctonia solani*, *Olpidium bornovanus*	Murcia, Spain; melons	Greenhouse trial; no consistent effect on fungal pathogens relative to untreated control soils. Fenamiphos matched the root galling reduction of 1,3-D in sandy but not clay soil.	Yes for oxamyl. No for fenamiphos	Montiel-Rozas et al., 2019
Fluopyram, oxamyl, fluazaindolizine, aldicarb, bacterial metabolites (burkholderia sp strain a396 cells and fermentation media), fluensulfone	Chemical (non-fumigant nematicides)	*Rotylenchulus reniformis*	St. Joseph, Louisiana; sweetpotatoes	Field trial; fluopyram, oxamyl, and aldicarb were capable of nematode suppression and/or yield increase, but the effects were inconsistent compared to 1,3-D.	Yes for oxamyl, fluopyram, fluensulfone, and bacterial metabolites. No for albicarb and fluazaindolizine	Watson et al., 2023
Fluopyram, oxamyl, fluazaindolizine, fluensulfone	Chemical (non-fumigant nematicides)	*Meloidogyne incognita*	Tifton, Goergia; pepper and squash rotations	Field trial; no difference or negative effect on squash yield relative to 1,3-D or 1,3-D+Pic; no difference in nematode control compared to fumigants.	Yes for oxamyl, fluopyram, and fluensulfone. No for fluazaindolizine	Nnamdi et al., 2022

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Soilless cultivation (coconut coir and perlite)	Cultural	No pests targeted	Mahabad, Iran; strawberry	Greenhouse and field trial; greenhouse-grown strawberries had higher yield, but field-grown berries had enhanced quality and better shelf-life.	n/a	Rahim Doust et al., 2023
Soilless cultivation (varying mixtures of cocopeat, peatmoss, perlite, and tuff)	Cultural	No pests targeted	Amman, Jordan; strawberry	Greenhouse trial; plants in 4:1 cocopeat:perlite showed greatest photosynthesis, transpiration, and fruit firmness while 4:1 peatmoss:perlite had the greatest yield and total phenolics.	n/a	Alsmairat et al., 2018
Soilless cultivation (coir, coir and rice hull, peat and perlite, peat and rice hull)	Cultural	No pests targeted	Santa Maria, California; strawberry	Field trial; growth in coir with irrigation at 200% of evapotranspiration increased yield by approximately 15% compared to field soil.	n/a	Wang et al., 2009

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Crop rotation (cereals; cereal, legume and brassica; cereals and legume)	Cultural	*Pratylenchus neglectus, Pythium* spp.*, Rhizoctonia solani, Pyrenophora tritici-repentis, Fusarium* spp.	Cunderdin, Western Australia; wheat	Field trial; rotations reduced *Pyrenophora* disease incidence by 55 to 85% in 2 of 3 years; rotations sporadically reduced *Rhizoctonia* root rot compared to monoculture; cereal, legume, and brassica rotation showed the greatest control of *Fusarium* spp., and *R. solani* compared to monoculture, but increased *Pythium* levels.	n/a	Flower et al., 2019
Cover cropping (Brassicaceae and Fabaceae crops)	Cultural	*Verticillium dahliae*	Auzeville, France; sunflower	Field trial; radish and purple vetch cover crops decreased incidence of wilt disease for 80 days; 0.77 to 0.9 tons/hectare increase in yield was inconsistently achieved after cover cropping compared to bare soil.	n/a	Ait Kaci Ahmed et al., 2022
Cover cropping (radish, mustard, and rapeseed crops)	Cultural	*Rhizoctonia solani*, *Sclerotium rolfsii*, and *Pythium* spp.	Charleston, South Carolina; pepper	Field trial; cover cropping improved pathogen control and yield compared to solarization or untreated control.	n/a	Hansen and Keinath, 2013

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Cover cropping (*Brassica* crops)	Cultural	*Meloidogyne javanica*	Wagga Wagga, Australia; grapes	Field trial; incorporation of cover crops resulted in suppression of soil nematodes comparable to oxamyl nematicide control, representing 75% reduction; suppresion of nematodes on roots did not match the oxamyl control; yield increased by 100% compared to untreated control and was similar to result obtained from oxamyl nematicide.	n/a	Rahman et al., 2011
Crop rotation (wheat and lupin)	Cultural	*Pratylenchus* spp., *Paratylenchus* spp.	Wagga Wagga, Australia; no crop target	Field trial; crop rotation significant decreased parasitic nematode levels compared to monoculture, and the effect varied but was up to >99% control.	n/a	Rahman et al., 2007

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Crop rotation, resitant crop, or cover cropping (resistant soybean, grain sorghum, sorghum sudangrass, castor bean)	Cultural	*Meloidogyne* spp., *Pratylenchus* spp.	Dorchester County, Maryland; cucumber	Field trial; no treatments consistently resulted in complete nematode suppression, all treatments matched the performance of fumigation with 1,3-D for the majority of time points; yield for all rotation and cover cropped treatments matched that achieved with fumigation with 1,3-D.	n/a	Kratochvil et al., 2004
Crop rotation (cotton and grains)	Cultural	*Verticillium dahliae*	Lubbock, Texas; cotton	Field trial; rotation improved disease control and yield for first 4 years, but effects diminished in the following years	n/a	Wheeler et al., 2019
Crop rotation (eggplant and broccoli)	Cultural	*Verticillium dahliae*	Isesaki, Japan; eggplant	Field trial; rotation decreased eggplant disease incidence by 53%.	n/a	Ikeda et al., 2015
Crop rotation (cauliflower and broccoli)	Cultural	*Verticillium dahliae*	Salinas, California; cauliflower	Field trial; rotation decreased Verticillium propagules in soil and decreased disease incidence by approximately 50% compared to monoculture; cover cropping did not match the control delivered by fumigation with MeBr and Pic.	n/a	Xiao et al., 1998

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Crop rotation (strawberry and broccoli or lettuce)	Cultural	*Verticillium dahliae, Pythium* sp.	Watsonville, California; strawberry	Field trial; rotation with broccoli, but not lettuce, decreased disease incidence; in one of two years, rotation with broccoli improved yield over rotation with lettuce and matched yields following fumigation with MeBr and Pic.	n/a	Njoroge et al., 2009
Crop rotation (strawberry and pepper or tomato)	Cultural	*F. oxysporum* f. sp. *Fragariae*	Crawley, Australia; strawberry	Potted plant trial; both rotations reduced disease severity compared to monoculture, with tomato rotation providing the greatest reduction.	n/a	Fang et al., 2012
Soil amendment with tilapia fish powder and plant growth-promoting rhizobacteria	Integrated - biopesticides and plant growth promoting bacteria	*Meloidogyne incognita, Tylenchulus semipenterans*	Sharqia Governorate, Egypt; cucumbers and navel oranges	Laboratory, greenhouse, and field trials; fish powder and inoculum combined increased early cucumber growth and reduced root galling by 81% compared to untreated control; powder and inoculum combined increased orange weight up to 9.9% and partially suppressed *T. semipenterans* compared to untreated control.	n/a	El-Ashry et al., 2023

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Dazomet and *Purpureocillium lilacinum*	Integrated - chemical (fumigant) and biological (biocontrol)	*Meloidogyne incognita*	Beijing, China; tomato	Microcosm trial; dazomet pretreatment of soil enhanced the activity of the biocontrol agent and resulted in near complete elimination of nematodes from roots.	Yes for dazomet	Nie et al., 2023
Solarization and cover cropping	Integrated - thermal and biological	*Mesocriconema* sp.; *Meloidogyne* spp.	Marion Co., Florida; peppers	Field trial; cowpea cover cropping followed by solarization was as effective as MeBr fumigation.	n/a	Saha et al., 2007
Anaerobic soil disinfestation with rice bran, mustard seed meal, and fish emulsion amendments	Integrated - thermal and biological	*Verticillium dahliae*	Castroville, Watsonville, and Santa Maria, California; strawberries	Field trials; viable pathogens were reduced by 80 to 100% across all disinfestation treatments; anaerobic soil disinfestation improved yield by approximately 65 to 100%, matching the benefits of fumigation with 1,3-D and Pic	n/a	Shennan et al., 2018
Anaerobic soil disinfestation with crude protein amendment	Integrated - thermal and biological	*Globodera pallida*	Wageningen, The Netherlands; no crop target	Microcosm trial; anaerobic soil disinfestation achieved complete nematode inactivation.	n/a	Stremińska et al., 2014

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Anaerobic soil disinfestation with rice bran, rapeseed cake, grape pomace or brewer's spent grain amendments	Integrated - thermal and biological	*Phytophthora nicotianae*	Extremadura, Spain; peppers	Laboratory and field trials; all amendments showed inactivation of *Phytophthora* in lab studies; in field trials, disinfestation with rice bran, rapeseed cake and grape pomace all resulted in approximately 60% reduction of the pathogen.	n/a	Serrano-Pérez et al., 2017
Biosolarization with compost and *Trichoderma asperellum* inoculum	Integrated - thermal and biological	*Rhizoctonia solani*, *Fusarium solani*, *Macrophomina phaseolina*	El-Qalubia governorate, Egypt; strawberries	Microcosm and field trial; biosolarization with biocontrol agent resulted in up to 75% reduction in root rot and up to 160% yield increase compared to untreated control.	n/a	Abd-El-Kareem et al., 2023
Biosolarization with almond hull and shell amendments	Integrated - thermal and biological	*Pratylenchus vulnus, Mesocriconema xenoplax*	Davis, California; almonds	Field trial; nematodes reduced below detection limit; inactivation kinetics exceeded solarization.	n/a	Shea et al., 2022

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Biosolarization with compost or anaerobic digestate amendments	Integrated - thermal and biological	*Brassica nigra, Fusarium oxysporum* f. sp. *lactucae*	Davis, California; no crop target	Field trial; biosolarization increased *B. nigra* inactivation by 12%, but the increase was not significant; biosolarization outperformed solarization for *Fusarium* inactivation, reducing the fungi below the detection limit in the upper 7 cm of soil and achieving >85% reduction at 14-20 cm depth.	n/a	Fernández-Bayo et al., 2018
Biosolarization with wheat + semi-composted manure or sunflower pellet amendment	Integrated - thermal and biological	*Fusarium oxysporum* f. sp. *lactucae*	Campo de Cartagena; lettuce	Field trial; in summer trials, all biosolarization treatments completely eradicated Fusarium in the soil and disease in lettuce; in autumn trials, Fusarium and root disease indices increased with soil depth, and only biosolarization with sunflower pellets maintained complete pathogen inactivation.	n/a	Guerrero et al., 2023
Anaerobic soil disinfestation with fresh pepper plant debris amendment	Integrated - thermal and biological	*Fusarium solani* f. sp. *cucurbitae*	Almería Province, Spain; zucchini squash	Greenhouse trial; biosolarization showed >99% reduction in Fusarium, but was not significantly different from untreated control soils.	n/a	Pérez-Hernández et al., 2017

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Biosolarization with chitin amendment	Integrated - thermal and biological	*Fusarium oxysporum* f. sp. *lactucae*	Davis, California; no crop target	Field and lab trials; both lab and field studies showed that biosolarization with chitin amendment resulted in variable Fusarium inactivation compared to untreated control, but biosolarization generally matched or underperformed compared to solarization.	n/a	Randall et al., 2020
Biosolarization	Integrated - thermal and biological	*Fusarium oxysporum* f. sp. *lactucae*	Davis, California; tomatoes and lettuce	Field trial; reduced Fusarium in soils after biosolarization but results not significant. Lettuce health and yield not significantly different from untreated control.	n/a	Pastrana et al., 2022
Solarization, soil amendment with organic fertilizer and/or vesicular arbuscular mycorrhizal spores	Integrated - thermal and biological	Undeclared	Rosetta City, Al-Behaira Governorate, Egypt; pepper	Field trial; solarization increased yield compared to untreated control soils. The combined effect of solarization, fertilizer and spore amendment resulted in maximum yields.	n/a	Zayed et al., 2013

Name	**Control strategy**	**Pest target(s)**	**Location(s) and crop(s) studied**	**Format and efficacy**	**Registered in CA**	**Reference**
Steam treatment with mustard seed meal amendment	Integrated - thermal and biopesticides	*Pythium ultimum*, various weeds	Salinas, California, and Watsonville, California; strawberry	Field trial; steam and amendment treatment resulted in significant weed reduction compared to untreated control soils; steam showed variable *Phythium* reduction that was sometimes an improvement over untreated control soils; steam increased marketable yield by 18% to 214% compared to untreated control soils.	n/a	Fennimore et al., 2014
Steam treatment with mustard seed meal amendment	Integrated - thermal and biopesticides	Various weeds, *Verticillium dahliae*, *Pythium ultimum*	Salinas, California; strawberry	Field trial; steam and amendment treatment showed complete or near complete inactivation of all target pathogens and weed propagules and was comparable to fumigation with Pic. Steam and amendment showed yield improvements comparable to Pic.	n/a	Kim et al., 2021
Solarization	Thermal	*Meloidogyne incognita*	Spain; olives	Nursery soil trial; solarization inactivated >95% of eggs.	n/a	Nico et al., 2003
Solarization	Thermal	*Pratylenchus vulnus, Mesocriconema xenoplax*	Davis, California; almonds	Field trial; nematodes reduced below detection limit	n/a	Shea et al., 2022

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Solarization	Thermal	*Fusarium oxysporum* f. sp. *lycopersici* and f. sp. *radicis lycopersici*, *Pyrenochaeta lycopersici, Meloidogyne* spp., *Orobanche ramosa*	Catania, Italy; tomato	Greenhouse trial; solarization resulted in greater inactivation of all target pests compared to fumigation with 1,3-D+Pic and improved plant growth and yield compared to fumigation.	n/a	Lombardo et al., 2012
Solarization	Thermal	Undeclared	Saltillo, Coahuila, Mexico; dry beans	Field trial; solarization resulted in a 59% increase in yield compared to untreated control soils.	n/a	Ibarra-Jiménez et al., 2012
Solarization	Thermal	*Meloidogyne javanica*	Metaponto, Southern Italy; tomato, melon	Greenhouse trial; solarization resulted in 79% to 100% inactivation of target nematodes and increased tomato and melon yield by 116% to 368% compared to untreated control soils.	n/a	Candido et al., 2008
Solarization	Thermal	Various annual and perennial weeds	Metaponto, Southern Italy; lettuce	Greenhouse and field trials; solarization generally decreased weed biomass and diversity. Certain weeds were stimulated by solarization. Lettuce yield increased approximately 20% compared to untreated control soils.	n/a	Candido et al., 2011

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Solarization	Thermal	Various weeds	Baton Rouge, Louisiana; lettuce	Field trial; solarization significantly decreased weed pressure and increased lettuce yield compared to untreated control soils.	n/a	Hasing et al., 2004
Solarization	Thermal	*Phytophthora cactorum, Phytophthora citricola, Verticillium dahliae*	Irvine, California; strawberry	Field trial; solarization decreased pathogen levels by 69% to 97% and increased yield by 12% to 28% compared to untreated control soils.	n/a	Hartz et al., 1993
Solarization	Thermal	Various weeds	Virginia Beach, Virginia; strawberry	Field trial; solarization decreased weed density compared to untreated control soils but resulted in lower yield compared to untreated soils and soils fumigated with 1,3-D and Pic.	n/a	Samtani et al., 2017

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Solarization	Thermal	*Phytophthora fragariae* var. *fragariae, Phytophthora fragariae* var. *rubi, Pythium, Rhizoctonia, Cylindrocarpon* spp.	Aurora, Oregon; strawberry; raspberry	Field trial; solarization decreased root disease in raspberries and strawberries compared to untreated control soils. Solarization increased raspberry yield by approximately 600% to 2,900% compared to untreated control soils; yield comparison not performed for strawberries.	n/a	Pinkerton et al., 2002
Solarization	Thermal	Undeclared	Mediterranean coastline in northeast Spain; strawberry	Greenhouse trial; solarization increased yield by 24% compared to untreated control soils.	n/a	Camprubí et al., 2007

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Steam treatment	Thermal	*Pythium ultimum*, *Macrophomina phaseolina*, various weeds	Salinas, California, and Watsonville, California; strawberry	Field trial; steam treatment resulted in significant weed reduction compared to untreated control soils, which was comparable to fumigation with 1,3-D and Pic; steam showed variable *Phythium* reduction that was sometimes an improvement over untreated control soils; steam increased marketable yield by 18% to 214% compared to untreated control soils and was comparable to performance with fumigation.	n/a	Fennimore et al., 2014
Steam treatment	Thermal	Various weeds, *Verticillium dahliae*	Salinas, California; strawberry	Field trial; steam injection resulted in complete or near complete inactivation of target weeds and reduced *Verticillium* similar to fumigation with MeBr and Pic in the upper 15 cm; steam treatment via injection but not surface sheet application improved yield compared to untreated control soils and was similar to fumigation with MeBr and Pic.	n/a	Samtani et al., 2012

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Steam treatment and solarization	Thermal	Various weeds, *Verticillium dahliae*	Salinas, California; strawberry	Field trial; steam and solarization generally resulted in complete or near complete inactivation of target weeds that matched or exceeded fumigation with MeBr and Pic. For steam delivery with pipes (as opposed to injection), steam and solarization reduced *Verticillium* similar to fumigation in the upper 15 cm; solarization with steam treatment via injection or surface sheet application improved yield compared to untreated control soils and was similar to fumigation with MeBr and Pic.	n/a	Samtani et al., 2012
Steam treatment	Thermal	Various weeds, *Verticillium* spp., *Tylenchulus semipenetrans*, *Pythium ultimum*	Macdoel, California; strawberry	Nursery soil trial; steam matched the reduction of weeds, Verticillium spp., *Tylenchulus semipenetrans* Phythium observed with fumigation using MeBr and Pic; stolon and daughter plant density was similar between steam and fumigation treatments.	n/a	Kim et al., 2022

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Steam treatment	Thermal	Various weeds, *Verticillium dahliae*, *Pythium ultimum*	Salinas, California; strawberry	Field trial; steam treatment showed complete or near complete inactivation of all target pathogens and weed propagules and was comparable to fumigation with Pic. Steam showed yield improvements comparable to Pic.	n/a	Kim et al., 2021
Steam treatment	Thermal	Various weeds, *Verticillium dahliae, Fusarium oxysporum, Phytophthora cactorum, Pythium* sp.	Nipomo, California, and Oxnard, California; cut-flowers	Greenhouse and field trials; steam injection generally reduced weed biomass and pathogen levels compared to untreated control soils and often matched or exceeded fumigation with MeBr and Pic.	n/a	Rainbolt et al., 2013
Steam treatment and solarization	Thermal	*Meloidogyne arenaria*	Palm City, Florida; ornamental flowers	Field trial; steam treatment decreased soil levels, but not root associated levels, of *M. arenaria* compared to MeBr fumigation (achieving up to 100% inactivation); steam decreased root galling by up to 95% compared to fumigation; steam improved shoot weight by up to 25% and shoot height by up to 9% compared to fumigation.	n/a	Kokalis-Burelle et al., 2016

Name	Control strategy	Pest target(s)	Location(s) and crop(s) studied	Format and efficacy	Registered in CA	Reference
Steam treatment	Thermal	Various weeds, *Sclerotinia sclerotiorum*, *Pythium* spp.	Salinas, California, and Yuma, Arizona; leafy greens, carrot	Field trial; steam treatment decreased disease frequency in lettuce compared to untreated control soils; steam improved lettuce yield in most trials compared to untreated controls; yield was not significantly improved in spinach and lettuce compared to untreated controls.	n/a	Guerra et al., 2022

Appendix C. Steering Committee Members

The Steering Committee (SC) oversees the report authors, reaches conclusions based on the findings of the authors, drafts recommendations and writes an executive summary.

Full curricula vitae for the SC members are available upon request. Please contact CCST at (916) 492-0996.

Steering Committee Members

- **Gerald J. Holmes, PhD (Chair)**, Strawberry Center, California Polytechnic State University-San Luis Obispo
- **Alan S. Kolok, PhD (Co-Chair)**, University of Idaho
- **Christine L. Carroll, PhD**, California State University, Chico
- **Julie Guthman, PhD**, University of California, Santa Cruz

Gerald J. Holmes

Chair, Steering Committee
Director, Strawberry Center
California Polytechnic State University-San Luis Obispo

Gerald Holmes is the Director of the Strawberry Center at Cal Poly State University in San Luis Obispo, California. The Center is a partnership between Cal Poly and the California Strawberry Commission. Gerald received his Ph.D. in Plant Pathology from UC Riverside in 1994 then worked as a University of California Cooperative Extension Farm Advisor in Imperial County for three years. For the subsequent 12 years he was an Extension Vegetable Pathologist and Associate Professor at North Carolina State University. He then worked six years as Product Development Manager for Valent USA Corporation before becoming Director of the Strawberry Center in 2014.

Alan S. Kolok

Co-Chair, Steering Committee
Professor Emeritus of Ecotoxicology, University of Idaho

Alan Kolok is a retired toxicologist whose research interests focus on the fate, transport, and biological impacts of anthropogenic chemicals, including pesticides. His academic background features a doctorate in environmental, population, and organismic biology from the University of Colorado, and a master's degree in fisheries and aquatic science from the University of Washington. He has published widely on a variety of topics, including environmental toxicology, chemicals and public health, environmental epidemiology, and the crowd sourced data revolution. His book, "Modern Poisons: A Brief Introduction to Contemporary Toxicology", has been used in classes across the United States and internationally. He is currently writing his second non-fiction book, titled "Forever Chemicals".

Christine L. Carroll

Associate Professor of Agricultural Policy and Agribusiness Management,
California State University, Chico
College of Agriculture

Christine Carroll is a Seattle-area native who earned her bachelor's degree in economics at Arizona State University and a PhD in agricultural economics at UC Davis. Her doctoral dissertation looked for economically viable control options for Verticillium wilt in lettuce crops in Monterey and the Salinas Valley. That research project, and the collaboration with growers, plant pathologists, and other disciplines, got her hooked on agricultural economics. She joined the College of Agriculture at CSU Chico in part because of the interdisciplinary structure of the college, which she sees as an opportunity build crossdisciplinary collaborations.

Julie Guthman

Distinguished Professor Emerita
Department of Sociology, Program in Community Studies
University of California, Santa Cruz

Julie Guthman has conducted multiple research projects on regulatory and civil society efforts to reduce the use of toxic substances in food production. This includes National Science Foundation- and USDA-funded projects that investigated the political economic and sociological challenges that California strawberry growers face for farming without fumigants or adopting more disease resistant varieties. Her book, *Wilted: Pathogens, Chemicals, and the Fragile Future of the Strawberry Industry* (2019) was awarded the highest book award in her home discipline of geography, the Meridian Prize of the American Association of Geographers. Most recently, she has been the principal investigator of the UCAFTeR Project, a multi-campus collaboration that investigated Silicon Valley's recent forays into food and agriculture and culminated in her newest book. Guthman's other publications include two other multi-award winning monographs, an edited collection and over sixty articles in peer-reviewed journals. She has received an Excellence in Research Award from the Agriculture, Food and Human Values Society, the Martin M. Chemers Award for Outstanding Research from the Social Sciences Division at UC Santa Cruz, and the Distinguished Career Award from the Cultural and Political Specialty Group of the American Association of Geographers.

Appendix D. Author Biosketches

Report Authors:

- **Chris Simmons, PhD**, University of California, Davis,
  Author

  Author Statement: As a faculty member at UC Davis, and as a separate activity from his authorship of this report, Simmons has conducted fumigant alternatives research sponsored by the Department of Pesticide Regulation.

- **Janet C. "Jenny" Broome, PhD**, University of California Santa Cruz
  Author

  No author statement.

Christopher W. Simmons, Ph. D
University of California, Davis
cwsimmons@ucdavis.edu

EDUCATION

2011 **Ph.D., Biological Systems Engineering**
University of California, Davis, CA

2007 **M.S., Biological Systems Engineering**
University of California, Berkeley, CA

2005 **B. S, Biological Systems Engineering**
University of California, Berkeley, CA

CURRENT AND PAST POSITIONS

Since 2021	**Chair** Department of Food Science & Technology, UC Davis
Since 2021	**Professor** Department of Food Science & Technology, UC Davis.
2019-2021	**Vice Chair** Dept. of Food Science & Technology, UC Davis
2017-2021	**Associate Professor** Dept. of Food Science & Technology, UC Davis
2017-2022	**Director of Research** Western Center for Agricultural Health & Safety, UC Davis
2018-present	**Director of Outreach** Western Center for Agricultural Health & Safety, UC Davis
2013-2017	**Assistant Professor** Department of Food Science & Technology, UC Davis
2013	**Postdoctoral Scholar** Department of Biological and Agricultural Engineering, UC Davis
2013	**Postdoctoral Scholar** Joint BioEnergy Institute

HONORS AND AWARDS

2023	UC Davis Distinguished Teaching Award - Graduate and Professional
2019	UC Davis Chancellor's Fellow
2018	Department of Pesticide Regulation's Integrated Pest Management Achievement Award

Janet C. " Jenny" Broome Ph. D

Independent Plant Health Consultant
jennybroome00@gmail.com

EDUCATION

1994	**Ph.D., Plant Pathology** University of California, Davis CA
1990	**M. S. Plant Pathology** University of California, Davis CA
1984	**BS Biological Sciences** Swarthmore College, Swarthmore, PA

CURRENT AND PAST POSITIONS

2023-present	**Principal Consultant**, Broome Plant Health Consulting
2024 - Present	**Assistant Adjunct Professor**, Department of Environmental Studies/Center for Agroecology, UC Santa Cruz
2010-2023	**Senior Research Manager/Senior Research Scientist,** Global Plant Health Department, Driscoll's Inc
2009-2010	**Project Scientist** Department of Plant Pathology, UC Davis
2008-2010	**Associate in the Agricultural Experiment Station** Department of Pathology, UC Davis
2006-2009	**Area Plant Pathologist/ Academic Coordinator III** UC Cooperative Extension, Sacramento, Yolo, and Solano Counties
2004-2006	**Visiting Scholar** Scottish Agricultural College, University of Edinburgh
1999-2006	**Associate Director** University of California Sustainable Agriculture Research and Education Program (UC SAREP)
1997-1999	**Biologically Integrated Farming Systems (BIFS) Coordinator** UC Sustainable Agriculture Research and Education Program
1994-1997	**Environmental Research Scientists** Department of Pesticide Regulation, Environmental Monitoring and Pest Management Branch

HONORS AND AWARDS

2007	American Society of Agronomy, Certificate of Excellence, for “California Dairies: Protecting Water Quality
2002	National Academy of Sciences (NAS) National Research Council (NRC) Opportunities in Agriculture Subcommittee on the Environment and Natural Resources member
1997	IPM Innovator Award, Department of Pesticide Regulation for the Central Coast Natural Vineyard Team’s Positive Points System
1995	California Environmental Protection Agency’s Certificate of Recognition
1992	Jastro Schields Research Fellowship, UC Davis
1992	Organization of American States PRA Fellowship

Appendix E. List of FCRs

Chapter 1: Pre-plant Soil Fumigants 1,3-D and Chloropicrin

1. **FINDING:** Because of the particularities of the nursery industry and the need for clean planting material and biosecure exports, the tradeoffs of fumigant use in the nursery industry are significantly different than commercial crop production. 36

2. **CONCLUSION:** For the time being, nursery applications should be given stronger consideration for continued use of 1,3-D and chloropicrin fumigants until there is more research and development of nursery-specific alternatives. 36

3. **FINDING:** Over the past 20 years, DPR, the U.S. EPA, and the fumigant company registrants have studied and then implemented a range of changes to fumigant application methods to attempt to contain the chemicals, reduce emissions, and mitigate the human health and environmental impacts of 1,3-D and chloropicrin. 42

4. **FINDING:** The development and use of totally impermeable films (TIFs) has increased fumigant effectiveness, reduced use rates, and mitigated emissions. However, the resultant plastic waste continues to be of concern. 42

5. **CONCLUSION:** TIFs significantly reduce fumigation emissions and associated acute risks to human health. 42

6. **FINDING:** To date, California's key specialty crops, especially strawberries, have significantly relied on pre-plant fumigants to control soilborne pathogens, nematodes, weeds, and arthropod pests. 54

7. **FINDING:** The use of chloropicrin and 1,3-D has increased since 1990. The increasing use of chloropicrin is due to expanded crop acreage, the phaseout of methyl bromide, and the discovery of new strawberry pathogens in California. 1,3-D use has varied more over time due to its limited supply as a by-product of the housing construction market, increases in almond acreage, and regulatory changes. 54

8. **CONCLUSION:** Fumigant use is dynamic and is influenced by regulations, crops, geography, pathogens, and seasons, and growers need tools to manage these dynamics. 54

20. **CONCLUSION:** More studies are needed using “exposure science” triangulating results from 1) toxicology using rodent models; 2) epidemiological studies of toxicants in the environment and their effects on human health; 3) environmental science; and 4) risk assessments; along with 5) social science studies using testimonials or other means of documenting the experience of exposure and illness to further understand the chronic and acute health effects of exposure. 66

21. **RECOMMENDATION:** DPR should consider supporting the use of exposure science to better understand and mitigate potential exposures in vulnerable populations.67

22. **RECOMMENDATION:** DPR should consider incorporating environmental justice work through various means (e.g., personnel, program focus) linked to their Environmental Monitoring branch so as to facilitate exposure science. 67

23. **FINDING:** It is not clear that the contributions of fumigation with 1,3-D are a significant source of greenhouse gases from agriculture. 68

24. **FINDING:** Few studies have investigated how repeated fumigations with 1,3-D impact the soil microbiome and nematode communities over time. 69

25. **CONCLUSION:** Greater knowledge about how 1,3-D impacts the functional roles of the soil microbiome and nematode communities would be informative for potential improvements in pathogen and nematode control efficacy and the development of methods to mitigate any possible negative effects such as impacts on soil nitrogen cycles. 69

26. **FINDING:** Soil fumigation with chloropicrin may indirectly lead to increased greenhouse gas emissions via impacts to microorganisms involved in nitrogen cycling. 70

27. **FINDING:** Insufficient research exists to determine the significance to which fumigation with chloropicrin impacts greenhouse gas emissions in California. 70

28. **CONCLUSION:** More research on the possible indirect impacts of fumigation on greenhouse gas emissions is needed. Such research would be most valuable for California regulators if performed in California and using fumigation methods that are standard for chloropicrin in this state. 70

29. **FINDING:** There is a dearth of information regarding the modes of action for these fumigants against both humans and target pests.. 72

30. **FINDING:** The CHAMACOS study has found that residential proximity to fumigant use during pregnancy is associated with lower birth weight and reduced IQ at age seven. However, additional studies looking at a larger and more diverse population with a greater range of agricultural fumigant use are needed to further explore the relationship of fumigant use and children's health. .73

31. **FINDING:** At present, totally impermeable film (TIF) is the most effective method for significantly reducing offsite 1,3-D and chloropicrin emissions. However, it is only commonly used while pre-plant fumigating strawberry, cane berries, fresh-market tomatoes, peppers, and ornamental fields. 76

32. **CONCLUSION:** TIF use during the pre-plant fumigation for other crops (e.g., almonds, grapes, carrots, and sweet potatoes) would decrease the emissions associated with 1,3-D and chloropicrin fumigation. However, increasing the use of TIF in crop settings that do not currently use tarps will increase plastic use and waste. .76

33. **FINDING:** Early research suggests that biochar and liquid slurry have the potential to reduce emissions from fumigation. 76

34. **FINDING:** To date, there have been no reports of pathogens, nematodes, weeds, or arthropod pests developing resistance to the pre-plant soil fumigants 1,3-D and chloropicrin. However, insect pest resistance to phosphine has been reported. 78

35. **CONCLUSION:** It is important to continue to watch for signs of resistance to fumigants developing in pathogen, nematode, weed, and arthropod pest populations. This would manifest as a loss of disease or weed control following use of the fumigants where previously control was achieved. 78

36. **FINDING:** A particular crop production system may become dependent on the use of fumigants to be economically viable and require the continued use of costly external inputs which may not always be available due to supply issues, economic or regulatory related decisions of the manufacturer or distributor, or direct regulatory actions. This may especially be true if the use extends over many years and influences decisions about research into developing alternative control methods. 78

37. **FINDING:** 1,3-D continues to be used for pre-plant soil fumigation in numerous countries, including members of the European Union where it is used under an Emergency Use Derogation (EUD) while undergoing registration. More than 10 million pounds of product were sold across 6 countries in 2024. 83

38. **FINDING:** Chloropicrin continues to be used for pre-plant soil fumigation in numerous countries, with an estimated annual average of 55 million pounds of active ingredient sold across seven regions, including within the European Union under an Emergency Use Derogation (EUD). 83

Chapter 2: Fumigant Alternatives

39. **FINDING:** Metam sodium and metam potassium are currently used in several California cropping systems. These fumigants can be used with similar soil preparation, application, and tarp covering practices compared to 1,3-D and chloropicrin. 110

40. **CONCLUSION:** Metam sodium and metam potassium can serve as broad spectrum soil fumigants, similar to 1,3-D and chloropicrin. However, the duration of soil pest control and the application rates for these fumigants can differ compared to 1,3-D and chloropicrin. 110

41. **FINDING:** Several non-fumigant pesticides are currently used in California to control soil pests. These pesticides target a narrower range of soil pests relative to 1,3-D and chloropicrin. By extension, and in contrast to fumigation, their more targeted action can allow for application during crop growth and not just during the pre-plant period. However, pest control effectiveness relative to 1,3-D and chloropicrin is inconsistent. 115

42. **CONCLUSION:** Non-fumigant pesticides are unlikely to match the broad-spectrum soil pest control of 1,3-D and chloropicrin unless used in combination or with other pest control measures. They may be useful in cases where phytoparasitic nematodes are the primary pest pressure or where there is need for nematode control post-planting, but research is needed to determine the pesticide application, environmental, pest, and crop variables that affect pest inactivation and influence yield outcomes. 115

43. **FINDING:** ASD and biosolarization use organic matter amendments in tandem with solar heating to induce multiple stresses that can lead to broad spectrum pest control. The addition of organic matter to the soil can provide secondary benefits to soil and crop health.. 124

44. **CONCLUSION:** ASD and biosolarization can match the pest control and yield benefits of fumigation under certain conditions related to weather and climate, cropping system, and soil amendments. The types and levels of organic matter amendments used are key factors in achieving broad spectrum pest control on par with fumigation. They also factor heavily into process cost.. 124

45. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to define best practices for ASD and biosolarization. These practices should aim to maximize broad spectrum pest control effectiveness for California crops that currently rely on fumigation while also mitigating risks such as of nitrate leaching to groundwater or emission of greenhouse gases. DPR and/or other relevant California state agencies should consider supporting work to identify or develop supply chains for various organic matter streams that can be used in ASD or biosolarization and are cost-effective for growers. 124

46. **FINDING:** Solarization has been studied for decades. Soil pest control and yield effects have varied based on location, crop, and pest type. Yield effects range from parity with fumigation to yield decreases relative to untreated controls. The scale of use of solarization in commercial California agriculture is unclear, as is the cost to deploy the technique. 128

47. **CONCLUSION:** Given its complete reliance on weather and climate conditions to achieve soil temperatures required for broad spectrum soil pest control, solarization will likely only be a possible fumigation alternative in cropping systems and regions that have a fallow period during several weeks of sustained hot, dry conditions.. 128

48. **FINDING:** There are biologically derived pesticide and biocontrol agent products on the market that contain active ingredients shown in laboratory, potted plant, or field studies to inhibit major pathogens and nematodes typically controlled through fumigation. However, there is little evidence that they are currently used for soil pest control in commercial agriculture.. 134

49. **CONCLUSION:** Inactivation of fungal pathogens and phytoparasitic nematodes via biologically derived pesticides or biocontrol agents, and associated disease reduction and yield effects in treated crops, is variable and may be highly transient. The costs of using biologically derived pesticides and biocontrol agents at a scale for soil pest control are not well characterized.. 134

50. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to determine the types of biologically derived pesticides and biocontrol agents, and their application practices, that maximize broad spectrum soil pest control with the aim of achieving parity with fumigation in California agriculture. If such conditions are identified, DPR and/or other relevant California state agencies should consider supporting analyses to determine the costs and net returns for growers. 134

51. **FINDING:** Strategic selection of cover crops can contribute to soil pest control by disrupting pest lifecycles—which depends on the host range of the pathogens and phytoparasitic nematodes in the soil—and by outcompeting weeds. Termination and soil incorporation (i.e., mixing) of certain cover crops can release biologically derived pesticides into soil, such as isothiocyanate compounds, which inhibit pests sensitive to these compounds. Cover crops can also provide multiple soil health benefits, including nutrient capture and retention and improved soil texture.. 139

52. **CONCLUSION:** Cover crops alone are unlikely to be an effective fumigation substitute. However, they can contribute to an integrated pest management strategy that uses multiple approaches to control soil pests. 139

53. **FINDING:** Crop rotations can help control soil pests that have a narrow host range by selecting crops that disrupt the pest's life cycle. Crop rotations are less effective at controlling soil pests with a broad host range.. 143

54. **CONCLUSION:** The use of crop rotations requires growers to be skilled in cultivating multiple crops. For effective soil pest control, growers must select rotated crops that can disrupt the host cycle of pests in their fields while also being compatible with their local soil, climate, land availability, and market conditions. These factors create hurdles to adoption. In cases where soil is infested with pests or pathogens with broad host ranges, or if multiple pests and pathogens are present with differing disease mechanisms, crop rotations may have more limited effectiveness as a fumigation alternative. 143

55. **FINDING:** There are commercially available resistant varieties or rootstocks for many of the crops in California that currently use soil fumigation. However, these varieties and rootstocks do not cover the full range of soil pests that are controlled through fumigation with 1,3-D and chloropicrin. Yield effects relative to non-resistant varieties may vary positively or negatively depending on the type and level of pest pressure in the soil.. 147

56. **CONCLUSION:** Resistant varieties and rootstocks can be effective in controlling certain classes of soil pests, such as specific nematode and fungal pathogen species. They are less likely to be effective fumigation alternatives in fields with multiple pest stresses unless other complementary pest control strategies are used.. 147

57. **FINDING:** There are a limited number of steam applicators available commercially or described in the research literature that can treat open fields in a way that would allow for displacement of fumigation. Design innovations have improved the delivery of steam to soil to better control the rate and depth of heating, but heating of soil beyond 20 cm depth is largely untested.. 151

58. **CONCLUSION:** Steam treatment can deliver broad spectrum soil pest control, but the reliance on specialized equipment, limited knowledge of heating depth, and slow treatment times for a single applicator present barriers to adoption.. 151

59. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting engineering and research efforts to characterize or enhance the depth of steam treatment along with work to improve steam treatment times for large fields. Additionally, given the fuel requirements to operate existing steam applicators, DPR and/or other relevant California state agencies should consider supporting life cycle assessments to understand the environmental impacts of using steam treatment in open field, greenhouse, and nursery settings and in response to different fuel types (e.g., natural gas, biogas, hydrogen).. 151

60. **FINDING:** Soilless cultivation systems span a variety of hydroponic and solid substrate approaches. By their nature, soilless systems can avoid pests in soil commonly controlled through fumigation. However, these systems can be vulnerable to pathogenic growth in nutrient solutions. 156

61. **CONCLUSION:** Soilless cultivation systems represent a substantial departure from conventional agriculture in open fields, requiring infrastructure, nutrient and water management practices, and sanitation methods that are markedly different from those used in fields. 156

62. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting analyses to determine the feasibility and cost of transitioning various open field cropping systems to different hydroponic or solid substrate soilless systems, such as substrate bags in open fields or atop tables. 156

63. **FINDING:** Diversified farming systems employ many non-chemical and biological methods in combination, especially cover crops, crop rotations, organic amendments, and intercropping, as a substitute for pesticides. 157

64. **CONCLUSION:** Greater study of potential mechanisms of the functional biodiversity on diversified farms and how it might relate to soil and plant health, in addition to reporting the costs and returns of diversified farming systems, could provide insights into how these farms operate without using fumigants. 157

65. **FINDING:** There is no comprehensive systematic tracking of fumigant alternative use across California or elsewhere. 157

66. **FINDING:** Research is inconsistent in the use of controls; some studies compared effectiveness against fumigation while others only compared against untreated soils.. . .158

67. **FINDING:** Overall, fumigant alternatives demonstrate varying levels of effectiveness compared to fumigation. Some alternatives show partial effectiveness, others are effective only under specific conditions, a few offer comparable effectiveness to fumigation for certain pest and crop targets, while others remain understudied or uncharacterized. 158

68. **FINDING:** Yield effects for each fumigant alternative may differ based on the crop studied, type of pest pressure, and process variables unique to each alternative. Moreover, yield effects must be qualified based on comparisons to untreated soils (negative controls) or soils fumigated with 1,3-D and chloropicrin (positive controls), and the data are inconsistent in the types of controls used. 158

69. **FINDING:** For all alternatives, there is evidence of yield benefits when compared against untreated soils for at least some crops that currently use fumigation. For alternatives that have been directly tested against fumigation, such as anaerobic soil disinfestation, biosolarization, solarization, and steam treatment, similar or greater yield enhancement has been achieved in certain crop and regional use cases relative to fumigation. 158

70. **FINDING:** There are major gaps in the types of crops and regions studied, as well as the use of fumigated positive controls, that challenge direct yield comparisons across fumigant alternatives and between alternatives and fumigation with 1,3-D and chloropicrin. 159

71. **FINDING:** Cost studies for fumigant alternatives capture only a small fraction of the use scenarios and crop systems that currently use fumigation with 1,3-D and chloropicrin. 159

72. **FINDING:** Even when cost information is available, it is often not tied to specific levels of pest inactivation or yield improvement (both of which directly impact net returns), making it difficult to compare costs between alternatives based on their relative effectiveness. 159

73. **FINDING:** Data have shown that methane production can occur during biosolarization and anaerobic soil disinfestation. 160

74. **FINDING:** The volatile compounds generated during biosolarization or ASD can differ based on the organic matter soil amendments and implementation method. 163

75. **CONCLUSION:** Additional research is necessary to define the biosolarization and anaerobic soil disinfestation process conditions (e.g., amendment nutrient profiles, duration of tarp coverage) that avoid methane and nitrous oxide emissions. 163

76. **CONCLUSION:** A full health risk assessment is required for the complete array of volatile compounds commonly produced during biosolarization and anaerobic soil disinfestation. 163

77. **FINDING:** The lack of an IDLH value for 1,3-D and absence of any NIOSH guidance for dimethyl disulfide, allyl isothiocyanate, or methyl isothiocyanate highlight gaps that require health risk assessments to enable comparisons against other fumigants. 166

78. **CONCLUSION:** Calculated exposure limits from DPR risk assessments for methyl isothiocyanate and allyl isothiocyanate do not indicate a clear reduction in exposure risk associated with adoption of these fumigants over 1,3-D and chloropicrin. However, a deeper analysis of the underlying data and methods used to determine acute, sub-chronic, and chronic exposure limits for each fumigant is needed to ensure valid comparisons of toxicity and exposure risk. 166

79. **FINDING:** There is evidence that biosolarization, anaerobic soil disinfestation, cover cropping, and alternative fumigants can require a plant-back time. Alternatives such as solarization, steam treatment, non-fumigant pesticides, and biologically derived pesticides and biocontrol agents do not require plant-back times. 168

88. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting basic science research to further explore the pest inactivation mechanisms of fumigant alternatives, as well as field demonstration studies that directly compare feasibility, cost, and pest inactivation effectiveness between multiple fumigant alternatives and fumigation in a given cropping system and environmental context. Such work may involve experimentation or meta-analysis of existing published data. Additionally, DPR and/or other relevant California state agencies should consider supporting appropriate risk assessments for each fumigant alternative. 174

Chapter 3: Research on Fumigant Alternatives

89. **FINDING:** Ethanedinitrile (EDN) has primarily been studied as a soil fumigant in the last 5 years. Published studies describe work conducted outside of California, although crops such as carrots, tomatoes, and strawberries overlap with those that currently use 1,3-D and chloropicrin fumigation in California. 199

90. **CONCLUSION:** Based on current data, ethanedinitrile (EDN) is inconsistent in its ability to control weeds, pathogens, and phytoparasitic nematodes while benefitting the health and productivity of crops. Additionally, there are poorly understood phenomena that affect transient inhibition and plantback times following EDN fumigation with higher application rates. There are no environmental or human health risk assessments for the use of EDN in California agriculture. 199

91. **RECOMMENDATION:** DPR and/or other relevant California state agencies should consider supporting research to determine the efficacy and safety of ethanedinitrile (EDN) use in the context of California agriculture. This could include field trials to study use in crops and regions that currently employ 1,3-D and chloropicrin fumigation in California. Additionally, the work should include measurement of EDN escape and risk of exposure and disease for agricultural workers, adjacent communities, and non-target organisms. 199

92. **FINDING:** Research has increasingly validated combination approaches that utilize multiple fumigant alternatives. 208

93. **CONCLUSION:** Additional targeted research would be useful to determine the most effective combination methods for major fumigant-reliant crops. 208

Chapter 4: Addressing Barriers and Increasing Adoption of Fumigant Alternatives

Appendix F. Oversight

Oversight Subcommittee of the Program Committee of CCST's Board of Directors

- **Pramod Khargonekar, PhD**, University of California, Irvine
- **Andy McIlroy, PhD**, Sandia National Laboratories
- **Ganesh Raman, PhD**, California State University

Report Monitor

- **Richard Flagan, PhD**, California Institute of Technology

Expert Reviewers

- **Kim Harley, PhD**, UC Berkeley
- **Jill Harrison, PhD**, University of Colorado – Boulder
- **Pierre Mérel, PhD**, UC Davis
- **Margaret Reeves, PhD**, Pesticide Action Network
- **Mike Stanghellini, PhD**, TriCal, Inc.
- **Hillary Thomas, PhD**, Naturipe Berry Growers, Inc.
- **Andreas Westphal, PhD**, UC Riverside
- **Mohammad Yaghmour, PhD**, UC Agriculture and Natural Resources

Appendix G. CCST Study Process

For 36 years, the California Council on Science and Technology (CCST) has been advising California on issues of science and technology by leveraging exceptional talent and expertise. CCST studies are viewed as valuable and credible because of the organization's reputation for providing independent, objective, and nonpartisan advice with high standards of scientific and technical quality. Checks and balances are applied at every step in the study process to protect the integrity of the studies and to maintain public confidence in them.

CCST entities involved in the study process

The study process, including accepting and defining projects and building the teams to carry them out, involves a number of entities that are a part of CCST.

1. **CCST Leadership** – Consisting of the CCST CEO and the CCST Deputy Director, these positions are generally involved in interfacing with the sponsor and working through the initial ideation of the project and securing the contract. They work with the Board on all steps after ideation.
2. **CCST Board of Directors ("Board")** – Consisting of directors from CCST's academic and research partner institutions as well as independent directors often from industry, philanthropy or with a policy background. The Board gives final approval to take on a peer-reviewed report.
3. **Program Committee** – A subcommittee of the CCST Board, the Program Committee oversees and advises the programs by which CCST fulfills its mission to provide science advice to inform decision-making in the State of California. The Program Committee provides oversight throughout the study process.

Study process overview: Ensuring independent, objective advice

CCST enlists the state's foremost scientists, engineers, health professionals, and other experts to address the scientific and technical aspects of society's most pressing problems. CCST studies are funded by state agencies, foundations, and other private sponsors. CCST provides independent advice; external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. Authors and the Steering Committee gather information from many sources in public and private meetings, but they carry out their deliberations in private in order to avoid political, special interest, and sponsor influence. After the report has been drafted, it undergoes a rigorous peer review process, overseen by an independent Report Monitor who ensures all Peer Reviewer comments are sufficiently considered.

Stage 1: Defining the study

Before the author(s) and Steering Committee selection process begins, CCST staff, and other CCST experts as needed and informed by the CCST Program Committee work with the study sponsors to determine the specific set of questions to be addressed by the study in a formal "statement of task," as well as the duration and cost of the study. In line with CCST's dedication to supporting diversity, equity, and inclusion (DEI) through its work, CCST intentionally integrates the social sciences and questions of equity. The statement of task defines and bounds the scope of the study, and it serves as the basis for determining the expertise and the balance of perspectives needed for the study authors, Steering Committee members, and peer reviewers.

The statement of task, work plan, and budget must be approved by CCST leadership in consultation with CCST's Project Director. This review sometimes results in changes to the proposed task and work plan. On occasion, it results in turning down studies that CCST believes are inappropriately framed or not within its purview.

Stage 2: Study authors and steering committee (SC) selection and approval

Selection of appropriate authors and SC members, individually and collectively, is essential for the success of a study. CCST intentionally recruits a diverse team of experts. All authors and SC members serve as individual experts, not as representatives of organizations or interest groups. Each expert is expected to contribute to the project on the basis of his or her own expertise and good judgment.

To build the SC and Author teams, CCST staff solicit an extensive number of suggestions for potential SC members and authors from a wide range of sources, then recommend a slate of nominees, and send invitations to each provisional SC member and author to complete a non-disclosure agreement (NDA), a conflict of interest (COI) form and submit their current Curriculum Vitaes (CVs). The NDA is essential for ensuring an environment which supports frank and open discussion among study participants, both in establishing the team and as the study is ongoing. CCST staff send the COIs and current CVs to outside counsel for a thorough COI review and then organize all results and recommendations from the outside counsel. CCST organizes an in-person meeting for the provisional SC and lead authors to discuss the balance of the committee and evaluate each person for any potential COIs based on the outside counsel feedback. Any issues raised in this discussion are investigated and addressed. CCST sends the proposed study participant list and associated COI information, including any recommendations or concerns noted at the in-person meeting, to the Program Committee of the CCST Board for final approval. In some cases, the Program Committee is asked to review potential COIs ahead of the in-person SC meeting at the discretion of CCST Leadership. While the lead authors attend the in-person meeting for the discussion of their own potential COIs, they do not contribute to the discussion of the provisional SC Members' COIs. Members of a SC and the lead author(s) are anonymous until this process is completed.

Careful steps are taken to convene SCs that meet the following criteria:

An appropriate range of expertise for the task. The SC must include experts with the specific expertise and experience needed to address the study's statement of task. A major strength of CCST is the ability to bring together recognized experts from diverse disciplines and backgrounds who might not otherwise collaborate. These diverse groups are encouraged to conceive new ways of thinking about a problem.

A balance of perspectives. Having content expertise is not sufficient for success. It is also essential to evaluate the overall composition of the SC in terms of different experiences and perspectives. The goal is to ensure that the relevant points of view are, in CCST's and the Program Committee's judgment, reasonably balanced so that the SC can carry out its charge objectively and credibly.

Screened for conflicts of interest. All provisional SC members are screened in writing and in a confidential group discussion about possible conflicts of interest. For this purpose, a "conflict of interest" means any financial or other interest which conflicts with the individual's service because it could significantly impair the individual's objectivity or could create an unfair competitive advantage for any person or organization. The term "conflict of interest" is beyond individual bias. There must be an interest, ordinarily financial, that could influence the work of the SC or that could be directly affected by the work of the SC, for an individual to be disqualified from serving. Except for a rare situation in which CCST and the Program Committee determine that a conflict of interest is unavoidable and promptly and publicly disclose the conflict of interest, no individual will be appointed to serve (or continue to serve) on a SC used in the development of studies while having a conflict of interest relevant to the required functions.

SC members and authors continue to be screened for conflict of interest at regular intervals throughout the life of the committee. (In addition to the SC and Authors, co-authors, peer reviewers and CCST staff working on each project are also screened for COI.)

Point of View is different from Conflict of Interest. A point of view or bias is not necessarily a conflict of interest. SC members are expected to have points of view, and CCST attempts to balance these points of view in a way deemed appropriate for the task. SC members are asked to consider respectfully the viewpoints of other members, to reflect their own views rather than be a representative of any organization, and to base their scientific findings and conclusions on the evidence. Each SC member has the right to issue a dissenting opinion to the study if he or she disagrees with the consensus of the other members. COIs are updated throughout the study process to capture any new or updated information and to ensure a continued lack of conflicts.

Diversity. CCST members are often asked to serve on an SC, though membership in CCST is not a requirement SC selection. CCST seeks a diverse SC in all dimensions, including women, individuals from underrepresented groups, and professionals in varying career stages where available.

Stage 3: Author and steering committee meetings, information gathering, deliberations, and drafting the study

Authors and the Steering Committee typically gather information through:

1. Meetings
2. Submission of information by outside parties
3. Reviews of the scientific literature
4. Investigations by the study authors and/or SC members and CCST staff

In all cases, efforts are made to solicit input from individuals who have been directly involved in, or who have special knowledge of, the problem under consideration.

The lead author(s) maintain continued communication with the SC as the study progresses through frequent updates and background meetings.

For larger reports, lead authors may request additional authors to ensure the appropriate expertise is included. Every author must be approved by the SC Chair(s) and CCST staff. Some of the additional authors may become section leads. The lead author reviews and approves the work of all other chapter authors, including section leads.

During the course of a report, authors' duties may shift which may change the lead author or section lead designations. Any such changes must be made in conjunction with CCST staff and the SC Chair(s). If the reorganization of author responsibilities or the addition of a new author raises conflict of interest concerns, they are presented to and resolved by the Program Committee.

The authors shall draft the study and the SC shall draft the Executive Summary which includes findings, conclusions, and recommendations (FCRs). The SC deliberates in meetings closed to the public in order to develop FCRs free from outside influences. All interim analyses and drafts of the study remain confidential.

Stage 4: Report review

As a final check on the quality and objectivity of the study, all CCST full commissioned reports must undergo a rigorous, independent external peer review by experts whose comments are provided anonymously to the authors and SC members. CCST recruits independent experts with a range of views and perspectives to review and comment on the draft report prepared by the authors and the SC. The proposed list of peer reviewers is approved by the Program Committee to ensure all report sections are adequately reviewed.

The review process is structured to ensure that each report addresses its approved study charge, that the findings are supported by the scientific evidence and arguments presented, that the exposition and organization are effective, and that the report is impartial and objective. Peer Reviewers will be made aware of any COIs that have been disclosed on the website by CCST.

The authors and the SC must respond to, but need not agree with, reviewer comments in a detailed “response to review” that is examined by one or more independent “report monitor(s)” responsible for ensuring that the report review criteria have been satisfied. After all SC members and appropriate CCST officials have signed off on the final report, it is transmitted to the sponsor of the study and the sponsor or CCST can release it to the public. Sponsors are not given an opportunity to suggest changes to the content of the reports though may ask clarifying questions about findings, conclusions, and recommendations. All reviewer comments and SC deliberations remain confidential. The names and affiliations of the report reviewers are made public when the report is released.

Fumigant Use in California and an Assessment of Available Alternatives

Phase I Report on 1,3-D and Chloropicrin

The California Council on Science and Technology is a nonpartisan, nonprofit organization established via the California State Legislature — making California's policies stronger with science and technology since 1988. We engage leading experts in science and technology to advise State policymakers — ensuring that California policy is strengthened and informed by scientific knowledge, research, and innovation.

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CCST
1017 L St, #438
Sacramento, California 95814
(916) 492-0996 • ccst@ccst.us • ccst.us • @CCSTorg