Fumigant Use in California and an Assessment of Available Alternatives

Phase II Report on Structural Fumigation with Sulfuryl Fluoride

PEER-REVIEWED REPORT

A commissioned report prepared by the California Council on Science and Technology

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Phase II Report on Structural Fumigation with Sulfuryl Fluoride

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Note on Units of Measurement
This report includes data and information drawn from a wide range of sources, including peer-reviewed literature, government reports, and technical documents. To preserve the accuracy and integrity of the original sources, this report retains the units of measurement as they were reported. When appropriate, the report provides a parenthetical equivalent in either imperial or metric units to aid interpretation. This approach ensures consistency with cited materials while supporting accessibility for a broad audience.

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Appendix V.

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 X*** 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 XI*** 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:

1. **Finding.** Fact(s) the study team finds that can be documented or referenced and that have importance to the study.
2. **Conclusion.** A reasoned statement the study team makes based on findings.
3. **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 VII*** 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 the use of sulfuryl fluoride (SO_2F_2; hereafter referred to as SF) for fumigating structures in California; 2) the currently available alternatives to SF fumigation and the extent of their use; 3) past and ongoing research dedicated to SF alternatives; 4) the viability of adopting these alternatives to effectively manage pests in California; 5) the barriers to and incentives for wide-scale adoption of alternatives; and 6) the areas where research may still be needed to answer some of these questions. The answers to these assessments are addressed across the four chapters of this report. Following the methodology outlined in the California Council on Science and Technology's study process (***Appendix VII***), the Steering Committee deliberated over published literature, data available in regulatory databases, and expert testimony to arrive at the findings, conclusions, and recommendations presented in this report.

This executive summary is designed to provide a high-level overview of the report's key findings and insights. Readers seeking detailed evidence, data, and references for the information provided within are encouraged to consult the full report.

Sulfuryl fluoride (SF) is a colorless, odorless, and nonreactive gas that has been an effective fumigant for structural pests for the past 30 years. Following the phaseout of methyl bromide as a structural fumigant in 2005, SF became the only fumigant federally approved for controlling pests in homes, garages, barns, storage units, and commercial warehouses in the United States. While SF is approved for use as a treatment to control more than a dozen pest species, its principal use in California is to control drywood termites—a pest of economic significance for wooden structures in California, Florida, and Hawaii. Treatments for other pests, such as wood-destroying beetles, bed bugs, rodents, cockroaches, and clothes moths compose a small yet significant share (approximately 6%) of SF fumigations in California.

The ability of SF to penetrate through walls, attics, and physically inaccessible spaces makes it a preferred treatment for extensive termite infestations. Although SF provides no residual protection against termites, the thoroughness with which it addresses current infestations allows pest management professionals (PMPs) to guarantee that treated structures are (at least temporarily) "pest free." However, its continued use as a structural fumigant comes with human health and environmental costs. These two themes are discussed in the next section, followed by an overview of the six assessments that guided this study.

Human health concerns

SF is a highly toxic chemical. For this reason, it is a strictly regulated, **restricted-use pesticide**. Despite this regulatory oversight, there are inherent risks to human health associated with its use. Studies have shown that inhalation of SF has neurotoxic and respiratory effects, as well as potential **genotoxic** effects. Exposure to lower concentrations of SF can cause headaches, slurred speech, muscle twitching, shortness of breath, throat and nasal irritation, coughing, and occasionally pneumonia and pulmonary **edema** (fluid buildup in lungs). Exposure to higher concentrations of SF can cause severe organ damage, including permanent brain damage or death. While the health impacts of **acute** (i.e., short-term, high-level) exposure to SF are well-documented in the literature, there have been very few investigations into the real-world impacts of **chronic** (i.e., long-term, low-level) exposures to SF.

SF poses risks not only to pest management professionals, but also to people who reenter improperly cleared structures and bystanders who are exposed due to either unintentional leaks or the intentional venting of SF following fumigations. As of 2006, the U.S. Environmental Protection Agency (EPA) requires that SF concentrations must be 1 part per million (ppm) or less before residents can reenter structures. However, evidence from the Pesticide Illness and Surveillance Program suggests that injuries and illnesses are still occurring as a result of SF fumigation. Since the 1 ppm reentry level was established, 112 injuries and illnesses sustained upon reentering fumigated structures have been reported to the program. While monitoring helps ensure that concentrations have declined to levels deemed safe by regulators, the EPA has determined that two of four available clearance devices could not reliably detect when concentrations of SF in ambient air exceeded 1 ppm (they had false negative rates of 100% and 80%). The EPA requires that devices have false negative rates of less than 30% to be deemed reliable. The EPA provides information regarding device reliability for the general awareness of users but neither regulates nor enforces reliability standards for clearance devices. Faulty clearance devices could explain some of the injuries and illnesses reported to the Pesticide Illness Surveillance Program.

Environmental concerns

Unlike its predecessor methyl bromide, SF is nonreactive and is not an **ozone**-depleting substance. However, SF is a potent greenhouse gas (GHG) with an impact on the climate that is 4,630 times that of carbon dioxide (CO_2) (over a 100-year timeframe). Given an average fumigation rate of 25.8 pounds of SF per structure, every fumigation is roughly equivalent to adding 119,500 pounds of CO_2 to the atmosphere (the same as driving a typical passenger vehicle 135,510 miles)—this is potentially an upper-bound estimate, as evidence suggests some SF may be destroyed in the process. Recent analyses demonstrate that global atmospheric concentrations and emissions of SF have increased more than eightfold since

1978 and that California is responsible for a majority of measurable SF emissions in the United States (although data are lacking regarding SF emissions from Florida, another state in which fumigations with SF for drywood termites are common). While California does not currently regulate SF like other common GHGs, a closer examination of possible efficiencies in the deployment and use of SF is warranted. To date, there has been no concerted effort, nor incentives made, to reduce the amount of SF used to control structural pests. However, there are a variety of approaches that could significantly reduce the amount of SF used while still ensuring effective pest control. These include ensuring tarps are in good condition, requiring monitoring for all fumigations, including a 10% CO_2 mixture along with SF, and capturing the SF from fumigation exhaust. All of these approaches deserve further consideration.

It is beyond the scope of this report to consider the life cycle of fumigants and their alternatives, including production, transportation, and disposal, although these may also have significant health and environmental impacts.

Assessment 1: The present state of SF use for structures in California

Fumigation patterns across California approximate the distribution of drywood termites. Fumigations occur most frequently in Los Angeles County, followed by San Diego, Orange, Santa Clara, Riverside, San Bernardino, and Santa Barbara counties. Fumigations are often associated with real estate transactions, and trends in SF use correlate with the volume of home sales and are influenced by the same economic factors that affect home sales (home prices, new construction, etc.).

SF fumigation involves covering the entire structure with polypropylene tarps and injecting the amount of gas needed to achieve lethal concentrations for target pests. Because SF is odorless, the inclusion of chloropicrin (another toxic chemical with its own hazards) is required as a warning agent. After approximately 24 hours, as per regulation, the entire structure is forced-air ventilated until concentrations reach levels 1 ppm or less. All tarps are then removed. Monitoring is the most reliable way to ensure that the concentrations of SF within structures have reached levels lethal to the target pest. However, not all fumigations are monitored, and there is evidence that unmonitored structures are overdosed with SF. Further, tarp conditions vary; poorer tarp conditions allow the premature escape of SF emissions, requiring pest management professionals (PMPs) to use additional SF to maintain lethal concentrations. Despite these factors, which lead to more SF being used than would otherwise be necessary for effective treatment, the amount of SF used per fumigated structure has declined over time in California. The reasons for this decline can only be speculated upon.

SF is a restricted-use pesticide, meaning that this fumigant can only be used by a certified PMP or someone under their supervision. Several state regulatory agencies, including the California Department of Pesticide Regulation (DPR), the Structural Pest Control Board (SPCB), and County Agricultural Commissioners, oversee the use of SF. Each of these agencies require PMPs to retain paperwork associated with each SF fumigation for three years. While these records contain a wealth of information that could reveal important trends about SF use, no publicly available studies have analyzed them to determine inspection and treatment outcomes.

Assessment 2: Currently available alternatives to SF and the extent of their use

Ten alternatives to SF fumigation were reviewed: 1) preventive measures, 2) whole-structure heat treatment, 3) localized chemical treatments, 4) localized heat treatments, 5) cold treatments, 6) electrocution, 7) microwaves, 8) biological treatments, 9) wood removal, and 10) no treatment. Treatments can be categorized as either whole-structure or localized. Whole-structure treatment refers to the simultaneous treatment of all wood in the structure. Currently, SF and whole-structure heat are the only two drywood termite treatment methods that fit this strict regulatory and industry definition. Localized refers to treating a single board or a specific area within a board.

Alternatives can also be categorized as either chemical or nonchemical. There are hundreds of chemical products registered for controlling drywood termites (chemical active ingredients inventory lists are provided in Tables 1.3–1.10 in Chapter 1 and Tables 2.3–2.4 in Chapter 2). Many of these chemicals have the advantage of residual protection against termite infestations—something that neither SF nor the nonchemical alternatives can provide. Toxicities of the chemical treatments vary, with some being extremely toxic Category II chemicals and others less so.

Localized treatments (both chemical and nonchemical) are highly reliant on the ability of PMPs to locate the exact site of infested boards and termite tunnel system. Although several detection devices have been tested in laboratory settings, none of the devices can reliably identify the presence and locations of drywood termites in structures.

Whole-structure heat treatments alone provide a similar degree of certainty regarding termite eradication as SF fumigation (effectively 100%, barring user error). Overall, existing research has not adequately characterized the costs and relative effectiveness of other alternative treatments to SF fumigation.

There is reason to believe that SF fumigation constitutes a small (though significant) share of drywood termite treatments in California. If trends are similar to a study conducted in the early 1990s, then roughly three-quarters of drywood termite infestations are already addressed with alternative, localized treatments. Information about the degree to which different alternatives are used—and the effectiveness of those treatments—is limited, although such information could be gathered via a comprehensive analysis of existing regulation inspection and notice of completion paperwork.

Assessment 3: Past and ongoing research dedicated to SF alternatives

Research on controlling wood-destroying insects that attack construction lumber, including drywood termites, has been sporadic and limited, primarily due to the limited range of these pests in the United States. This narrow range correlates with a relatively small market for pest control compared with that of other pests. Consequently, there is little incentive to invest the significant resources required to identify successful alternatives and bring them to market. Indeed, most funding for urban pest management is from the Structural Pest Control Research Fund (SPCB), administered by the SPCB and supported by a $2 fee paid by pest control companies every month (generating approximately $160,000 annually). No central agency exists to coordinate the research and extension needs of the structural pest control industry and the public in California.

California has hosted more research into SF alternatives than any other state, primarily driven by individual faculty members at the University of California (UC) Berkeley, UCLA, and UC Riverside over the past 70 years. But as these faculty members have aged and retired, research priorities have shifted, and research on alternatives to fumigation has slowed considerably. The expanding range of the drywood termite makes California the logical place for research into drywood termite treatment alternatives.

Over the past 30 years, research into drywood termite control has focused on six key areas: 1) improving inspection devices, 2) age-dating drywood termite pellets, 3) localized chemical treatments, 4) drywood termite baits, 5) molecular studies, and 6) the use of essential oils. Other fumigants have also been considered for structural applications, although this line of research has not constituted a significant area of effort. Some of these avenues for research perpetuate society's reliance on chemicals to resolve pest challenges.

Given the reliance of localized treatments on finding precise termite locations, more accurate inspection devices would directly increase the effectiveness of alternative treatments. Six-sided fecal pellets are telltale signs of termite infestations, but inspectors may confuse pellets from previous infestations as signs of an active one. Thus, rapid age-dating pellet tests would provide important information that would affect treatment recommendations and eliminate unnecessary treatments. Localized chemical treatments are a popular option for treating termite galleries that are both accessible and limited in extent. However, some of the most effective active ingredients have had their registrations revoked due to serious environmental and human health concerns, and those currently in production are less effective at eliminating infestations. Attractants and pheromones, when combined with spot treatments, could improve the effectiveness and range of drill-in-treat chemical methods. Baits have proven effective for the control of subterranean termites, and this approach may hold promise for drywood termites, although more research is needed to identify effective baits for drywood termites. Molecular biomarkers may provide a means to determine the size, age, and extent of a termite infestation, allowing for more informed treatment recommendations, although conducting a molecular study before treatment is not yet feasible in practice. Finally, research has shown that some essential oils exhibit short-term toxicity against termites and can prevent termite feeding; however, this approach is likely to be ineffective as a standalone treatment. Two fumigants have been proposed as possible alternatives—ethyl formate and ethanedinitrile. Neither holds much promise in structural applications due to their high flammability.

Overall, given the limited market for drywood termite treatments, the structural pest control industry would benefit from a program like the IR-4 Project, which supports research and funding for pest management for California's specialty crops (i.e., those that compose a small share of the market) that would otherwise not receive sufficient investment.

Assessments 4 and 5: Viability of adopting these alternatives to effectively manage pests in California and barriers to and incentives for wide-scale adoption of alternatives

Alternative treatments are already widely used in California to address drywood termite infestations. However, expanding the use of these alternatives beyond their current use levels will be challenging due to several significant barriers. Because the California Structural Pest Control Act prioritizes whole-structure treatments over localized treatments, there are some situations where SF remains the only legally viable option for PMPs to recommend—specifically, when termite infestations extend into areas inaccessible to PMPs within structures that are not amenable to whole-structure heat treatment. As the Structural Pest Control Act stands today, PMPs who recommend localized treatments in such circumstances would be in violation of the Act, making the PMPs vulnerable to legal action. Other barriers include the risk tolerance of property owners in response to the threat that termites pose to their properties and requirements from some loan agencies that properties be certified as pest-free.

The limited number of alternative whole-structure treatments also presents a barrier. At present, heat treatments are the only whole-structure alternative capable of controlling termites. While heat treatments are equally effective as SF fumigation in controlling infestations, retail heat treatments cost approximately twice as much as fumigating. Furthermore, not all structures can be heat-treated. The high temperatures required for control can damage heat-sensitive materials like vinyl, Formica cabinets, and newly installed wood flooring.

There are also several factors that may contribute to unwarranted fumigations, as well as situations where infestations could have been prevented. For example, because PMPs are not required to remove or cover signs of termite infestations following treatment, future inspectors may confuse these remnants with evidence of a new infestation requiring treatment. Some property owners may not have the will or means to conduct adequate building maintenance or integrated pest management that might otherwise prevent infestations that would prompt fumigation.

Incentives to develop and adopt alternatives to SF include alignment with integrated pest management and sustainable pest management frameworks, which DPR supports through grant programs and regulatory mandates aimed at reducing or eliminating the use of high-risk pesticides by 2050. Adoption of alternatives to structural fumigation could be enhanced by improving access to clear, up-to-date data on the effectiveness, cost, and long-term outcomes of these treatments. Empowering PMPs with this information and supporting their ability to communicate it effectively to homeowners could help shift consumer decisions away from SF. However, adoption also depends on property owner perceptions, financial constraints, and their motivations, which remain poorly understood. Targeted research into these sociocultural and economic factors is needed to inform effective outreach and policy. Climate change and increased development in California's more arid environments are contributing to the spread of drywood termites. Building codes that encourage the use of materials less vulnerable to infestation would decrease the need for fumigation over the long term.

At the time of writing this report, only four individuals at California's land-grant university, the University of California, are dedicated to addressing the state's vast and varied indoor insect pest problems, including ants, bed bugs, cockroaches, and termites. This is despite California having the largest urban population in the United States and one of the highest densities of wooden homes. For greater impact and stakeholder engagement, resources should be directed toward creating and maintaining additional pest management research and extension personnel who can explore alternative control measures to fumigation and help educate the public about these alternatives.

Assessment 6: Areas where research may still be needed to answer some of these questions

While many of the questions that guided this study can, in theory, be answered using existing data maintained by County Agricultural Commissioners, DPR, and the SPCB, these resources are fragmented and often housed in formats that are not readily analyzable. Improving data accessibility and standardization would support more comprehensive assessments of fumigant use and alternatives.

In terms of health and environmental impacts, research on long-term occupational exposure to SF remains limited. Only two studies have investigated these effects, both conducted more than 25 years ago and before California's updated reentry guidelines, leaving a critical gap in understanding current exposure risks. Similarly, data on the effectiveness, cost-effectiveness, human health risks, and environmental trade-offs of many alternative treatments are sparse. There are also few mechanisms to systematically track the extent to which alternatives are being adopted in practice.

Finally, there is a notable lack of sociological research on structural and urban pest control. Compared to agricultural contexts, little attention in the peer reviewed literature has been given to the social and institutional factors that shape pest management decisions in urban settings. This includes property owner decision-making, barriers to adopting more sustainable practices, and the environmental justice implications of current control methods. This information is essential for understanding how to reduce the use of this highly toxic material.

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. Findings, Conclusions, and Recommendations are numbered sequentially (FCR #). The full list of FCRs, including Findings, can be found in ***Appendix IX***.

Chapter 1: Sulfuryl Fluoride as Structural Fumigant

Chapter 2: Alternatives to Sulfuryl Fluoride

Chapter 3: Research on Alternatives to Sulfuryl Fluoride

Chapter 4: Addressing Barriers and Increasing Adoption of Fumigant Alternatives

Chapter 1: Sulfuryl Fluoride as Structural Fumigant

Section 1.1: Chapter Overview

This chapter discusses the use of sulfuryl fluoride (SO_2F_2; hereafter referred to as SF) to control structural pests, with a particular focus on the control of drywood termites. The use of SF as a commodity fumigant is beyond the scope of this report. Section 1.2 discusses the physical properties as well as the attributes of SF that make it a preferred structural fumigant. Section 1.3 describes the pests for which the use of SF has been approved and their prevalence in California and the United States. This section also includes other insecticides **registered**[1] in California to control drywood termites and other pests. Section 1.4 provides a brief description of the process of fumigating a structure. Section 1.5 considers possible means of reducing the amount of SF used to fumigate structures. Section 1.6 discusses usage patterns and trends. Section 1.7 provides a detailed discussion of the potential human health risks associated with SF. Section 1.8 addresses the environmental and ecological concerns related to SF use. Section 1.9 discusses the limited data available on the use of SF outside of California. Finally, Section 1.10 considers tradeoffs related to the use of SF.

Chapter 1 contains 50 FCRs: 33 Findings, 14 Conclusions, and 4 Recommendations.[2]

Section 1.2: Introduction

SF is a colorless, odorless gas used to control drywood termites and other pests. While it has some limited uses in industrial applications, SF is primarily used to fumigate structures to treat pests. SF was first registered in 1959 to fumigate closed structures and their contents, such as domestic dwellings, garages, barns, storage buildings, commercial warehouses, ships in port, and railroad cars. It kills numerous insect pests, including termites, powderpost beetles, old house borers, bedbugs, carpet beetles, clothes moths, and cockroaches, as well as rats and mice.

By definition, a fumigant exists in the gaseous state, at a required temperature and pressure, in sufficient concentrations to be lethal to a given pest organism (Munro, 1969). In the California Structural Pest Control Act, a fumigant is defined as a substance having a vapor pressure

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

[2] 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.

greater than 5 mm of mercury at 25°C that is labeled for the destruction of plant and animal life. Chloropicrin, liquid nitrogen (N_2), and carbon dioxide (CO_2) are exempted from this definition because chloropicrin is a warning agent, and liquid nitrogen and CO_2 are asphyxiants (Section 8505.1, SPCB, 2021).

The U.S. Environmental Protection Agency (EPA) has determined that SF labels must carry the signal words, "DANGER POISON," signifying the highest level of toxicity. This determination is based upon the **acute** inhalation hazard that SF poses as a colorless, odorless gas. At the federal level, SF is classified as a **restricted-use pesticide**[3] and can only be used by a certified pest management profession (PMP) or someone under their supervision (EPA, 2024). SF is also classified as a **restricted material** in California by the California Department of Pesticide Regulation (DPR) and is designated as a **toxic air contaminant** (DPR, 2006).

The physical properties of SF are provided in ***Table 1.1***. Several properties make SF a preferred fumigant for controlling drywood termites. It has a high vapor pressure of 13,442 mmHg at 25°C, which is eight times greater than methyl bromide (1,380 mmHg at 25°C) (Kenega, 1957). It is a gas over a broad range of ambient temperatures because of its high vapor pressure and low boiling point. SF penetrates wooden substrates more effectively than methyl bromide, except for hydrated wood (Stewart, 1957; Scheffrahn & Thoms, 1993). It is noncorrosive and is less reactive to substrates than methyl bromide, which reacts with sulfur-containing materials such as rubber, fur, leather, and wool to produce a mercaptan (sulfur-like) odor (Derrick et al., 1990). The solubility of SF in water is 750 ppm. SF is 3.5 times heavier than air, and fans and air circulation are required to ensure rapid and uniform distribution. It is **hydrolyzed** in sodium hydroxide (NaOH) solutions and soluble in **biosolvents** (Eisenbrandt & Hotchkiss, 2010; Liang et al., 2018).

The modes of action of SF are not well understood. The current hypotheses to explain SF's toxicity suggest that the hydrolysis of fluoride ions and the inhibition of enzymes involved in energy production are responsible. In drywood termites exposed to SF, the glycolysis pathway was blocked (i.e., sugar could not be broken down), and there was an increase in consumption of oxygen (Meikle et al., 1963). Meikle et al. (1963) proposed that the remaining pathways of energy production through proteins and amino acids in termites exposed to SF were insufficient to maintain the increased metabolism, and the termites died. Kodani (2012) proposed an additional mode of action that involves the inhibition of various enzymes such as glutathione S-transferase (GST), glutathione (GSH), and cholinesterase. This could explain the long latent mortality period of five days required to kill termites (Osbrink et al., 1987). To date, there have been no reports of pests developing resistance to SF.

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

Table 1.1. Physical properties of sulfuryl fluoride

Physical and chemical properties of sulfuryl fluoride	
Chemical name, IUPAC name, Chemical Abstracts Service registry number	Sulfuryl fluoride, sulfuryl difluoride, 2699-79-8
Common names	Sulfuryl fluoride, sulfuric oxyfluoride
Trade names (structural fumigants only)	Vikane®, Zythor
Physical appearance	Colorless, odorless gas, nonflammable, noncorrosive
Molecular formula	SO_2F_2
Molecular weight	102.1 g/mole
Specific gravity (25°C)	
Compared to water at 4°C	1.34
Compared to air	3.52
Vapor density (20 °C)	4.3 g/L
Vapor pressure	17.7 atm at 20°C (13,442 mmHg at 25°C) 15.2 atm at 25°C (11,552 mmHg at 20°C)
Henry's law constant (atm m^3/mol)	0.11[b] 1.57 0.0328[c]
Boiling point (1 atm)	-55°C
Melting point (1 atm)	-136°C
Octanol-water partition coefficient (K_{ow}), with log Kow in brackets	2.57 [0.41][d] 1.38 [0.14] at pH 7, 20°C[e]
Solubility (g/L)	
In water (25°C)	0.75
In water (20°C)	1.04
In n-Octanol (20°C)	14
Hydrolysis: Half-life @25°C	5.3 days (pH 2), 3.1 days (pH 5.9), 7.0 hours (pH 7), 10 min (pH 8.3)
Mass spectrum	102 M+, 83 M+-F, 67 m/z 83 -O
Conversion factor	1 ppm = 4.17 mg/m^3
(25°C and 760 mmHg)	1 oz/1,000 ft^3 = 1 g/m^3 = 241 ppm

Source: DPR (2020).
Notes:
[a] Calculated on the average water solubility measured at 1 atm, 23°C: 100 mL water dissolved 23.3 cm^3 SF gas (2 cm^3 gas contains 8 x 10^{-5} moles of SF).
[b] Estimated.
[c] Estimated using a structural fragment method.
[d] Calculated.

Since the registration of SF for fumigation, most of the regulatory concerns have focused on its safety to PMPs, bystanders, and occupants of the structures (EPA, 1993). A Reregistration Eligibility Document was prepared in 1993, at a time when regulations required that SF levels in the air had to be less than 5 ppm before reentry into the structure was permitted. As part of the reregistration process, additional comments and research were requested on the amount of SF permitted in the structure prior to reentry. As a result of these evaluations, the reentry level decreased to less than 1 ppm in 2006. In 2023, the EPA issued a Sulfuryl Fluoride Revised Mitigation and Response to Comments on the Draft Interim Re-Entry Mitigation Measures. A change in the labeling of SF was issued in 2024, which included additional directives regarding no-entry warning signs, site-specific fumigation logs, a list of portable clearance devices, and longer active and passive aeration times (EPA, 2024). Many of the changes were already required by California regulations.

In California, the structural pest control industry developed the Tarpaulin and Removal Aeration Plan (TRAP) in the 1990s, which was approved by DPR and was the standard for clearing structures of methyl bromide and SF. When the reentry concentration of SF was reduced to 1 ppm or less before structures could be safely entered, the California structural pest control industry led the development of a replacement for TRAP, resulting in the California Aeration Plan (CAP). DPR approved CAP, and it was first adopted in 2010 to replace TRAP (CAP, 2013). CAP was revised in 2013 (FAN, 2014).

In California, three agencies have jurisdictions that intersect with the structural pest control industry. The California Structural Pest Control Board (SPCB) promotes outreach, education, and regulation of the structural pest management profession (SPCB, 2025). DPR regulates pesticide sales, monitors pesticide use, and fosters reduced-risk pest management (DPR, 2025a). Lastly, the County Agricultural Commissioners (CAC, appointed locally but reporting to the CDFA Secretary and DPR) enforce the proper, safe, and effective use of pesticides at the county level (CAC, 2025), including through inspections of structural fumigations. These inspections by the CAC provide some insights into the frequency with which there are violations of structural fumigation protocols. For example, in Los Angeles County, 826, 784, and 715 structural fumigation use monitoring inspections were conducted in 2021, 2022, and 2023, respectively (CACLA, 2023). Violations were found in 3.5%, 2.8%, and 4.2% of the inspections in 2021, 2022, and 2023, respectively.

The Structural Fumigation Enforcement Program was started by the California structural pest control industry. It began in 1993 in Los Angeles County as a 2-year pilot project. A fee of $5 per fumigation was established to support additional inspection and enforcement activities. Orange County joined the program in 1996 and Santa Clara County joined in 2007. In 2009, San Diego became a member of the program (SD, 2025). In 2014, the fee was increased to $8 per fumigation. In 2022, the law was extended until January 1, 2029, for Los Angeles, Orange, and Santa Clara counties (CAL, 2025a).

The use of the fumigant methyl bromide to control structural pests was suspended in 2005 under the Montreal Protocol on Substances that Deplete the Ozone Layer, and this product was discontinued. By then, SF fumigation in California (3,337,600 lb in 2004) had replaced methyl bromide (17,483 lb in 2004) as the primary method for controlling structural pests. SF has proved equally effective as methyl bromide in killing drywood termites and wood-destroying beetles. Of the 78,834 structures fumigated in 2023 in California, it is estimated that fewer than 400 fumigations (0.005%) failed to control target pests. These failures are most likely attributable to a failure of the application or company, rather than the fumigant or normal process (T. Ineichen, pers. commun., 4/21/2025). However, it should be noted that this estimate does not include fumigation failures that were successfully mitigated directly between the consumer and contractor, nor does it include the number of failures that went unidentified.

1. **FINDING:** Sulfuryl fluoride is the only fumigant approved for the control of pests in domestic dwellings, garages, barns, storage buildings, and commercial warehouses in the United States.

2. **FINDING:** The physical properties of sulfuryl fluoride that make it an effective fumigant for structural pest control include its low boiling point, high vapor pressure activity, ability to penetrate wood substrates, noncorrosive nature, nonreactivity with substrates, and low solubility in water.

3. **CONCLUSION:** Sulfuryl fluoride has been an effective replacement for methyl bromide as a structural fumigant.

Section 1.3: Pests Managed or Controlled

Surveys of wood-destroying organisms encountered in California structures have not been conducted for the last 30 years. In 1931, drywood termites reportedly infested 3% of structures in Los Angeles (Hunt, 1949). By 1948, this had increased to 75% of the homes inspected (Hunt, 1949). Of 240,926 inspection reports submitted in California in 1962, 35.7% indicated the presence of drywood termites. In Los Angeles County, 46.8% of the reports were positive for drywood termites (Ebeling & Wagner, 1964). Drywood termites were reported in 1%, 2%, 5%, and 11% of the Wood Destroying Pests and Organisms Inspection Reports filed with the SPCB (***Appendix I***) for the northern counties of San Francisco, Marin, Alameda, and San Mateo, respectively (Wilson, 1979). In contrast, the southern counties of Los Angeles and San Diego had infestation rates of 75% and 73%, respectively. Another survey of southern counties (Los Angeles, Orange, and San Diego) reported higher incidences of drywood termites than in northern counties (Alameda, Contra Costa, and Santa Clara) (Brier et al., 1988). Attics and garages were the most heavily infested sites in southern counties (44% and 32%, respectively), whereas only 4% and 6%, respectively, were infested in northern counties. In a survey of SPCB reports from August 1992 to June 1993, 55% of the structures inspected in Orange, Riverside, and San Bernardino counties had evidence of drywood termites, 22% had evidence of subterranean termites, and the presence of damp wood termites or beetles was insignificant (T. Atkinson, pers. commun., 2/5/2025). Older urban centers showed higher incidences of drywood termites than did newer developments. This 1994 survey was the last extensive survey of wood-destroying insect reports in California. In a 2013 DPR report, it was estimated that about 3% of the fumigations were conducted to control powderpost and deathwatch beetles.

Prior to treatments for wood-destroying insects by pest management professionals (PMPs) in California, structures are inspected by licensed inspectors (SPCB, 2021). The inspectors provide the homeowner or property owner with a report that indicates the type of wood-destroying insects present, a schematic drawing of the structure with notations regarding the infestations, conditions conducive to pest infestations, recommendations for their remediation, and costs (***Appendix I***). California state law does not require these inspections and reports for real estate transactions. However, many loan agencies and buyers stipulate that inspections for wood-destroying insects be conducted and that all active infestations of wood-destroying organisms, or damage resulting from those infestations that were identified, be certified as eradicated, eliminated, repaired, or replaced prior to funding the real estate transaction. These reports contain valuable information regarding wood-destroying insects in California, including their location within the structure, primary and secondary control recommendations, and the cost of control and repairs (***Appendix II***). When the work has been completed, a Standard Notice of Work Completed and Not Completed is retained by the PMP for three years (CAL, 2025b). The number of original inspections, limited inspections, reinspections, corrected or supplemental reports, and notices of work completed in California is shown in ***Figure 1.1***. The number of inspection reports and associated paperwork peaked in 2017 at 1.4 million and declined to 1 million in 2023. It would be a tremendous undertaking to sort the reports and gather all the information for each structure inspected in California.

Other structural pests, including bed bugs, clothes moths, cockroaches, and rodents, are also occasionally fumigated with SF. According to select representatives of California companies that provide fumigation services, approximately 5% of fumigations are for bed bugs, while treatments for cockroaches, rodents, and clothes moths collectively account for 1% of fumigations. The remaining 94% are for drywood termites (D. Wadleigh, pers. comm., 7/30/2025). Data regarding these treatments are not recorded on the wood-destroying organisms inspection reports and have not been documented in the literature. The number of fumigations performed to control pests other than wood-destroying organisms has never been published.

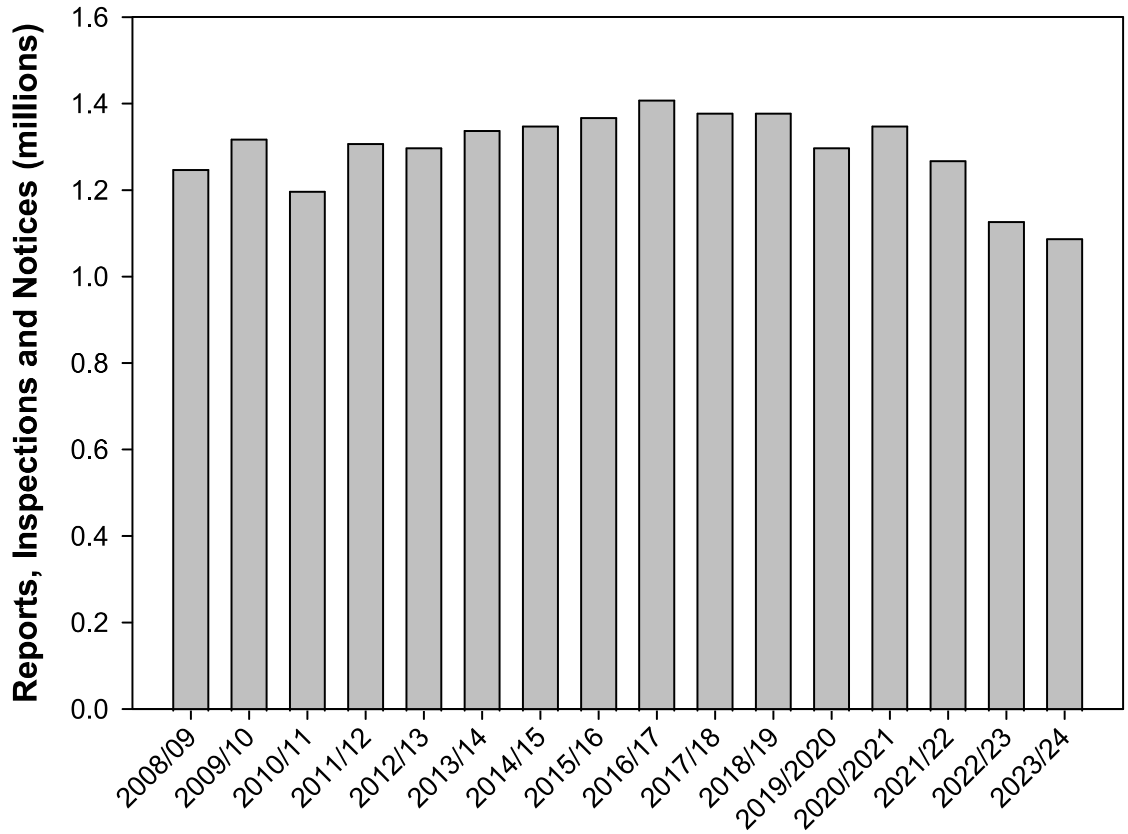

Figure 1.1. Number of original inspections, limited inspections, reinspections, corrected or supplemental reports, and notices of work completed filed in California with the Structural Pest Control Board.

Wood-Destroying Pest Species in California

The pests of structural wood and wooden materials and objects include termites, fungi, beetles, carpenter ants, carpenter bees, and wood wasps. The importance of each group primarily depends on geographical location in the United States and California. For example, anobiid beetles are major structural pests in the United Kingdom and northern Europe but are limited to the northwestern and southeastern United States. Some beetles and wood wasps only deposit their eggs on trees with bark on them and will not reinfest structural lumber. Termites, some beetles, carpenter ants, and carpenter bees can also attack or lay eggs on structural wood and wood products without bark. Termites and beetles that can lay eggs or reinfest processed wood require remedial control.

The western drywood termite, *Incisitermes minor* (Hagen), is one of the most important termite pests in California (***Figure 1.2***). Its distributional range extends from northern Mexico northward into Mendocino County, California, and eastward into Arizona (Light, 1934a, 1934b). In recent years, its range has expanded along the Colorado River system into Utah and Colorado (Jones, 2004).

The distribution of structures fumigated in California approximates the extent of the *I. minor* range in California (DPR, 2024; ***Figure 1.3***). Two major centers of termite activity are the counties around San Francisco Bay and the southern coastal and inland counties encompassing Los Angeles. In Riverside and San Bernardino counties, most fumigations occur in the populous areas of the Inland Empire west of the San Bernardino Mountains. The incidence of drywood termites has increased with the urbanization of more desert and arid communities in Central and Southern California (Rust, 2006). Its range is probably limited by winter temperatures, which restrict its northern range and its spread into mountain communities. *I. minor* will likely expand its range outside California by 2050 due to global warming (Buczkowski & Bertelsmeier, 2017; ***Figure 1.4***). While the number of fumigations performed in each county is a useful metric, it is an imperfect one for understanding the relative abundance of this species in California because the number of fumigations will be correlated with housing and building density. As such, this metric may understate the impacts of this species in rural areas.

Figure 1.2. Western drywood termites (*Incisitermes minor* (Hagen)). (Left) winged alates (reproductive individuals) and soldiers (without wings). Photo credit: Ansel Oomen. (Right) worker. Photo credit: Pest and Diseases Image Library, Bugwood.org.

Figure 1.3. Number of structures fumigated in 2022 in California. This approximates the distribution of *I. minor* in California, as well as provides a rough indicator of its abundance (note that the number of fumigations will necessarily correlate with building density). Source: Unpublished data from DPR (2024) provided to the California Council on Science and Technology.

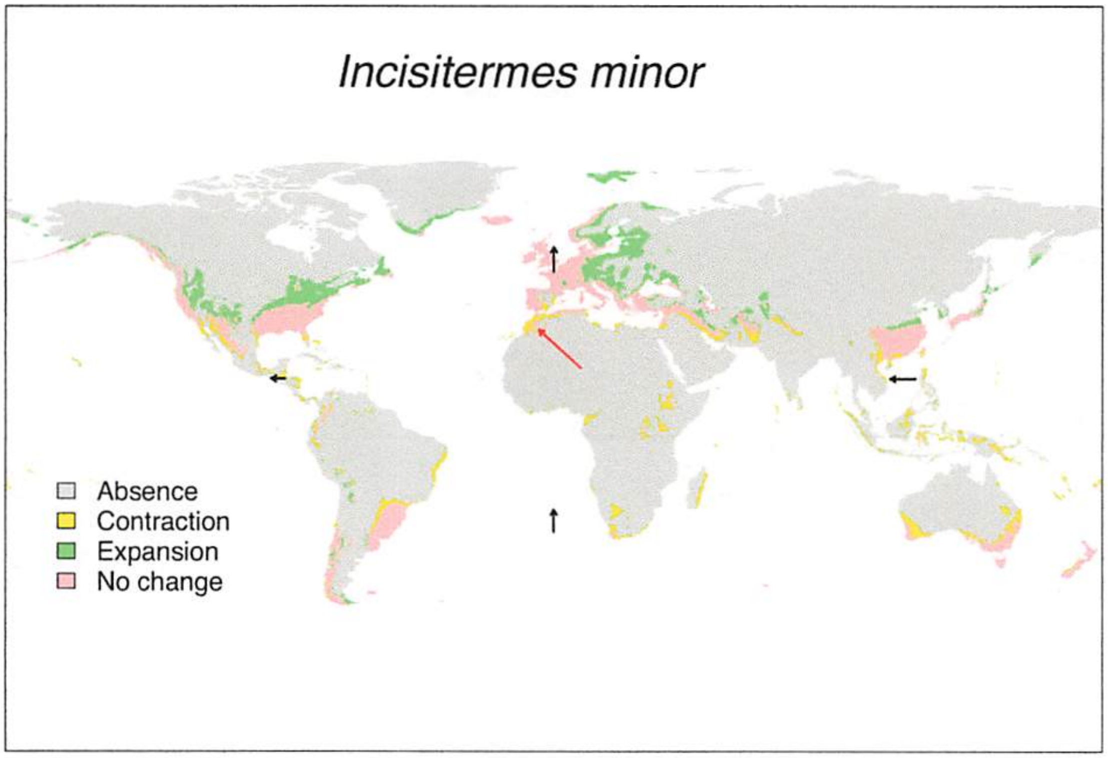

Figure 1.4. Expansion into the green areas may occur by 2050, and areas in yellow are suitable today but not in 2050 (losses). Areas in pink are suitable in both years, and areas in gray are suitable in neither of these years. The black arrows indicate changes of the range margins in all four cardinal directions, and the red arrow represents the shift vector of the center of gravity of the species' potential distribution. Reprinted from Buczkowski & Bertelsmeier (2017). Used under Creative Commons Attribution License.

Established colonies of *I. minor* have been reported in Florida, Louisiana, and Georgia. Its spread is attributable to interstate commerce and the movement of infested objects. Over the past decade, it has gained international attention as an invasive species and is now established in China, Japan, and Korea (Evans et al., 2013; Lee et al., 2024).

Another drywood termite, *Marginitermes hubbardi* (Banks), is occasionally encountered in the Sonoran Desert areas of Southern California and Arizona. On rare occasions, the invasive drywood termite *Cryptotermes brevis* (Walker) has been reported infesting wooden objects imported into California (Ebeling, 1975).

In semitropical and tropical climates, the invasive Formosan subterranean termite, *Coptotermes formosanus*, constructs aerial nests that are not connected to the ground and often nests within wooden ships and boats. PMPs would normally recommend fumigation to treat these aerial nests. Since 1995, nine infestations have now been positively identified in California

(C.-Y. Lee, pers. commun., 7/27/2025). However, no aerial nests have been reported in structures in California.

The most important species of wood-destroying beetle in the western United States is the so-called Pacific or California deathwatch beetle, *Hemicoelus gibbicollis* (LeConte) (***Figure 1.5***). It belongs to the family Anobiidae. It is a structural pest in coastal areas of British Columbia, Washington, Oregon, and northern California, and prefers lumber that has less moisture than green Douglas fir in structures 8–122 years old (Suomi & Akre, 1992a). Infestations are primarily found in crawl spaces, basements, and outbuildings, particularly in unfinished pieces of wood (Linsley, 1943; Suomi & Akre, 1992a). Inspections in coastal Oregon indicated that 28% of structures had evidence of beetle infestations (Mankowski & Morrell, 2000). This species has not been reported from the dry inland areas of Washington or Oregon (Suomi, 1992). Ninety percent of wood members infested with *H. gibbicollis* had wood moisture contents from 13% to 17% (Suomi & Akre, 1992a). This species will reinfest wooden items. In Washington, it was reported to cause $7 million to $8 million in replacement and treatment costs annually (Suomi & Akre, 1992b), or $18 million when adjusted to 2024 values. This is probably the most frequently encountered beetle in northern California, but precise data regarding its incidence and economic importance in northern California are not available.

Figure 1.5. Wood-boring insect known as the deathwatch beetle (*Hemicoelus gibbicollis* (LeConte)). Photo credit: Pest and Diseases Image Library, Bugwood.org.

Several beetles belonging to the family Bostrichidae (powderpost and false powderpost beetles) have been reported as pests in structures, wooden items, and furnishings in California. These are the most frequently encountered wood-destroying beetles in Southern California.

The lead-cable borer, *Scobicia declivis* (LeConte), prefers seasoned hardwoods such as oak (Burke et al., 1922). Its common name refers to its ability to penetrate lead sheathing previously used to cover telephone cables. This practice has been largely discontinued because of exposure risks to lead (Shiel, 2004). It is reported as a pest of wooden wine barrels, as well as hardwood paneling and flooring. This species lays eggs and reinfests wooden items (Ebeling, 1975).

The oriental wood borer, *Heterobostrychus aequalis* (Waterhouse), is native to India and Southeast Asia, where it is a serious pest of seasoned hardwood timber (Woodruff, 1967; Wylie & Peters, 2016; Woodruff & Fasulo, 1987). It attacks plywood, furniture, and other manufactured goods. In California, it is occasionally found in furniture and other manufactured goods.

The black polycaon beetle or Stout's branch borer, *Polycaon stoutii* (LeConte), is found throughout California and Arizona. It will burrow through finished materials to emerge from infested wood but will not lay eggs in finished wood products (Ebeling, 1975).

Beetles belonging to the subfamily Lyctinae attack hardwoods, some softwoods, and bamboo. Two species, *Lyctus planicollis* (LeConte) and *Lyctus brunneus* (Stephen), are found in hardwood flooring, decorative wooden items, and furniture (Ebeling, 1975). The beetles will reinfest hardwood items.

In 1938, one study estimated that beetles belonging to the families Bostrichidae and Anobiidae caused $35 million in damage annually to forest products (Hyslop, 1938; equivalent to $849 million in 2024 adjusted values). However, the reduction in the number of homes with crawl spaces, changes in building practices, the use of central heating, the use of laminated wood, and other modern building practices have greatly reduced the importance of these wood-destroying beetles (Williams, 1980).

Wood-Destroying Species Outside California in the United States

In Hawaii and Florida, the invasive West Indian drywood termite, *Cryptotermes brevis* (Walker), is an important pest of structures. *C. brevis* is native to Peru and has expanded its range to Australia, Africa, the New World tropics, and tropical oceanic islands (Scheffrahn et al., 2008; Evans et al., 2013). Outside its native range it is the most important drywood termite structural pest worldwide. *C. brevis* has been found on rare occasions in wooden items in California, but it is never known to have established colonies. There is considerable literature regarding its prevention and control that directly bears on this report.

In Florida and the southeastern U.S. coast, the eastern drywood termite, *Incisitermes synderi* (Light), is of structural importance. Research has been conducted on the control of this species that bears relevance to this report.

Euvrilletta peltata (Harris) is the most common anobiid beetle in the southern United States (Williams, 1980; Wright, 1959). Inspections of crawl spaces in 11 southern states found that more than 99% of the confirmed infestations were attributed to *E. peltata*. Infested houses were from 9 years old to more than 100 years old (Williams & Smythe, 1978). In 1970, an estimated 53,000 treatments for wood-destroying beetles were performed in 11 southern states. The cost estimates for treatment were approximately $4.9 million, but this did not include any repair costs. There has been a considerable decline in homes built with crawl spaces in the southern United States, resulting in a sharp decline in *E. peltata* infestations. The addition of central heating and air conditioning has also reduced wood moisture content and anobiid infestations (Williams, 1980). Similar changes in construction practices in Western states have also reduced the likelihood of anobiid infestations. High wood moisture content favors larval development, and methods to reduce moisture in crawl spaces help control wood-destroying beetle infestations (Williams, 1983).

Lyctus brunneus and *L. planicollis* are two lyctid beetles occasionally found attacking hardwoods in structures. Their importance has declined because most hardwoods are kiln-dried or used as veneers, in which the drying process and the glues help prevent attack (Williams, 1980).

The old house borer, *Hylotrupes bajalus* (L.), belongs to the family Cerambycidae and is probably native to North Africa. It is an invasive pest of homes in the eastern United States, especially in homes that are 2–7 years old (Cannon & Robinson, 1982). The beetle will reinfest rough-cut lumber.

Wood-Destroying Species Outside the United States

The import of wood and products made from wood from outside the United States increases the likelihood that an invasive pest species might enter California and become established. Important pest groups attacking structures and wood products include drywood and subterranean termites and several families of beetles. Invasive beetles belonging to the family Cerambycidae (longhorn beetles) and Bostrichidae (auger or false powderpost beetles) are especially important because they attack lumber used as packaging materials for international shipments. The infested packing material is discarded, and the adult beetles emerge. The adult beetles lay eggs on native trees in Canada, the United States, and Europe. Several beetle species are found in wooden products imported into California, especially from Southeast Asia. There are several species of drywood termites that might become structural pests if they were to successfully establish themselves.

In addition to the invasive drywood termite *C. brevis*, other species of *Cryptotermes* are important regional pests, such as *C. dudleya* and *C. havilandi*. In northern Brazil, approximately 7% to 10% of the structures inspected were infested with *C. dudleya* (Vasconcellos et al., 2002; Albuquerque et al., 2012). It is commonly found attacking structures and lumber in India, Indonesia, and Malaysia.

Surveys in the United Kingdom from 1960 to 1965 indicated that the common furniture beetle, *Anobium punctatum* (De Geer), was found in 75% of all buildings inspected, totaling 106,620 infestations. Deathwatch beetles and weevils were also reported in approximately 5% of the inspections. *Lyctus* spp. were found in 0.9% of the buildings inspected. Drywood termites were not reported (Hickin, 1975).

Hylotrupes bajulus is the most serious pest of seasoned softwoods in the United Kingdom and Europe. However, the incidence of the beetle in Germany and Sweden has declined significantly over the past 60 years (Lukowsky, 2017). Factors that have reduced the importance of the old house borer include the following: 1) preventive and remedial chemical treatments, 2) changed building practice and use of attics, 3) reduced introduction of beetles, and 4) changing wood quality and greater use of planed timber for roof structures (Lukowsky, 2017).

4. **FINDING:** The western drywood termite, *Incisitermes minor*, is the major pest in California targeted with sulfuryl fluoride fumigation. Other wood-destroying insects, such as carpenter ants, carpenter bees, beetles, and wood wasps, are regional pests.

5. **FINDING:** The nonnative and destructive drywood termites *Incisitermes synderi* and *Cryptotermes brevis* are unlikely to become established in California.

6. **FINDING:** Trends concerning the incidence and importance of insect pests encountered by pest management professionals could be determined from their required record-keeping. The data have never been thoroughly analyzed and reported.

7. **FINDING:** The distribution and importance of *Incisitermes minor* will likely increase in response to climate change.

Other Structural Pests of Concern

The German cockroach, *Blattella germanica* (L.), is the most important cockroach pest species found indoors worldwide. They infest apartments, homes, restaurants, and food preparation areas in hospitals, hotels, and ships. German cockroaches pose a risk to human health because they are mechanical vectors of disease and produce allergens that can cause asthma (Ebeling, 1975). German cockroaches have developed behavioral and physiological resistance to many of the chemicals listed in ***Table 1.4***.

The common bed bug, *Cimex lectularius* L., was once thought to have been eradicated in California. However, by 2005, there was a resurgence of this pest throughout the state, especially in low-income housing. Bed bugs are not known to transmit any infectious diseases, but their bites do cause cutaneous reactions, potential dermatological complications, and considerable anxiety (Hwang et al., 2018). Bed bugs have developed physiological resistance to some of the chemicals listed in ***Table 1.6***, especially pyrethroids (Romero, 2018).

In California, the webbing clothes moth, *Tineola bisselliella* (Hummel), is the most frequently encountered clothes moth (Ebeling, 1975). Larval clothes moths primarily feed on fabrics made of wool and made of a mixture of wool and synthetics or vegetable origin. Clothes moths may also infest abandoned bird, rodent, and insect nests. The larvae typically remain on the food source.

In California, the black carpet beetle, *Attagenus megatoma* (F.), and the furniture carpet beetle, *Anthrenus flavipes* (LeConte), are the two most frequently encountered carpet beetles (Ebeling, 1975). Like clothes moths, the larvae are responsible for damage to fabrics and other items consisting of fur, feathers, or skins. The black carpet beetle is also a pest of stored grains. Larvae may crawl about and are often found some distance from the food source.

In California, there are two important rat pest species, the Norway rat, *Rattus norveigicus* (Berkenhout), and the roof rat, *Rattus rattus* L. Rats harbor disease organisms, including plague, murine typhus, and leptospirosis (Ebeling, 1975). Their chewing activities can cause damage to electrical wires, plastic, galvanized pipes, and garbage cans.

Pests Listed on Sulfuryl Fluoride Labels

In California, two products containing SF—Vikane and Zythor—are approved for the control pests in dwellings (including mobile homes); buildings; construction materials; household furnishings; shipping containers; and vehicles, including automobiles, buses, passenger railcars, recreational vehicles, and surface ships (Vikane, 2022; Zythor, 2024). An additional SF-containing product, ProFume, is approved for nonresidential structures, food-handling establishments, stationary vehicles, chambers, and storage structures (ProFume, 2025). However, these applications of ProFume are classified by DPR as “commodity” rather than “structural” and are thus beyond the scope of this report. The pests included on the labels for Vikane and Zythor are various arthropods and rodents (***Table 1.2***). When a pest is “on the label,” this means that the fumigant is legally approved for use against that pest, per the EPA.

Table 1.2. Summary of various arthropod and vertebrate pests on SF labels in California.

Pest	Dosage–multiple drywood termite rate[a]	Life stages	Notes
Rodents	0.5x		
Carpet beetles	1x	Eggs not killed	After egg hatch, more than one fumigation may be needed
Cockroaches	1x	Eggs not killed (except German cockroach)	
Clothes moths	6x		
Furniture carpet beetles	3x	Eggs not killed	After egg hatch, more than one fumigation may be needed
Bed bugs	1.9–3x		
Old house borer	4x		
Formosan termites	4x		Above ground termites are killed
Powderpost beetles	10x		
Deathwatch beetles	10x		
Drywood termites	1x		

[a] Because drywood termites are the most commonly targeted pest for SF, dosage rates for other pests are calculated relative to the drywood termite dosage.

The egg is the insect life stage most tolerant of fumigants such as methyl bromide, ethylene oxide, and SF (Kenaga, 1957). The **lethal accumulated dose (LAD)** of SF required to kill 99% of carpet beetle eggs is 156 mg x hour/liter, approximately 15 times to 20 times the rate required to kill nymphal drywood termites (Su & Scheffrahn, 1990). However, SF fumigation does not need to target drywood termite eggs because newly hatched first instar termites (i.e., termite larva) do not have the ability to digest wood (they lack the symbionts or microorganisms that enable wood digestion). The first instars are provided with the protozoans and microbes from slightly older, although still immature, larval and nymphal termites. Thus, if all the immature termites are killed by the fumigant, then the first instars will die.

The amount of SF applied to control drywood termites or other pests on the label is influenced by the pest species, temperature, exposure period, tarpaulin condition, seal condition (where a tarp is sealed to the ground, structural and landscape features, another tarp, etc.), wind speed, volume of fumigated space, underseal (concrete for slab or soil type for crawlspace), and whether the fumigation is monitored (Vikane, 2022; Zythor, 2024). The Fumiguide Calculator (Vikane) and Fumicalc App (Zythor) assist PMPs in determining the dose required for each pest, existing conditions, and structure (***Appendix V***).

Even though many pests are listed on the SF labels, most SF fumigations are conducted to control drywood termites. SF fumigation is rarely the primary recommendation for the control of household and structural pests such as ants, bed bugs, carpet beetles, cockroaches, fleas, subterranean termites, flies, stored product insect pests, and fabric pests. Fumigation is expensive compared with more conventional treatments to control these pests. Additionally, SF does not readily penetrate the eggs of most insects, requiring high dosages to kill them. A second fumigation may be required to kill immature insects that emerge from fumigated eggs. The costs to fumigate a structure twice would be prohibitive for many homeowners and property owners.

Despite these disadvantages, SF is viewed by some PMPs and property managers as an essential tool of last resort for controlling severe infestations of bedbugs, cockroaches, and rodents in low-income housing. These types of pest infestations tend to be worse in areas of disinvestment, property owner neglect, and public housing (Biehler, 2009; Biehler et al., 2019). These pests, in particular, are notable for their negative impacts on public health. For example, German cockroaches—the major indoor pest found in housing, food-handling establishments, hotels, public transportation, and hospitals in California—can transmit pathogenic microbes such as *Salmonella*, *Staphylococcus*, and *Streptococcus*. Further, the fecal material, metabolic waste, skin, and dead bodies of cockroaches are known sources of allergens and are associated with the development and worsening of asthma (Schal & DeVries, 2021). Bedbug bites and feeding can cause numerous adverse reactions as well as psychological distress (Hwang et al., 2018).

SF fumigation can provide immediate and complete control in situations where severe infestations have proved resistant to conventional treatments. By providing immediate relief, SF fumigation could reduce the extent to which residents, desperate for a solution, take it upon themselves to treat the infestations with potentially even more dangerous and toxic chemicals. However, SF fumigation will not eliminate or correct the conducive conditions that permitted the severe pest infestations to occur, nor will it prevent bedbugs, cockroaches, or rodents from rapidly returning if those conducive conditions are not corrected. Integrated pest management (IPM) programs have proved successful at reducing cockroach and bedbug problems in high-rise apartment buildings (Wang et al., 2019). The IPM program included the education of residents; intensive monitoring; encasing mattresses and box springs; vacuuming; laundering; and applications of cockroach baits, dust, and sprays when necessary.

8. **FINDING:** In severe cases of infestations of pests of public health concern, SF fumigation could be warranted as a tool of last resort.

9. **FINDING:** SF fumigation alone is not capable of addressing pests of public health concern in low-income housing because it does not address the underlying problems that allowed pest infestations in the first place.

10. **CONCLUSION:** For maximum effectiveness and safety, integrated pest management is the preferred method for dealing with pests of public health concern.

Other Pests and Means of Control

Although SF is approved for use against numerous other pests, western drywood termites are the primary target of SF fumigations in California, and this report only considers alternatives available to control drywood termite infestations. To provide further context and justification for this focus, the variety of other active ingredients and chemistries of insecticides registered in California to kill the remaining insect pests listed on the SF label were reviewed. The mode of action and the general class of each insecticide are provided when available. Currently, there are 37 different categories of insecticides established by the Insecticide Resistance Action Committee (IRAC) and a few active ingredients for which their mode of action has not been categorized (IRAC, 2024). This categorization is extremely important when physiological or behavioral resistance develops to a particular category of insecticide. Information concerning the formulation of insecticides is usually provided, but it is difficult to determine if some formulations are **emulsifiable concentrates**, **suspended concentrates**, or **capsule suspensions**. When in doubt, the products were listed as suspended concentrates.

Carpet Beetles

Fumigation of carpet beetles with SF is not often recommended because it is too expensive, and the rate of SF required to kill eggs is 10–15 times the drywood termite rate (Su & Scheffrahn, 1990). The label does allow for a second fumigation to kill larvae that have successfully hatched from treated eggs. SF fumigation provides no residual protection to fabrics, feathers, skins, or other items likely to be infested with carpet beetles.

Numerous products and different chemistries are currently registered to kill carpet beetles in California (***Table 1.3***). Many of the sprays belong to the pyrethroid and pyrethrin chemistry (IRAC 3A). In addition to chemical treatments, cleaning processes such as dry cleaning will kill all stages of carpet beetles. Infestations of museum items are frequently treated with heat, cold, or **modified atmospheres**.

Table 1.3. Representative list of products and active ingredients registered in California to kill carpet beetles.

Product	IRAC	Class	Active ingredient(s)	Formulation
Bifen I/T	3A	Pyrethroid	Bifenthrin	EC
Cy-Kick CS	3A	Pyrethroid	Cyfluthrin	CS
D-Fense NXT	15 3A 7C	CSI Pyrethroid JH	novaluron deltamethrin pyriproxyfen	A
Demand CS	3A	Pyrethroid	δ-cyhalothrin	CS
Dragnet SFR	3A	Pyrethroid	Permethrin	EC
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
EcoPco AR-X	3A	Pyrethrins	pyrethrin 2-phenethyl propionate	A
Hot Shot No-Mess Fogger	3A 3A	Pyrethroid	tetramethrin cypermethrin PBO	TRA
NyGuard Plus	3A 7C	Pyrethroid IGR	d-phenothrin pyriproxyfen	A
Onslaught Fast Cap	3A 3A	Pyrethroid	esfenvalerate prallethrin PBO	MES
Ortho Home Defense	3A 3A	Pyrethroid Pyrethroid	bifenthrin Z-cypermethrin	RTU
PT 565 XLO	3A	Pyrethrins	pyrethrins, PBO	A
PT Alpine	4A	Neonicotinoid	Dinotefuran	A
PT Phantom II	13	Pyrrole	chlorfenapyr	A
Pyganic Dust	3A	Pyrethrins	Pyrethrin	D
Reefer-Galler Moth-Tex		Fumigant	p-dichlorobenzene	Solid
Suspend SC	3A	Pyrethroid	deltamethrin	SC
Tandem	3A 4A	Pyrethroid Neonicotinoid	δ-cyhalothrin thiamethoxam	CS
Tempo Ultra	3A	Pyrethroid	β-cyfluthrin	WP, SC, WSP
Temprid FX	3A 4A	Pyrethroid Neonicotinoid	β-cyfluthrin imidacloprid	SC

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, CS – capsule suspension, D – dust, EC – emulsifiable concentrate, MES – microencapsulated formulation, SC – suspended concentrate, RTU – ready to use, TRA – total release aerosol, WP – wettable powder, WSP – water soluble packets.

Cockroaches

Fumigation is rarely conducted to kill cockroaches because it is too expensive, and SF does not provide residual activity. Most pest species (except German cockroaches) deposit their eggs inside an ootheca or egg capsule, which are unaffected by fumigation at those label rates. The use of gel bait is currently one of the primary recommendations being made to control cockroaches. Resistance in German cockroaches, *Blattella germanica* (L.), to pyrethroid and pyrethrin chemistry is widespread. There are increasing reports of behavioral and insecticidal resistance developing to bait. SF fumigation may be warranted in situations with heavy and persistent infestations of cockroaches after repeated failures with conventional pest management strategies. SF fumigation of shipping containers, automobiles, buses, rail cars, and recreational vehicles might be considered in exceptional cases.

Numerous products are registered in California to kill cockroaches. The use of bait and sprays is currently the most widely used strategy for controlling indoor and outdoor pest species (***Table 1.4***).

Clothes Moths

Fumigations are rarely conducted to control clothes moths. SF does not provide any residual activity to protect animal-based fabrics, furs, and feathers, and requires six times the drywood dose to kill eggs. It also typically requires special fumigation chambers. Alternative treatments such as heat, cold, and modified atmospheres are often used to control infested objects. Cleaning processes, including dry cleaning, will kill all stages of the moth. Numerous sprays and chemistries are registered in California to kill clothes moths (***Table 1.5***).

SF fumigation may be warranted in situations with heavy and persistent infestations of clothes moths after repeated failures with conventional pest management strategies.

Furniture Carpet Beetle

The labeled rate of SF for furniture carpet beetle, *Anthrenus flavipes* (LeConte), control is three times that of the drywood termite rate. However, Su & Scheffrahn (1990) have shown that the rates should be between 15 times and 20 times the drywood termite rate to ensure carpet beetle eggs are killed. Numerous products are approved for the control of carpet beetles and other dermestids (***Table 1.3***).

Table 1.4. Representative list of products and active ingredients registered in California for cockroaches.

Product	IRAC	Class	Active ingredient(s)	Formulation
Advion Cockroach Gel Bait	22A	Oxadiazines	indoxacarb	B
Bifen I/T	3A	Pyrethroid	bifenthrin	EC
Conquer	3A	Pyrethroid	esfenvalerate	EC
Combat Max Roach Killing Bait	13	Pyrrole	fipronil	B
Cy-Kick CS	3A	Pyrethroid	cyfluthrin	CS
D-Fense NXT	15 3A 7C	CSI Pyrethroid JH	novaluron deltamethrin pyriproxyfen	A
Demand CS	3A	Pyrethroid	δ-cyhalothrin	CS
Dragnet SFR	3A	Pyrethroid	permethrin	EC
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
EcoPco AR-X	3A	Pyrethrins	pyrethrin 2-phenethyl propionate	A
Hot Shot Liquid Roach Bait	4A	Neonicotinoid	dinotefuran	B
Hot Shot No-Mess Fogger	3A 3A	Pyrethroid	tetramethrin cypermethrin PBO	TRA
NyGuard Plus	3A 7C	Pyrethroid IGR	d-phenothrin pyriproxyfen	A
Onslaught Fast Cap	3A 3A	Pyrethroid	esfenvalerate prallethrin PBO	MES
Optigard Flex	4A	Neonicotinoid	thiamethoxam	SC
Optigard Cockroach Gel Bait	6	Avermectin	emamectin benzoate	B
Ortho Home Defense	3A 3A	Pyrethroid Pyrethroid	bifenthrin ζ-cypermethrin	RTU
PT 565 XLO	3A	Pyrethrins	pyrethrins, PBO	A
PT Alpine	4A	Neonicotinoid	dinotefuran	A
PT Phantom II	13	Pyrrole	chlorfenapyr	A
Pyganic Dust	3A	Pyrethroids	pyrethrin	D
Suspend SC	3A	Pyrethroid	deltamethrin	SC
Tandem	3A 4A	Pyrethroid Neonicotinoid	δ-cyhalothrin thiamethoxam	CS
Tempo Ultra	3A	Pyrethroid	β-cyfluthrin	WP, SC, WSP
Tempo 1% dust	3A	Pyrethroid	cyfluthrin	D
Temprid FX	3A 4A	Pyrethroid Neonicotinoid	β-cyfluthrin imidacloprid	SC
Vendetta Plus Cockroach Gel Bait	6 7C	Avermectin IGR	abamectin pyriproxyfen	B

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, B – bait, CS – capsule suspension, D – dust, EC – emulsifiable concentrate, MES – microencapsulated formulation, SC – suspended concentrate, RTU – ready to use, TRA – total release aerosol, WP – wettable powder, WSP – water soluble packets.

Table 1.5. Representative list of products and active ingredients registered in California against clothes moths.

Product	IRAC	Class	Active ingredient(s)	Formulation
Bedlam	3A	Neonicotinoid	phenothrin, MGK-264	A
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
Onslaught Fast Cap	3A 3A	Pyrethroid	esfenvalerate prallethrin PBO	MES
PT 565 XLO	3A	Pyrethroid	pyrethrins, PBO	A
Reefer-Galler Moth-Tex		Fumigant	p-dichlorobenzene	Solid
Suspend SC	3A	Pyrethroid	deltamethrin	SC
Tempo SC Ultra	3A	Pyrethroid	β-cyfluthrin	SC
Temprid FX	3A 4A	Pyrethroid Neonicotinoid	β-cyfluthrin imidacloprid	SC
Temprid Ready Spray	3A 4A	Pyrethroid Neonicotinoid	β-cyfluthrin imidacloprid	RTU

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, CS – capsule suspension, MES – microencapsulated formulation, SC – suspended concentrate, RTU – ready to use.

Bed Bugs

Over the past two decades, there has been a resurgence of the common bed bug, *Cimex lectularius* L., and the tropical bed bug, *Cimex hemipterus* (F.) (Doggett & Lee, 2023). Phillips et al. (2014) have reported that lower rates of SF will kill all stages of bed bugs including the eggs. Bed bug eggs have special openings that allow fumigants to readily enter the egg.

There are many products registered in California to control bed bugs (***Table 1.6***). Alternatives to chemical treatments include heat treatments, the use of steam, low temperatures using liquid CO_2 or nitrogen, exclusion techniques, and vacuuming (Kells, 2018).

SF fumigation may be warranted in situations with heavy and persistent infestations of bed bugs after repeated failures with conventional pest management strategies.

Table 1.6. Representative list of products and active ingredients registered in California to kill bed bugs.

Product	IRAC	Class	Active ingredient(s)	Formulation
Bifen I/T	3A	Pyrethroid	bifenthrin	EC
Cimexa		Inorganic	silica gel	D
Cy-Kick CS	3A	Pyrethroid	cyfluthrin	CS
D-Fense NXT	15 3A 7C	CSI Pyrethroid JH	novaluron deltamethrin pyriproxyfen	A
Demand CS	3A	Pyrethroid	δ-cyhalothrin	CS
Dragnet SFR	3A	Pyrethroid	permethrin	EC
Drione	3A	Pyrethrins	pyrethrin PBO silica gel	D
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
EcoPco AR-X	3A	Pyrethroid	pyrethrin 2-phenethyl propionate	A
Hot Shot Bed Bug Killer Dust		Inorganic	diatomaceous earth	D
Hot Shot No-Mess Fogger	3A 3A	Pyrethroid	tetramethrin cypermethrin PBO	TRA
NyGuard Plus	3A 7C	Pyrethroid IGR	d-phenothrin pyriproxyfen	A
Nuvan Prostrips	1B	Organophosphate	dichlorvos	RS
Onslaught Fast Cap	3A 3A	Pyrethroid	esfenvalerate prallethrin PBO	MES
Ortho Home Defense	3A 3A	Pyrethroid Pyrethroid	bifenthrin ζ-cypermethrin	RTU
PT 565 XLO	3A	Pyrethrins	pyrethrins, PBO	A
PT Alpine	4A	Neonicotinoid	dinotefuran	A
PT Cy-Kick	3A	Pyrethroid	cyfluthrin	A
PT Phantom II	13	Pyrrole	chlorfenapyr	A
Pyganic Dust	3A	Pyrethrins	Pyrethrin	D
Suspend SC	3A	Pyrethroid	deltamethrin	SC
Tandem	3A 4A	Pyrethroid Neonicotinoid	δ-cyhalothrin thiamethoxam	CS
Tempo 1% dust	3A	Pyrethroid	cyfluthrin	D
Tempo Ultra	3A	Pyrethroid	β-cyfluthrin	WP, SC, WSP
Temprid FX	3A 4A	Pyrethroid Neonicotinoid	β-cyfluthrin imidacloprid	SC

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, CS – capsule suspension, D – dust, EC – emulsifiable concentrate, MES – microencapsulated formulation, SC – suspended concentrate, RS – resin plastic, RTU – ready to use, TRA – total release aerosol, WG – water dispersible granule, WP – wettable powder, WSP – water soluble packets.

Insecticide resistance is believed to be a major factor contributing to the resurgence of bed bugs. Resistance has been demonstrated to pyrethroids, organophosphates, carbamates, chlorinated hydrocarbons, and neonicotinoids, but not to SF (Doggett & Lee, 2023). Miller & Fisher (2008) reported on the successful eradication of bed bugs in an apartment complex using SF. Some units in the complex had been treated several times during the previous two years unsuccessfully. Fumigation may be a viable treatment of shipping containers, automobiles, buses, surface ships, rail cars, and recreational vehicles in exceptional cases.

Old House Borer

The old house borer, *Hylotrupes bajulus*, belongs to the beetle family Bostrichidae and is believed to be native to northern Europe. It has been introduced into many of the Atlantic Coast states (Ebeling, 1975). It is widespread in Europe and probably the most important softwood-destroying insect (Hickin, 1975), but it is only an occasional problem in the eastern United States. It is rarely reported in California (Ebeling, 1975). It will reinfest attics and substructures of structures. The most common treatment strategy in the United Kingdom and Europe is to apply insecticidal sprays to exposed pieces of timber. The infested wood pieces are cut away, removing heavily tunneled sapwood (i.e., wood that has been extensively damaged by boring beetles). The newly exposed areas are sprayed. There are some sprays and foam applications specifically registered in California to kill old house borers (***Table 1.7***).

Table 1.7. Representative list of products and active ingredients registered in California to kill old house borers.

Product	IRAC	Class	Active ingredient(s)	Formulation
Bora-Care	8D	Borate	disodium octaborate tetrahydrate	SP
Conquer	3A	Pyrethroid	esfenvalerate	EC
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
Fuse Foam	13	Phenylpyrazole	Fipronil	RTU Foam
Optigard Flex	4A	Neonicotinoid	thiamethoxam	SC
Premise Foam	4A	Neonicotinoid	imidacloprid	RTU Foam
PT Cy-Kick	13	Pyrethroid	cyfluthrin	A
Tempo 1% dust	3A	Pyrethroid	cyfluthrin	D
Termidor Foam	13	Phyenylpyrazole	Fipronil	RTU Foam
Tim-bor	8D	Borate	disodium octaborate tetrahydrate	SP
Totality Wood Treatment	3A	Pyrethroid	bifenthrin	EC

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, CS – capsule suspension, D – dust, EC – emulsifiable concentrate, RTU – ready to use SP- soluble powder.

Formosan Subterranean Termites

The Formosan subterranean termite, *Coptotermes formosanus* Shiraki, is an invasive species in California, Hawaii, and the continental United States. This termite is primarily a subterranean termite but will often construct large amounts of carton material above ground and occasional aerial nests. SF fumigation will only kill termites above ground. Fumigation of boats to eradicate Formosan subterranean termites is the most common application of SF against subterranean termites (Scheffrahn, 2023).

Numerous products are registered for the control of subterranean termites in California (***Table 1.8***). These products include soil treatments, baits, and sprays applied to wood surfaces.

Table 1.8. Representative list of products and active ingredients registered in California to kill subterranean termites.

Product	IRAC	Class	Active ingredient(s)	Formulation
Advion WDG	22A	Oxadiazine	Indoxacarb	WG
Bifen I/T	3A	Pyrethroid	Bifenthrin	EC
Bora-Care	8D	Borate	disodium octaborate tetrahydrate	SP
Cy-Kick CS	3A	Pyrethroid	Cyfluthrin	CS
D-Fense NXT	15 3A 7C	CSI Pyrethroid JH	novaluron deltamethrin pyriproxyfen	A
Dominion 2L	4A	Neonicotinoid	Imidacloprid	EC
Dragnet SFR	3A	Pyrethroid	Permethrin	EC
Fi-Pro Aerosol	13	Phenylpyrazole	Fipronil	A
Fuse Foam	13 4A	Phenylpyrazole Neonicotinoid	fipronil imidacloprid	RTU Foam
EcoPco AR-X	3A	Pyrethroid	pyrethrin 2-phenethyl propionate	A
Masterline Bifenthrin	3A	Pyrethroid	Bifenthrin	EC
Phantom	13	Pyrrole	Chlorfenapyr	SC
PT Phantom II	13	Pyrrole	chlorfenapyr	A
Shatter	15	Benzolureas	hexaflumuron	B
Spectracide Terminate	13	Pyrrole	Sulframid	B
Suspend SC	3A	Pyrethroid	deltamethrin	SC
Tarus SC	13	Phenylpyrazole	Fipronil	SC
Talstar P	3A	Pyrethroid	bifenthrin	SC
Tempo Ultra	3A	Pyrethroid	β-cyfluthrin	WSP
Tim-bor	8D	Borate	disodium octaborate tetrahydrate	SP
Totality Wood Treatment	3A	Pyrethroid	Bifenthrin	EC
Trelona ATBS	15	Benzoylureas	Novaluron	B

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, B – bait, CS – capsule suspension, D- dust, EC – emulsifiable concentrate, MES – microencapsulated formulation, SC – suspended concentrate, SP – soluble powder, RTU – ready to use, WG – water dispersible granule, WSP – water soluble packets.

Powderpost beetles

Beetles belonging to the family Bostrichidae are known as powderpost beetles and have a worldwide distribution. Species such as *Lyctus brunneus* and *Lyctus planicollis* are most frequently mentioned as pests of hardwood items in structures. Other species, such as *Lyctus linearis* (Goeze) and *Trogoxylon parallelopipduem* (Melsheimer), are reported as pests in the United Kingdom (Hicken, 1975). The beetles attack sapwood of susceptible hardwoods and are found in flooring and other wooden objects. These beetles will reinfest suitable wood within structures.

In the United States and California, *Polycaon stouti* and the lead-cable borer, *Scobicia declivis* (Leconte), are occasionally pests of hardwood objects and materials in structures. Other invasive beetles belonging to this group include *Dinoderus minutus* (F.), *Heterobostrychus aquealis* (Waterhouse), and *Heterobostrychus brunneus* (Murray) are common to Africa and Southeast Asia. These are occasionally encountered within wooden furniture and objects imported from Southeast Asia.

SF fumigation is rarely used to control powderpost beetles because of the high doses required to kill the egg stage. Alternative control measures include surface sprays, heat treatments, kiln drying, wood removal, and the use of pre-treated lumber (Hickin, 1975).

There are several insecticides registered to kill powderpost beetles in California (***Table 1.9***).

Table 1.9. Representative list of products and active ingredients registered in California to kill powderpost beetles.

Product	IRAC	Class	Active ingredient(s)	Formulation
Bora-Care	8D	Borate	disodium octaborate tetrahydrate	SP
Conquer	3A	Pyrethroid	Esfenvalerate	EC
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
Fuse Foam	13	Phenylpyrazole	Fipronil	RTU Foam
Optigard Flex	4A	Neonicotinoid	Thiamethoxam	SC
Premise Foam	4A	Neonicotinoid	Imidacloprid	RTU Foam
PT Cy-Kick	3A	Pyrethroid	Cyfluthrin	A
Tempo 1% dust	3A	Pyrethroid	Cyfluthrin	D
Termidor Foam	13	Phenylpyrazole	Fipronil	RTU Foam
Termidor SC	13	Phyenylpyrazole	Fipronil	SC
Tim-bor	8D	Borate	disodium octaborate tetrahydrate	SP

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, CS – capsule suspension, D – dust, EC – emulsifiable concentrate, SC – suspended concentrate, SP – soluble powder, RTU – ready to use.

Deathwatch beetles

The deathwatch beetle belongs to the family Anobiidae, and several species are important structural pests. In northern California, the most important species is the so-called Pacific or California deathwatch beetle, *Hemicoelus gibbicollis* (LeConte). The furniture beetle, *Anobium punctatum* (De Geer), is an invasive species and occasionally reported infesting furniture items (Ebeling, 1975). The deathwatch beetle, *Xestobium rufovillosum* (De Geer), is a serious pest in the United Kingdom and Europe.

Structures are rarely fumigated to control Anobiid in the United States or Europe because of the high doses of SF required to kill beetle eggs and the lack of residual activity. There are several insecticides registered to kill deathwatch beetles in California (***Table 1.10***). Suomi & Akre (1992b) found that surface applications of disodium octaborate tetrahydrate (DOT) reduced larval numbers of *H. gibbicollis* by 96% to 99%. DOT did not prevent adult females from depositing eggs on treated surfaces, and therefore, applications should be made prior to adult females laying eggs from June to August.

Fumigation is typically reserved for individual bundles of lumber or pieces of furniture (Creffield, 1996) and is not recommended for structures because of its high cost and lack of residual protection (Suomi, 2006).

Table 1.10. Representative list of products and active ingredients registered in California to kill deathwatch beetles.

Product	IRAC	Class	Active ingredient(s)	Formulation
Bora-Care	8D	Borate	disodium octaborate tetrahydrate	SP
Conquer	3A	Pyrethroid	Esfenvalerate	EC
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
Fuse Foam	13	Phenylpyrazole	Fipronil	RTU Foam
Optigard Flex	4A	Neonicotinoid	Thiamethoxam	SC
Premise Foam	4A	Neonicotinoid	Imidacloprid	RTU Foam
PT Cy-Kick	3A	Pyrethroid	Cyfluthrin	A
Tempo 1% dust	3A	Pyrethroid	Cyfluthrin	D
Temprid 1% Dust	3A	Pyrethroid	Cyfluthrin	A
Termidor Foam	13	Phyenylpyrazole	Fipronil	RTU Foam
Termidor SC	13	Phyenylpyrazole	Fipronil	SC
Tim-bor	8D	Borate	disodium octaborate tetrahydrate	SP

[a] IRAC categorization of active ingredients according to their mode of action.
[b] A – aerosol, CS – capsule suspension, D – dust, EC – emulsifiable concentrate, SC – suspended concentrate, RTU – ready to use, SP – soluble powder.

11. **FINDING:** The lack of residual activity and the high concentrations of sulfuryl fluoride required to kill the egg stages of other insects limits its utility beyond drywood termites.

12. **FINDING:** Numerous alternative nonchemical and chemical treatments are available for the control of the other insects and vertebrates for which SF is registered.

13. **CONCLUSION:** Sulfuryl fluoride is primarily valued for drywood termite control in California because its practical effectiveness is limited for other pests and numerous viable alternatives already exist for most other insect pests.

Section 1.4: Application Methods

The steps and procedures required to fumigate and monitor structures are described in detail on the labels of SF products (Vikane, 2022; Zythor 2024). Structures and containers must be made as gas tight as possible to retain the SF. Most homes are covered with a tarpaulin coated with a gas-resistant coating. Larger structures with concrete, brick, or metal walls can be secured by a tape-and-seal method to limit the escape of gas.

The SF is released in the structure along with the warning agent chloropicrin. Specifically, five minutes prior to releasing the SF, 1 oz of chloropicrin is released for every 10,000 to 15,000 cubic feet in the structure (Vikane, 2022; Zythor, 2024). The gases are heavier than air and require fans to circulate them throughout the structure during the fumigation. After 20–24 hours, the gases are evacuated from the structure. In California, the California Aeration Plan (CAP) is followed to clear the structure of SF. The aeration ducting (minimum 18-inch diameter) is secured to a fan inside the structure. The ducting extends through the tarpaulins covering the building to the first story roofline or at least 10 feet above ground-level for higher rooflines. Inlet devices allow fresh air to create negative air pressure and promote cross-ventilation of the structure. Inlet devices must have an opening of at least 240 square inches up to a maximum opening of 381 square inches. The number of ducting and inlets used is based on the calculated cubic footage of the structure being fumigated, and there is a calculated ratio for the number of ducts and inlets to ensure negative pressure is maintained during the ventilation process. The fresh air is drawn into the structure, and the SF is exhausted upward out of the structure for a minimum of 12 hours, after which the tarpaulins are removed, and the living space is tested with a clearance device. Per the CAP and federal label requirements, only after a clearance device indicates that the concentration of SF is 1 ppm or less is the structure deemed safe to reenter (CAP, 2013).

Monitoring the concentration of SF within a structure during a fumigation is the only way to accurately determine if the accumulated lethal dose has been obtained, and it will greatly reduce the likelihood of failure. The monitoring can be done on site or remotely (FFM, 2021). Structures that are taped and sealed should be monitored because the SF calculators are not as accurate for this type of fumigation (FFM, 2021). Large buildings where it would be costly to redo the fumigation should also be monitored. Lastly, fumigations involving 10 times the drywood termite rate should be monitored. Two readings taken at equilibrium (1–2 hours after the introduction of SF) and before the tarp is removed are required to determine that the lethal accumulated dose has been achieved, ensuring that all pests have been killed.

Lethality of SF for target pests is a product of both the concentration of the fumigant and the duration of exposure, often represented in units of oz/hours. After the necessary oz/hours of SF have accumulated, the tarps can be removed and the structure cleared of SF in accordance with the CAP (CAP, 2013). The entire process can take 2–3 days.

Section 1.5: Emission-Reduction Measures

Many factors influence the amount of fumigant required to control pests within structures: pest species, temperature, exposure period, tarpaulin condition, seal condition (where a tarp is sealed to the ground, structural and landscape features, another tarp, etc.), wind speed, volume of fumigated space, underseal (concrete for slab or soil type for crawlspace), and whether the fumigation is monitored (Vikane, 2022; Zythor, 2024; ***Appendix V***). During the process, fumigant is gradually lost to the environment. The time it takes for half of the fumigant to dissipate from the structure is known as its **half-loss time (HLT)**. Temperature, wind speed, underseal, seal condition, and tarp condition all affect the HLT. Only the tarpaulin condition and seal condition can typically be controlled by the PMP. It is generally believed that the greatest gas losses occur at the ground seal (***Appendix V***).

> 14. **FINDING:** The nature of the ground seal for the tarps affects the emissions of sulfuryl fluoride during each fumigation.

During SF fumigations, structures are covered with gas-resistant tarps. These tarps play a critical role in temporarily containing the gas by creating a sealed environment around the structure. These tarps are made of PVC, neoprene, and vinyl-coated nylon fabrics that will last for years if protected from excessive abrasion (FFM, 2021). The quality of the tarps affects the HLT of the fumigant during the fumigation (FFM, 2021, ***Appendix V***). The tarps themselves are costly to replace. For example, a 35 feet x 60 feet tarp costs around $1,200, and it takes approximately seven to eight tarps to cover a 2,100-square-foot home. Importantly, more SF is required to achieve concentrations lethal to pests when tarps are in poor condition, as they are less effective at containing the SF.

> 15. **FINDING:** Poor tarp conditions increase the emissions of sulfuryl fluoride during each fumigation.

To date there has not been a concerted effort or incentive to reduce the amount of SF used to control structural pests. The primary regulatory concerns have focused on potential health impacts on workers, bystanders, and residents. Only with the realization that SF is a potent greenhouse gas (GHG) has there been active interest in reducing the emissions of SF associated with fumigation (Mühle et al., 2009). Recent publications by Gressent et al. (2021) and Gaeta et al. (2024) have led to renewed interest in the climate impacts of SF (see ***Section 1.8*** for more details).

Even though the label application rate for controlling drywood termites and various pests has not changed since SF was registered in 1959, the amount of fumigant applied per structure has steadily decreased since 2007. From 1994 to 2006, an average of 38.49 pounds was applied per structure. From 2007 to 2023, the average decreased to 25.78 pounds (DPR, 2024b; ***Figure 1.6***). The reasons for the decline in the amount of SF used in each structure have not been definitively established. Part of this reduction could theoretically be due to the costs of SF. However, according to a Dow Chemical Company representative, these reductions are not correlated with historical prices of SF, and she was unable to provide an explanation (E. Thoms, pers. commun., 7/30/2025). One potential factor for explaining the decreasing fumigant rate is better training of PMPs. UC Riverside and industry have conducted annual 2-day training seminars devoted to fumigation since 2004. Over the past 20 years, hundreds of PMPs have attended these seminars. One topic that has been emphasized in each training seminar was the accurate determination of the volume of structures. Another possible explanation could be changes to the Vikane label that were implemented in 2009 to explain how monitoring could be used to more accurately determine the HLT, thereby prompting more PMPs to monitor their fumigations (EPA, 2009).

Factors that affect the dosage of SF introduced to the structure are exposure time, ounce-hour dosage to be accumulated for the target pest, volume of the fumigated space, fumigant confinement, and if the fumigation is monitored, according to the Florida Fumigation Manual (2021). The manual states on page 135, "The dosage of a non-monitored fumigation is 33% more than that of a monitored fumigation. The higher dosage for a non-monitored fumigation compensates for possible errors in estimating the HLT and weighing SF during introduction. A monitored fumigation will determine if the initial SF concentration and actual HLT are sufficient to accumulate the required dosage." Monitoring the amounts of SF is only required for quarantine fumigations and when the contract requires it.

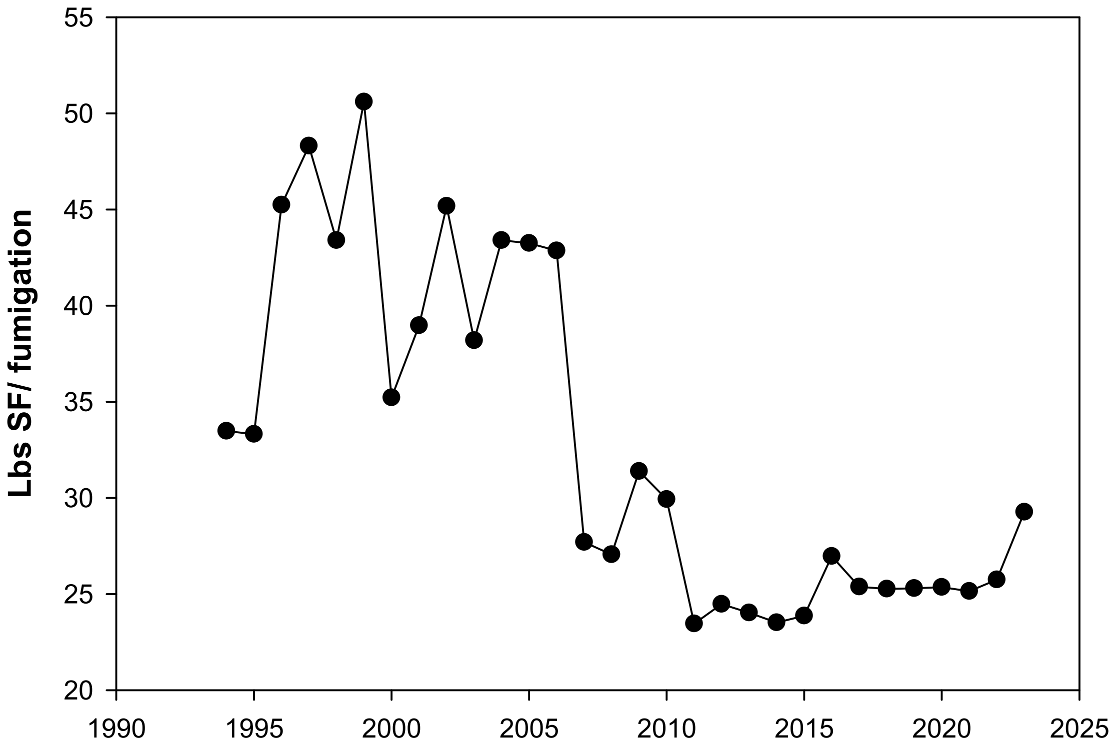

Figure 1.6. Pounds of SF used per fumigation from 1993 to 2023 in California (DPR, 2024b).

Fumigant lethality is a product of both its concentration and the duration for which a pest is exposed to the fumigant. Each pest has a lethal accumulated dose (g x h/m^3)—the total amount of fumigant the pest needs to absorb over a specified period to be killed. Because the LAD is a product of concentration and time, lethality can be achieved even over extremely short time frames, so long as the concentration is sufficient. Likewise, low concentrations can be equally lethal if the pest is exposed to the fumigant for long enough. Structural fumigations typically last 22–24 hours, so PMPs must ensure that the appropriate concentration is reached and maintained over this period to achieve lethal effects. Accurate determination of the structure's volume is critical, as it directly informs the amount of SF that must be applied to reach the necessary concentration for lethality.

Field studies have quantified accumulated SF dosages during structural fumigations and measured higher-than-necessary concentrations for effective lethality. Tao (2019) reported that field monitoring data showed that 14 of 23 fumigations had accumulated dosages ($g \times h/m^3$) 1.5 times higher than the required LAD, and nine dosages were two times higher than that required. She concluded that monitoring fumigations—so that PMPs could be certain that the appropriate concentration is being maintained rather than overcompensating by using additional SF—could reduce the amount of SF being applied and its subsequent emission.

Some pathways for reducing the required SF concentration per fumigation have been explored. For example, Scheffrahn et al. (1995) found that the addition of 10% CO_2 reduced the amount of SF needed to kill the drywood termite *I. synderi* (Light). The LAD95 was reduced from 40.1 to 26.9 mg × h/liter. In practical terms, the addition of 106 kg of CO_2 to a typical fumigation of a structure (21,188 ft^2) with 2.4 kg of SF would yield an accumulated dose of 45 mg × h/liter compared with 5.3 kg of SF without CO_2. In short, the use of CO_2 could reduce the concentrations of SF required to kill termites by 45% (Scheffrahn & Su, 1994). It is unknown if combinations of SF and CO_2 would also lower the concentrations needed to kill wood-destroying beetles. CO_2 is a much smaller and lighter molecule than SF, which could create challenges for its containment during fumigations. The concept of adding a synergist to a fumigant to enhance effectiveness has been explored previously: A methyl bromide-CO_2 mixture was registered in 1993. This product was discontinued when the use of methyl bromide for structural fumigation was suspended in 2005.

There has been renewed interest in the potential for recapturing or "scrubbing" SF from fumigation exhaust. Several promising chemical-based solutions have been proposed and demonstrated as effective. SF is slowly hydrolyzed (broken down) in water but can undergo rapid hydrolyzation in alkaline solutions (Kollman, 2006). It is completely absorbed by a sodium hydroxide solution and is fixed and converted to sodium fluoride (NaF), sodium fluorosulfanate ($NaSO_3F$), and sodium sulfate (Na_2SO_4) (Nie et al., 2015). In other words, SF can be removed from the air with the help of various solvents. Liang et al. (2019) determined the solubility of SF in biobased solvents such as dibutyl succinate, gamma-valerolactone, gamma-butyrolactone, ethyl levulinate, butyl levulinate, bis(2-ethylhexyl) azelate, methyl laurate, and diethyl succinate. SF was more readily dissolved in solvents that contained an ester functional group (RCOOR'), suggesting that SF could be selectively removed from exhaust gases after fumigation. Liang et al. (2018) reported that tributyl phosphate (TBP) possessed the potential to capture SF due to the relatively large solubility and low absorption internal energy for SF. There is a potential for removing SF from exhaust air (Liang et al., 2019). Zhang et al. (2024) suggest that the addition of reactive gas (hydrogen (H_2) plus water (H_2O)) can promote the degradation of SF. The breakdown products—thionyl fluoride (SOF_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), and hydrogen fluoride (HF)—are toxic gases, and therefore, secondary treatment will be required. The breakdown products could be absorbed by saturated calcium hydroxide ($Ca(OH)_2$) solutions.

Douglas Products and the U.S. Department of Agriculture (USDA) Agricultural Research Services have been conducting studies to determine if SF can be captured after the fumigation of commodities (agricultural or manufactured products that are subject to pest infestations during storage, processing, or transport). In pilot studies, the exhaust from large shipping containers fumigated with SF was scrubbed with a liquid air scrubber configuration containing potassium hydroxide (KOH) and a catalyst (H. Kern, pers. commun., 5/5/2025). In 2022, following successful pilots, the research progressed to a commercial trial in which logs in a shipping container were fumigated with SF and the exhaust was scrubbed. Within 90 minutes, 96% of the SF was captured. The size of the containers was 67.5 m^3 (2,385 ft^3). For context, the average home consists of approximately 600 m^3 (21,188 ft^3). Assuming SF could be scrubbed at a similar rate from fumigated homes and given that fumigated structures are usually aerated for 24 hours, SF could be scrubbed from structural fumigation exhaust using a similar method without prolonging the fumigation process.

Most of the volume of space within a structure consists of air. However, the critical volume of space occupied by drywood termites is the wood in walls, floors, ceilings, and attics. It may be feasible to reduce the volume of air within structures by inserting bags containing gases such as nitrogen.

16. **FINDING:** There has been a substantial reduction in the amount of sulfuryl fluoride applied per structure since 2006. From 1994 to 2006, an average of 38.49 pounds per structure was applied whereas from 2007 to 2023, the average was 25.78 pounds per structure (a 33% reduction). The reason for this reduction can only be speculated upon.

17. **FINDING:** Fumigations which are not monitored use more sulfuryl fluoride than monitored fumigations.

18. **CONCLUSION:** Monitoring fumigations will reduce the amount of sulfuryl fluoride used while still ensuring the levels are sufficient to treat termite infestations.

19. **RECOMMENDATION:** Additional research should be conducted to determine if it is feasible to require that all fumigations be monitored.

20. **FINDING:** The combination of sulfuryl fluoride and CO_2 increases the toxicity of sulfuryl fluoride against drywood termites, potentially reducing the amount of sulfuryl fluoride needed to effectively treat drywood termites by up to 45% per fumigation. The effects of sulfuryl fluoride and CO_2 on other wood-destroying beetles are unknown, and the feasibility of this approach has not been demonstrated at a practical level.

21. **CONCLUSION:** Incorporating CO_2 during fumigations could be a cost-effective means of reducing the amount of sulfuryl fluoride required to treat drywood termites and other wood-destroying organisms. However, more research is needed.

22. **RECOMMENDATION:** Additional research should be conducted to determine whether it is logistically feasible to include CO_2 during structural fumigations.

23. **FINDING:** Sulfuryl fluoride is soluble in several biosolvents and rapidly hydrolyzed in alkaline solutions. Pilot studies have already demonstrated that these qualities make sulfuryl fluoride amenable to capture using liquid air scrubbers following commodity fumigation.

24. **CONCLUSION:** As specified by the clearing process outlined in California's Aeration Plan for structural fumigations, sulfuryl fluoride is exhausted through a special vertical tubing. This method of exhaust would allow the sulfuryl fluoride to be readily directed into scrubbing devices containing one or more of these solutions with little change to the overall fumigation process. The safe disposal of the captured sulfuryl fluoride will determine the appropriateness of this method.

25. **RECOMMENDATION:** The potential for capturing sulfuryl fluoride from fumigation exhaust should be actively pursued, pending safe disposal options.

Section 1.6: Use Patterns and Trends

In California, structures are inspected by licensed inspectors prior to any treatment by PMPs (SPCB, 2021). The inspectors provide the customer and the SPCB with a report that indicates the type of wood-destroying organisms present, a schematic drawing of the structure with notations regarding the location of the infestation(s), recommendations for their remediation, and cost estimates (***Appendix I***; SPCB, 2024a). When the work has been completed, a completion notice is retained by the pest control company (***Appendix II***; SPCB, 2024b). The reports are retained for 3 years. Following fumigation, a copy of the fumigation log is sent to the prime contractor. Both the prime contractor and the PMP conducting the fumigation retain the fumigation log for 3 years. The fumigation log provides the location and description of the fumigated structure. This report details conditions at the time of the fumigation including tarp condition, seal condition, wind (miles per hour), estimated volume of the structure, underseal, temperature, hours of exposure, and whether the fumigation was monitored. The amounts of warning agent and SF are also recorded (***Appendix III***). These various reports contain valuable information regarding treatment patterns and trends. However, they are difficult to access and in formats that are not readily amenable to analysis. These data have never been systematically reviewed and analyzed.

> 26. **FINDING:** Data regarding fumigations are plentiful but dispersed, being collected by the County Agricultural Commissioners, California Department of Pesticide Regulation, and the Structural Pest Control Board.

> 27. **CONCLUSION:** Enhanced coordination of data collection among California's agencies that regulate, license, and oversee fumigations would improve the availability and completeness of data on sulfuryl fluoride use, allowing for deeper insights into fumigant use patterns and underlying drivers in the state.

Most of the fumigations conducted in California occur in coastal and some inland counties from San Francisco to San Diego (***Figure 1.3***). In Riverside and San Bernardino counties, most fumigations occur in the western portions of each county (i.e., within the Inland Empire). In 2023, 72.3% of the fumigations conducted in California were in Los Angeles, Orange, Riverside, San Bernardino, San Diego, Ventura, and Santa Barbara counties (DPR, 2024). Most of the counties in northern California had fewer than 50 fumigations annually in 2022. The incidence of fumigations in California corresponds with the northern range and extent of the western drywood termite. The colder and wetter climates and lower housing density in parts of Northern California likely also contribute to fewer drywood termite infestations and the lower number of fumigations. Between 2019 and 2023, an average of 91,976 structures were fumigated annually in California.

Fumigations are often associated with real estate transactions, at the request of either the loan agency or the buyer. Approximately 70% to 75% of all fumigations in California are the result of inspections that are done based on a request for purchase of a property (T. Ineichen, pers. commun., 4/21/2025). Within the United States, the economic recession of 2007–2009 resulted in a dramatic decline in the number of existing homes sold from 2007 to 2011 (***Figure 1.7***; Stat, 2025). There was a corresponding decline in the number of structures fumigated with SF from 2006 to 2011 (***Figure 1.8***; DPR, 2024). However, the effects of this decline were not apparent for many years because of the slow development of drywood termite colonies. It typically takes 4–5 years before a drywood termite colony matures enough to produce "swarming" reproductives (winged reproductive individuals or **alates**). The number of structures fumigated peaked in 2015 at 110,200 and declined to 78,834 in 2023 (***Figure 1.8***). Two factors might account for the peak of fumigations in 2015. First, drywood termite infestations of the large number of structures built prior to the recession were mature enough to produce "swarmers" and fecal pellets, making them more apparent to occupants, property owners, and inspectors. Secondly, those structures that were not fumigated during the recession would be detected later and treated as the sales of the existing housing market increased.

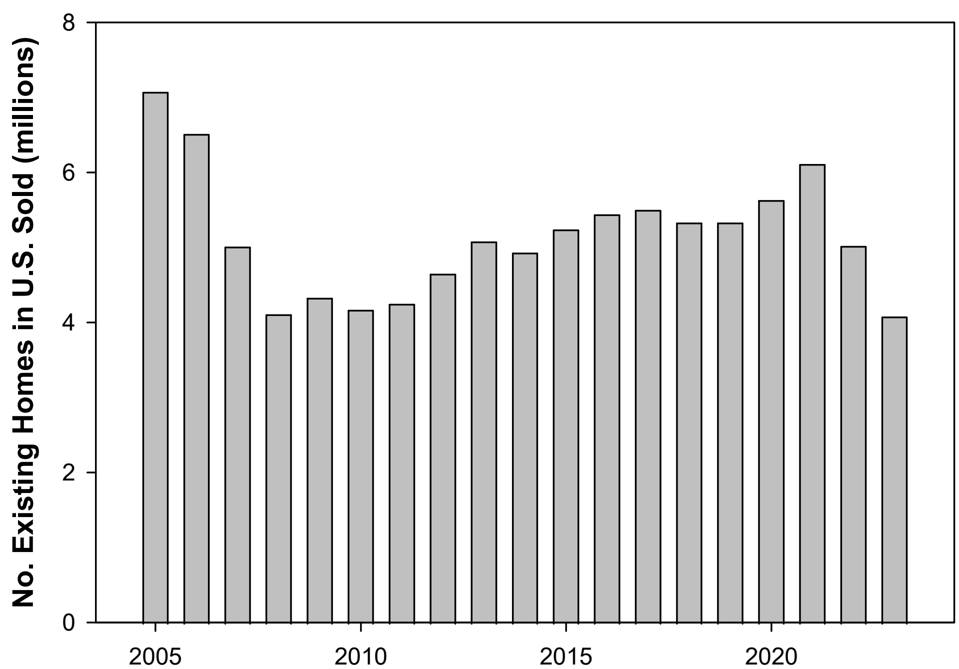

Figure 1.7. Number of existing houses sold in the United States from 2005 to 2023 (Statista, 2025).

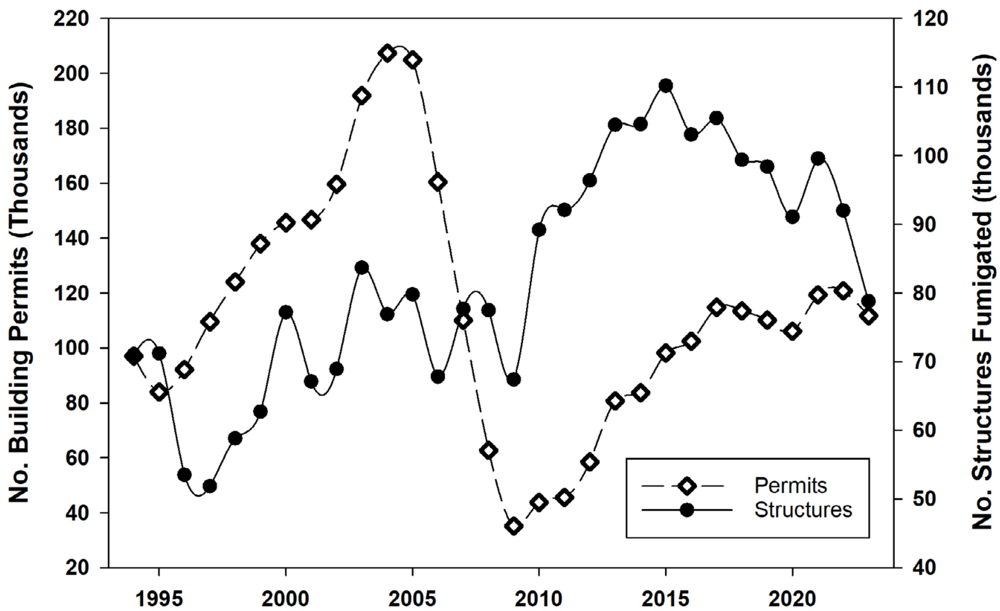

Figure 1.8. Number of building permits issued and the number of structures fumigated with SF in California from 1994 to 2023 (DPR, 2024; U.S. Census Bureau, 2025).

The amount of SF used in structural fumigation since 1993 in California is shown on ***Figure 1.9***. The increase in SF use from 1993 to 2006 is in part attributed to the decline in the use of methyl bromide, which was no longer permitted as a structural fumigant after 2005 (Lim, 2006). The 2007–2009 economic recession and its corresponding lack of home sales contributed to the dramatic decline in the amount of SF used during that timeframe.

28. **FINDING:** The amount of sulfuryl fluoride applied to structures and the number of structures fumigated in California have steadily declined since 2015.

29. **FINDING:** Fumigations are often associated with real estate transactions. Thus, economic factors affecting the cost of homes, the number of single-family and multifamily units constructed, and home sales have an impact on the use of sulfuryl fluoride.

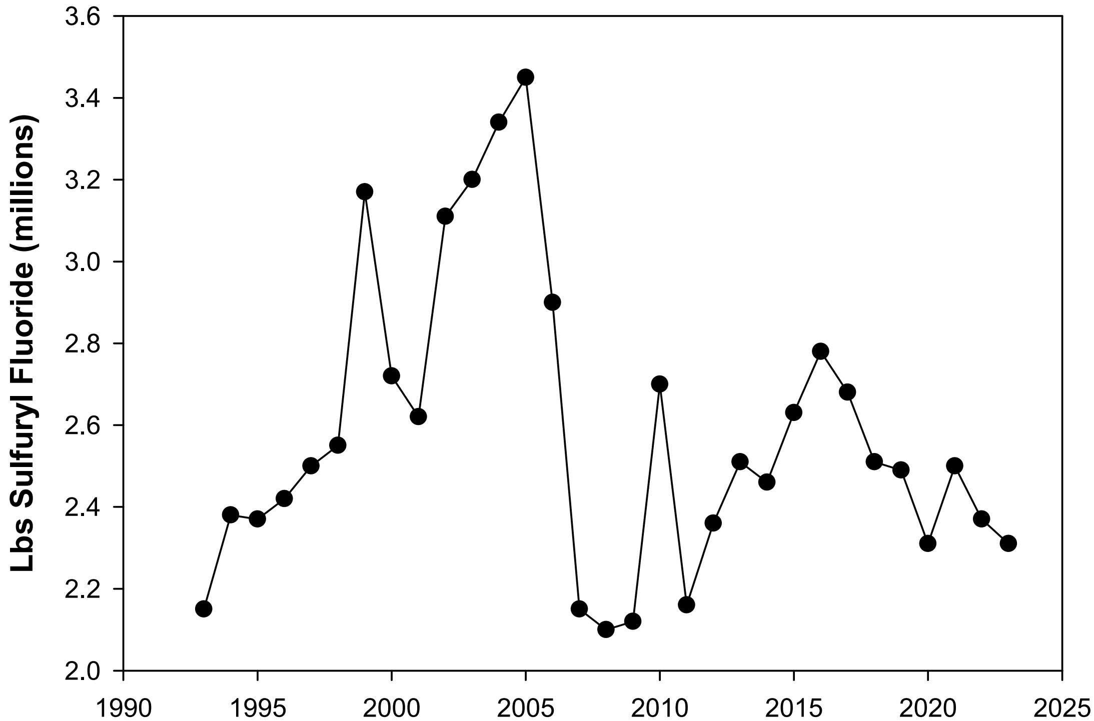

Figure 1.9. Total amount of SF used in California over time (DPR, 2024b).

Section 1.7: Human Health Impacts of Sulfuryl Fluoride

Human Exposure Risk to Sulfuryl Fluoride

Sulfuryl fluoride (SF) is a colorless, odorless gas used as a broad-spectrum insecticide and rodenticide for structural fumigation of otherwise occupied residential homes and workplaces, unoccupied structures, as well as stored commodities. SF is a highly toxic chemical and is federally classified as a restricted-use pesticide because of its potential toxicity and associated health risks to PMPs, non-occupational bystanders, and consumers. In 2006, DPR identified SF as a toxic air contaminant due to its neurotoxic effects and potential to drift from fumigated structures if and when engineering controls are inadequate (DPR, 2020). Because of its known toxicity, use of SF is highly regulated at both the federal and state level. Strict procedures for its use are outlined on the label and defined in state regulations. Despite this regulatory oversight, there are inherent risks to human health associated with its use, particularly when regulations are violated or safety precautions fail.

In California, structural applications of SF require that chloropicrin be added as a warning agent. Chloropicrin is a potent **lacrimator** (tear gas) with a pungent odor and serves to alert PMPs and bystanders of potential exposure before concentrations reach lethal levels. California is likely the largest SF emitter in the United States, given recent atmospheric modeling (Gaeta et al., 2023) and estimates of the number of structural fumigations performed in the state compared to others (***Section 1.9***). When SF is released into the environment, it can remain chemically stable in the atmosphere, persisting for many years with an estimated atmospheric lifetime of 36 years (±11 years) (Gaeta et al., 2024). Its persistence in the environment raises concerns about its contributions to climate change, which carries implications for public health.

Exposure Pathways

Human exposure to SF is influenced by its physical and chemical properties. SF has a higher vapor density than air (approximately 3.5 times that of air), which plays a critical role in how and where it accumulates. The primary route of exposure to SF is via inhalation, although oral and dermal exposure are possible though less common. A pharmacokinetic study in rats exposed to SF showed that 18% of the inhaled dose was absorbed and retained in the body (Mendrala et al., 2002, as cited in DPR, 2006). The highest concentrations of sulfur were detected in the lungs, while fluoride ions accumulated in the brain, kidneys, blood, and urine (Mendrala et al., 2005). DPR uses this 18% absorption rate to estimate how much SF people might retain during inhalation exposure (DPR, 2020). Human exposure to SF varies by context and is influenced by several key factors including the duration and frequency of exposure during the various phases of structural fumigation (i.e., application, aeration, reentry/certification, and post-clearance).

PMPs who handle, store, and apply SF are the most at risk for both **acute** and **chronic** inhalation exposures, making them the most vulnerable to SF's potential immediate and long-term health effects (DPR, 2006; Aribou & Ng, 2022). Fumigators are also more likely to be involved in all phases of structural fumigation. During application and fumigation of enclosed spaces, SF gas disperses and penetrates porous materials to eliminate pests, posing a significant risk to fumigators and others assisting with active fumigation. SF's high volatility and capacity to diffuse within materials increases the potential for accumulation of residual gas, thereby increasing the risk of inhalation exposure.

Despite perceptions that ancillary tent workers—who are not directly applying SF (e.g., tasked with tarping or removal of tents)—are at minimal risk of exposure to SF, their handling of contaminated tarpaulins and close proximity to fumigated structures in the aeration phase places them at risk for inhalation exposure (DPR, 2006). Effective aeration practices, such as the removal of tarps and the use of fans, is important to facilitate the dissipation of gas and to minimize SF inhalation exposure. The most hazardous occupational scenarios for acute inhalation exposure typically result from inadequate aeration, failure to follow reentry protocols (clearance testing > 1 ppm), and a lack of adequate personal protective equipment.[4]

[4] Note: The terms "reentry level" and "clearance level" are used interchangeably to denote the SF air concentration at which treated areas are deemed safe for tenant re-occupancy or worker reentry.

Indoor air monitoring conducted by PMPs ensures that SF concentrations have decreased to levels deemed safe by the CAP and as required by the label before reentry is permitted. However, occupants, homeowners, and/or renters who are permitted reentry to inadequately aerated structures may be unintentionally exposed to SF from engineering and administrative control failures (e.g., clearance equipment or device failure, improper ventilation, etc.) (DPR, 2006). During post-clearance, prolonged off-gassing of SF from porous material may be harmful, particularly to children who have higher respiratory rates, developing lungs, and lower body mass (resulting in a higher dose per body weight compared with adults), all of which make them more vulnerable to inhaled toxicants (Carroquino et al., 1998; CDC, 2023; EPA, 2008). Moreover, a monitoring study conducted by Shurdut (1995) demonstrated that even after SF concentrations decline to 5 ppm, SF concentrations can remain at detectable and elevated levels in homes for at least 48 additional hours, with models suggesting persistence for several days (up to 7 days) before declining to near zero. These findings are consistent with later monitoring results reported by Barnekow & Rotondaro (2015) and summarized by DPR (DPR, 2006, 2020).

Unlike occupants of fumigated structures, who are instructed to leave home, individuals in close proximity to a fumigated structure (e.g., neighbors) are not. This creates a situation in which neighbors to adjacent treated structures can potentially be exposed to SF gas leaks. These "passive" exposures may be short term and may include scenarios such as children playing outside, sitting in a parked car, or walking by a treated structure. The greatest risk for residents living close to fumigated buildings is during the aeration phase, when the structure is being ventilated. It is expected that the SF levels experienced by neighbors during the post-clearance phase would be no higher than the levels experienced by occupants upon reentry (DPR, 2006). However, failures in engineering controls can cause SF to leak from the fumigated structures, potentially leading to unintended dispersion and exposure to surrounding neighborhoods and communities. Under certain climatic conditions, such as high winds, leaked SF gas can move beyond the fumigated site, posing a health risk to nearby areas. For instance, DPR reported a case where high winds caused a tarp on a fumigated structure to come loose, leading to SF exposure among nearby individuals (DPR, 2020). To mitigate risks, DPR utilizes air dispersion modeling to estimate the buffer zone distances to protect exposure of residential bystanders. Lastly, to a lesser degree, humans can also be exposed to SF in their diets (food and water), as SF can be absorbed by many materials (e.g., high-fat foods) (DPR, 2006).

The pesticide labels for SF, approved by the EPA, mandates that food products be removed or bagged prior to fumigation to prevent contamination and minimize the potential for pesticide residues on foods. Beyond workers directly exposed or indirect exposure to occupants returning to fumigated structures where they may work or live, certain subpopulations may be at heightened risk of SF exposure. Infants, children, pregnant people, older adults, people with disabilities, and those with preexisting chronic conditions may be especially susceptible due to their physiological vulnerability to environmental toxicants (Varshavsky et al., 2023).

Residents of low-income, immigrant, linguistically, or racially/ethnically marginalized communities may bear a disproportionate burden from other pollutants due to substandard housing conditions, as well as neighborhood characteristics that may compound cumulative risk (Cushing et al., 2015; Morello-Frosch et al., 2011; Rauh et al., 2008). Individuals from these communities are more likely to be rental tenants, live in multiunit or substandard housing, and reside near sources of environmental pollutants, such as agricultural fields, toxic waste sites, industrial facilities, highways, sewage plants, etc. Additionally, they may face economic and cultural barriers that impede adherence to safety guidance (e.g., temporary relocation during fumigation). Taken together, these environmental factors may contribute to health disparities in California.

Mechanisms of Action

SF's mechanism of action in humans is not fully understood. Upon inhalation, SF is rapidly absorbed in the lungs and metabolized to fluoride ions. At high levels, fluoride ions have been shown to inhibit key enzymes such as enolase, which disrupts cellular energy production from glucose (Warburg & Christian, 1941). Recent evidence also suggests that the formation of other metabolites, such as sulfate and fluorosulfate, may contribute to SF toxicity in humans (Mendrala et al., 2005). In addition to the inhibition of glycolysis (the breakdown of glucose for energy), other proposed mechanisms include the induction of oxidative stress (the buildup of unstable oxygen molecules that can damage cells) and the disruption of acid-base balance (a disturbance to the body's normal pH levels) (Johnston et al., 2020). The rapid elimination of SF from the human body, reflected by its short half-life of 1–4 hours, coupled with a lack of a reliable biomarker of exposure, presents significant challenges for exposure assessment and biomonitoring of SF exposure in human populations. A better understanding of these mechanistic pathways could enhance knowledge of the human health effects associated with SF exposure, which are discussed in the following section.

Human Health Outcomes

This overview summarizes toxicological and epidemiological studies on the potential adverse health effects of SF exposure in the United States. If not handled properly, SF is a highly toxic fumigant capable of causing illness and even death. As such, the EPA dictates the ways in which this fumigant must be used, while DPR has additional regulatory procedures. Given that California is the largest known emitter of SF in the United States, primarily due to structural fumigations targeting drywood termites (Gaeta et al., 2024), **background levels** of exposure may be higher than that of other regions. Human health effects are described in terms of:

- Routes of exposure (inhalation, dermal, oral)
- Exposure period (acute, intermediate, chronic)
- Type of health outcome (acute v. chronic)
- Study types (toxicological, epidemiological)

Acute Health Outcomes

Acute health outcomes are characterized by a sudden onset of symptoms occurring shortly after a brief exposure to a harmful agent. There are several different ways that information about possible acute human health impacts is gathered. These include toxicological studies (controlled laboratory experiments that assess chemical effects on live animals), epidemiological studies (observational research examining patterns, causes, and effects of health conditions in human populations), registrant-submitted data (research conducted by chemical companies and submitted to the EPA for regulatory review), and tracking health outcomes following accidents and injuries contributing to surveillance data.

Regulatory agencies such as the EPA and DPR may use registrant data along with peer-reviewed literature to conduct **risk assessments** and determine if a pesticide product, when used according to its label, meets safety standards. While these industry-sponsored studies undergo internal regulatory review for compliance purposes, they are not subject to independent peer review nor are they available through academic journals. Studies sponsored by the pesticide industry and submitted to the EPA pesticide program are assigned unique eight-digit master record identifiers (MRIDs). These MRIDs are provided in the following subsections when information is derived from such studies.

Toxicological Studies

Table 1.11 summarizes studies on animals exposed to acute (< 9 days) and short-term (10–14 days) concentrations of SF via inhalation and their health effects. Exposure definitions are based on DPR's "Sulfuryl Fluoride Addendum to the 2006 Risk Characterization Document: Update of the Toxicology and Reference Concentrations" (2020). Neurological symptoms—such as hyperactivity in rabbits, tetany (involuntary muscle spasms) in dogs, and increased motor activity in rat pups—were observed following short-term exposure to SF concentrations of up to 300 ppm (Eisenbrandt et al., 1985; DPR, 2020; Hayes & Krieger, 2010). Brain vacuoles were observed in mice and female rabbits following short-term SF inhalation exposure with a lowest observed effect level of 30 ppm (MRID 43129401; Eisenbrandt & Hotchkiss, 1989). Other less frequent complications were respiratory and kidney inflammation. In reproductive studies of pregnant rats and rabbits, decreased maternal body weight was observed in dams (female parent animals) at the highest exposure levels, but teratogenic effects (developmental malformations) were not observed in fetuses (Hanley et al., 1989).

Table 1.11. Toxicological studies of short-term SF inhalation studies of animals.

Species	Exposure frequency[a]	Dose (ppm)	Examples of adverse effects[b]	Study/MRID
Mouse	Short-term	0, 100, 300, 600, 6 h/d, 5 d/w, 2 w	300 ppm: Brain vacuoles	43129401
Rats	Short-term	0, 100, 300, 600, 6 h/d, 5 d/w, 2 w	300 ppm: Kidney lesions and inflammation	Eisenbrandt et al. (1985); ref. DPR (2020)
Pregnant rats	Short-term	0, 30, 100, 300, 6h/d, 5 d/w, 2 w, gestational days 6–15	300 ppm: Decreased maternal body weight; minimal liver and kidney damage	Hanley et al. (1980); ref. DPR (2020)
Rabbits	Short-term	0, 100, 300, 600, 6 h/d, 5 d/w, 2 w	300 ppm: Hyperactivity, brain vacuoles, inflammation of respiratory tract	Eisenbrandt et al. (1985); ref. DPR (2020)
Pregnant rats and pups	Short-term	0, 5, 20, 150, 6 h/d, 2 w, postnatal days 11–21	20 ppm: Elevated motor activity in male pups, decreased maternal body weight	49609101
Pregnant rabbits	Short-term	0, 30, 100, 300, 6 h/d, 5 d/w, 2 w, gestational days 6–15	300 ppm: Decreased maternal body weight	Hanley et al. (1980); ref. DPR (2020)
Pregnant rabbits and pups	Short-term	0, 25, 75, 225, 5 d/w, 2 w, gestational days 6–15	225 ppm: Decreased maternal body weight	Hanley et al. (1981); ref. DPR (2020)
Dogs	Short-term	0, 30,100, 300, 6 h/d, 5 d/w, 2 w	200 ppm: Tremors, tetany, inflammation of respiratory tract	Nitschke & Quast (1992); ref. DPR (2020)

[a] Acute exposure less than 9 days; short-term between 10 and 14 days; subchronic from 15 to 89 days; chronic greater than 90 days (vs. humans > 1 year). These definitions are based on the Sulfuryl Fluoride Addendum to the 2006 Risk Characterization Document: Update of the Toxicology and Reference Concentrations (DPR, 2020).
[b] Lowest observed effect level reported when provided.

Acute Toxicity

Determining **acute toxicity** exposure levels are important to public health and critical to emergency response and environmental and occupational safety efforts. In **toxicology**, doses are administered to animals to observe adverse effects and even death. Lethal concentration deadly to 50% of experimental animals (LC_{50}) of SF inhalation experiments are shown in ***Table 1.12***. At concentrations as low as 4,000 ppm, rats displayed neurotoxicological symptoms such as tremors and convulsions after 45 minutes of **acute exposure** before dying several hours later (Nitschke et al., 1986).

Table 1.12. LC_{50} of experimental studies of acute SF inhalation of animals.

Species	LC_{50}	Duration (hours)	MRID
Mice	Males: 660 (2.6 mg/L) Females: 642 (2.5 mg/L)	4	41769101
Rats	4,507 (17.5 mg/L)	1	41099001

Epidemiological Studies

Much of what is known about the immediate human health effects of SF originates from surveillance data, including case reports, injuries, and illnesses following acute exposure.

Accurately quantifying chemical exposures in epidemiological studies is critical for the understanding of health effects in vulnerable subpopulations, whether these are acute (occurring rapidly following a brief exposure) or chronic (involving repeated, cumulative doses over years or a lifetime). Updated exposure assessments are critical for informing risk assessments and protecting public health, in particular with growing concern that regulatory approaches may underestimate potential harm (Vandenburg et al., 2023). While biomarkers are often considered the gold standard as they provide direct evidence of internal dose, no validated biomarker exists for SF. As a result, SF exposure assessments are reliant on environmental data, such as outdoor and indoor air concentrations, proximity to known sources (which make assumptions about how people interact with SF), and other co-occurring chemicals.

Consistent with animal data, acute exposure to SF in humans often first leads to neurological symptoms, such as headaches, slurred speech, and muscle twitching (Barreau et al., 2019). Short-term exposures have been shown to depress the central nervous system and cause seizures and convulsions (Mulay et al., 2016a; Schneir et al., 2008). SF is also a respiratory irritant that causes shortness of breath, throat and nose irritation, and coughing for exposed individuals. In more severe cases, SF exposure can lead to pneumonia and pulmonary **edema** (CDC, 1987; Scheuerman, 1986; Schneir et al., 2008). Gastrointestinal effects include abdominal pain, diarrhea, and constipation (Taxay, 1966). Higher concentrations of SF have also been reported to cause severe organ damage in residential fumigation incidents (Barreau et al., 2019).

These data underscore the real-world implications of exposure, which are further illustrated by rare but serious case reports involving children. Two such cases highlight the dangers of reentry into a home post-fumigation, especially for young children (Carroquino et al, 2022; CDC, 2023; EPA, 2008). In 2015, a family in Florida was hospitalized for chemical toxicity 48 hours after entering their fumigated home. The 9-year-old boy in the family suffered permanent brain damage and spent a month in the hospital and a rehabilitation facility, where he continued to have long-term effects as a result of basal ganglia necrosis (nerve cell death in a region of the brain responsible for motor control, emotion, and cognition). Based on an immediate investigation, the Florida Department of Agriculture and Consumer Services found that the pest control company had failed to measure SF levels and had not provided the required worker training. The pest control company's license was revoked, and two fumigation workers pled guilty in federal court.

In a separate case from Orange County, California, in 2016, a family reported symptoms consistent with SF poisoning after reentering their SF-treated home. The parents reported that their 13-month-old had started to exhibit behavioral changes, such as head banging and cessation of verbalizing. Five weeks later, DPR conducted an investigation and found that the air bladder of a mattress (an inflatable, flexible chamber within the mattress that can be adjusted to change mattress firmness) contained SF levels at 2.4 ppm. It was suspected that off-gassing from the air bladder was the source of the lingering SF that had affected the child. Regulations would now require such a mattress to be removed prior to fumigation (DPR, 2020; Barreau et al., 2019; Mulay et al., 2016b). Incidents, while rare, could be prevented if more thorough indoor air monitoring—including closer testing and inspection of porous material—were conducted in homes with children.

In 2016, the EPA's Office of the Inspector General (OIG) conducted an evaluation to determine the extent and nature of adverse effects caused by structural fumigants, highlighting ongoing public health concerns in California and Florida (Office of the Inspector General, 2016). Growing concerns over SF exposure are reflected in recent data from multiple sources, including a 2021 EPA report documenting 2,349 exposure reports to the American Association of Poison Control Centers between 2008 and 2018, as well as an investigation identifying 1,291 calls to California Poison Control between 2010 and 2016 from joint SF and chloropicrin exposures (EPA, 2021; Barreau et al., 2019). In addition to restricting access to treated sites and enhanced training for PMPs, the OIG report emphasized the need to evaluate the reliability of clearance devices specified on product labels. In response, during testing conducted in 2021, the EPA found that certain devices previously approved for product label inclusion did not accurately measure post-fumigation clearance levels of SF residues at the clearance level of 1 ppm, likely leading to preventable injuries and illnesses following residential fumigation (EPA, 2024b; EPA 2021; EPA, 2016). Of the four commercially available devices assessed, two models reported high rates of false negatives (i.e., said that air concentrations did not exceed 1 ppm when they did). Based on the data generated using both dry and ambient air variants, the SF ExplorIR and GF1900 devices exhibited average false negative rates that ranged from 50% to 70%. When considering only ambient air data, which better represents normal field conditions, the false negative rates increased to 100% for SF ExplorIR and 80% for GF1900 (EPA, 2021). Therefore, these two brands are no longer recommended for accurately measuring the 1 ppm SF clearance level (EPA, 2025b). However, these devices may still be in circulation, posing human health risks following SF fumigations.

Additionally, the EPA has an established false negative tolerance threshold of 30%, such that devices that meet or exceed this rate are deemed "unreliable" (while those that have false negative rates of less than 30% are acceptable by the EPA standard). A 30% false negative signifies that approximately 1 in 3 measurements could falsely indicate safe clearance levels when SF levels are greater than the 1 ppm concentration (although it should be noted that the rates of false negatives for these devices decline the higher the concentration) (EPA, 2021). Given the severe risk associated with SF exposure from preventable illnesses, injuries, and fatalities, the EPA's 30% false negative tolerance level warrants critical evaluation to determine whether it is sufficiently protective for occupants returning to treated structures.

On July 30, 2024, the EPA announced new safety measures for reentry of homes fumigated with SF, including federally mandated product label changes to all SF fumigation products used in residential structural settings, including Vikane and Zythor (EPA, 2024; Ogawa & Marciano, 2025). These label changes require that a clearance device be used but do not clearly specify that the clearance device used meets reliability or accuracy standards. Users are simply directed to the EPA for "more information and a list of effective clearance devices." The EPA does not regulate the use of specific clearance devices (EPA, 2025b). The CACs would be the local authorities responsible for regulating the use of clearance devices. However, due to the complexity of interagency enforcement, interpretation of policies may differ and enforcement may be uneven. This regulatory gap poses a serious risk to PMPs, occupants of treated structures, and surrounding communities, emphasizing the need for stricter oversight of clearance devices to prevent harmful overexposure to SF.

Injuries and Illnesses

The Pesticide Illness Surveillance Program (PISP), mandated by the State of California, was established to protect workers and bystanders from pesticide-related illnesses and injuries (DPR, 2025b). PISP data indicate that SF-related exposure and cases of injury and illness from structural fumigations are a growing concern in California, as highlighted in the 2016 OIG report.

From 1992 to 2022, DPR investigated 275 reported cases of SF-related injuries and illnesses from structural fumigations (***Table 1.13***). The 275 case reports included here are "implicated cases" wherein the pesticide is the only credible contributor. The majority of cases (n=163; 59%) were determined to be "possible" (***Table 1.13***). For context, approximately 91,976 structures are fumigated annually in California (***Section 1.6***).

Table 1.13. California PISP case reports of injury and illness from SF exposure (1992 to 2022).

Case reports	Category	Definition
24	Definite	High degree of correlation between pattern of exposure and resulting symptomatology. Requires both medical evidence (such as measured cholinesterase inhibition, positive allergy tests, characteristic signs observed by a medical professional) and physical evidence of exposure (environmental and/or biological samples, exposure history) to support the conclusions.
88	Probable	Relatively high degree of correlation exists between the pattern of exposure and the resulting symptomatology. Health effects correspond well to the reported exposure, and causality is supported by limited or circumstantial evidence. Either medical or physical evidence is inconclusive or unavailable.
163	Possible	Some degree of correlation is evident. Health effects correspond generally to the reported exposure, but evidence is not available to support a "definite" or "probable" relationship. Both medical and physical evidence are inconclusive or unavailable.
Total: 275		

Structural fumigations with SF resulted in 275 cases of injury or illness, including 20 deaths, reported to the PISP over a 30-year period (1992–2022) (***Table 1.14***). These PISP case reports included fumigation workers handling SF (n=14, 5.1%); 911 calls activating emergency responders to treated structures (n=13, 4.7%); bystanders exposed to SF drift from nearby treated structures (n=34, 12.4%); employees re-entering their places of work post-fumigation (n=35, 12.7%); residents accessing their yards or entering homes (n=124, 45.1%); and non-residents (n=53, 19.3%)—such as transients, neighbors, and utility workers—entering fumigated properties.

Narrative descriptions and exposure types were examined to categorize exposures into three fumigation phases: active fumigation, post-clearance, and post-fumigation. Case reports including the descriptor "SPCO [structural pest control operator] cleared for re-entry" were coded as "post-clearance." All other reports from non-active fumigations were coded as "post-fumigation" exposures. Structural fumigation of buildings (e.g., coded as "routine indoor", "routine outdoor" or "routine other") included both resident and non-resident entry into treated buildings, homes, or premises.

Table 1.14. California PISP illness and injury reports of SF-related exposure type of structural fumigations (non-ag) by phases of treatment (1992-2022).

Exposure Type	Active fumigation	Post-clearance	Post-fumigation	Total Cases
Occupational Applicator/Handler	13	0	1	**14**
Resident Entry	21	91	12	**124**
Contaminated bedding/food	0	14	3	**17**
Non-Resident Entry	41	9	3	**53**
Transient/Burglary Entry	24	1	0	**25**
Neighbor Entry (pet rescue, kids, relatives)	17	0	0	**17**
Service Worker Entry (utilities, housekeeping, landscaping)	0	8	3	**11**
Employee/Workplace Entry	0	33	2	**35**
Emergency Responder Entry	12	0	1	**13**
Bystander drift / off-movement	27	0	7	**34**
Unspecified	2	0	0	**2**
Total Cases	**116**	**133**	**26**	**275**

* CalPiQ Search Filter: "Year Case Identified==1992-2022" AND "Ag/Non-Ag==Non-Ag" AND "Exposure Type==ALL". Next, applied text search to "Narrative Description" for iterations indicating "SPCO cleared for re-entry" then coded as binary (post-fumigation==0 and post-clearance==1): Total N=275.

Of the 124 case reports involving resident exposures from treated homes, 16.9% (n=21) occurred while fumigation was still active, and where residents presumably accessed their fumigated properties at times when entry was prohibited. However, the majority (83.6%, n=103) of resident exposures occurred after homes were cleared for re-entry (i.e., post-clearance, n=91) or post-fumigation (n=12). Of the PISP cases in which residents entered the property either post-clearance or post-fumigation, and for which sufficient evidence was available from the PISP online query, we used case narratives to derive study-specific classifications of PMP compliance and likely exposure circumstances. Based on text search and explicit language in the narrative description, 20 cases were coded as indicative of PMP compliance with regulators and no citations cited, 17 cases were coded as likely resulting from off-gassing from bedding or contaminated food or water, 8 cases coded as suspected improper fumigation practices, and 1 case was coded as PMP was cited. In 11 cases where SF concentrations were re-tested post-fumigation, 2 still had detectable levels of SF. These study-specific classifications were based solely on explicit narrative text publicly available, and PISP variables remained unchanged. We note that narrative text is limited in length and may not capture all details, and acknowledge that these are not an official DPR/PISP designation; therefore, these classifications should be interpreted with caution.

Of the 53 reports of non-resident exposure following entrance into fumigated properties, 77.4% (n=41) occurred during an active fumigation. These included transients or burglars (n=24) and neighbors or pet rescue (n=17). All cases of service worker (e.g., utility workers, housekeepers, landscapers) exposure (n=11) occurred post-clearance or post-fumigation. In 1 case where follow-up testing was performed, SF levels were found to be between 1 and 4 ppm 12-days post-clearance.

Additionally, there were 35 cases of employees exposed upon re-entering their workplaces post-clearance or post-fumigation. The majority of these workplace incidents were re-tested post-clearance (n=29), with 9 noted to have elevated levels of SF. In 13 of these work-place related cases, there was suspicion of improper fumigation practices.

There were 13 cases of emergency response workers entering fumigated buildings, mainly during active fumigations.

Bystander exposures from potential off-site movement or drift occurred mainly during active fumigations (n=27) but some incidents occurred post-fumigation (n=7). Of the 11 bystander cases with available data, there were 4 cases where the PMPs were found to be in compliance and no citations were issued, 4 cases where the PMPs were cited, 1 case that was attributed to ripped tarps, 1 case that was suspected to be due to improper fumigation protocol, and 1 case which led to retesting of SF concentrations which found "negative" results.

Despite stricter regulatory changes implemented in 2006, the number of incidents/injuries and deaths reported to the PISP have not declined (***Table 1.15***). Before 2006, regulations required that air concentration of SF had to be less than 5 ppm before reentry was permitted. In 2006, the "clearance level" was lowered to 1 ppm or less. Since then, there have been a total of 187 cases, compared with 88 cases from 1992–2005. Note, however, that caution is warranted when comparing the number of case reports across these two time periods as Poison Control—which fields many reports of pesticide illnesses, including from SF fumigation, and submits these to the PISP—lacked funding for operations from 1991–1998 and from 2003–2006 (DPR, 2018). Thus, the PISP cases prior to 2006 are likely underestimates of SF-related illnesses and injuries. While the PISP has limitations, including inconsistent follow-up or lack of case validation, it serves as an important source of information for identifying potential health concerns, particularly in real-world settings where exposures may otherwise go undetected (e.g., faulty clearance devices).

Over this 30-year period, 66% (n=12) of deaths from suspected SF exposure at structural fumigation sites were attributed to unauthorized entry by non-residents during active fumigations, whereas a smaller number were due to unauthorized access by residents (n=4, 22%) or were unspecified (n=2). One fatal case in 2018 was classified as likely post-fumigation with unknown clearance status. To help reduce fatalities from unauthorized entry into fumigated structures, the OIG report recommended a label change to require measures to "create a barrier to access, use detection mechanisms, or require similar measures designed to prevent access into fumigation tents" (EPA, 2016).

The potential health effects from SF exposure included neurological symptoms, headaches, nausea, eye issues, breathing difficulties, and nose and throat irritation. While some of the incidents from the PISP may have been related to the use of clearance devices found by the EPA to be "unreliable," the data available through the PISP do not allow us to determine which devices were used during the fumigations associated with reported injuries and illnesses.

Table 1.15. California PISP illness and injury reports from SF exposure associated with structural fumigations. Case numbers are categorized by fumigation phases and specific regulatory periods (1992-2005 and 2006-2022).

	Active fumigation		Post-clearance		Post-fumigation		Totals
	1992 - 2005	2006 - 2022	1992 - 2005	2006 - 2022	1992 - 2005	2006 - 2022	1992-2022
Occupational	7	6	0	0	1	0	**14**
Resident Entry	5	16	22	69	5	7	**124**
Non-Resident Entry	7	34	5	4	2	1	**53**
Employee Entry	0	0	2	31	2	0	**35**
Emergency Responder Entry	11	1	0	0	1	0	**13**
Bystander drift	10	17	0	0	7	0	**34**
Unspecified	1	1	0	0	0	0	**2**
Totals	**41**	**75**	**29**	**104**	**18**	**8**	**275**

Chronic Health Outcomes

Chronic health outcomes refer to long-term disorders or diseases that develop over time and potentially in response to long-term **environmental exposures** that may be exacerbated by **risk factors,** including genetic, behavioral, and environmental factors. Environmental risk factors include biological, chemical, physical, and social conditions that can influence health. Both intrinsic (e.g., age, genetics, comorbidities) and extrinsic (e.g., housing, socioeconomic status, proximity to fumigated structures) factors may affect, and in some cases compound, an individual's susceptibility to chemical exposures (Varshavsky et al., 2023). Chronic health conditions require ongoing medical treatment and management for as long as they persist, which can be for years or throughout the lifetime of the individual. Few human studies to date have investigated the impacts of **chronic exposure** to low levels of SF (e.g., as experienced by structural or commodity PMPs) or acute exposure risk among occupants of fumigated structures. However, subchronic exposure to SF of 15–89 days and chronic exposure to SF greater than 90 days have been shown to have adverse health outcomes. Toxicological studies of inhalation for 13-weeks duration have shown harmful effects across multiple organ systems (***Table 1.16***). As SF is inhaled and metabolized in the body, it primarily releases fluoride ions as a byproduct. These ions accumulate in tissues like teeth and bones. With ongoing, continuous exposure to SF, this can lead to systemic effects including **dental fluorosis** (tooth discoloration and enamel damage), reductions in body weight, and skeletal toxicity.

Table 1.16. Subchronic and chronic inhalation studies of animal models exposed to SF.

Species	Exposure frequency[a]	Dose (ppm)	Examples of adverse effects[b]	Study/MRID
Rats	Subchronic	30, 100, 300, 6 h/d, 13 w	300 ppm: Inflammation and lesions of nasal cavity, lung damage, brain lesions 100 ppm: fluorosis of teeth	40890902 40839902 40890903
Rats	Subchronic	0, 30, 100, 300, 6 h/d, 5 d/w, 13 w	Dental fluorosis, nasal and lung inflammation, slight kidney and brain damage	Eisenbrandt & Nitschke, 1989
Rabbits	Subchronic	30, 100, 300, 6 h/d, 90 d (11, 38, 114 mg/kg/day)	100 ppm: Dental fluorosis, brain damage, nasal olfactory irritation, lung damage	40890901
Dogs	Subchronic	0, 30, 100, 200 ppm, 90 d	200 ppm: Brain lesions, tremors	42256601
Mice	Chronic	0, 5, 20, 80, 6 h/d, 5 d/w, 18 mo	Brain vacuoles, lung inflammation, thyroid damage, heart thrombus	43354903
Pregnant rats	Chronic	0, 5, 20, 150, 6 h/d, 5 d/w, 2 y, 2 gen	150 ppm: Maternal brain vacuoles; maternal dental fluorosis, maternal lung inflammation, low birth weight of pups	42179801
Rats	Chronic	0, 5, 20, 80, 6 h/d, 5 d/w, 24 mo	80 ppm: Brain vacuoles, nasal and lung inflammation, kidney damage 20 ppm: Dental fluorosis in males	43354902
Dogs	Chronic	0, 20, 80, 200, 6 h/d, 5 d/w,1 2mo	80 ppm; Dental fluorosis, lung inflammation 200 ppm: Brain damage	43354901

[a] Acute exposure less than 9 days; short-term (10–14 days); subchronic 15–89 days; chronic greater than 90 days (vs. humans > 1 year).
[b] Lowest observed effect level reported when provided.

Neurological

In rodents, rabbits, and dogs, histopathological evidence (from analyses of tissues using microscopes) indicates that the brain is the main target of prolonged exposure to SF via inhalation (DPR, 2020). In rodents, chronic exposure to levels greater than 80 ppm led to the development of brain lesions and vacuoles (fluid-filled sacs) (DPR, 2020). Histopathological exams in animals found that continuous, low exposure to SF led to thyroid hypertrophy as well (DPR, 2020).

To date, two occupational studies of fumigation workers in the United States have examined the association between low-dose exposure to SF and neurological and cognitive performance. The first study of structural fumigation workers was conducted in California. The study found that individuals exposed to low levels of sulfuryl fluoride had poorer performance on neurological assessments compared with nonexposed individuals, although the results were not statistically significant (i.e., the results may have been due to chance or random variation) (Anger et al., 1986). Authors attributed the lack of statistical significance to demographic differences between the control group and the exposed group. In a separate study from Florida of 123 male workers, researchers examined SF and methyl bromide fumigators (i.e., "shooters") and tarp/tent crew workers (Calvert et al., 1998). The median period of sulfuryl fluoride exposure in this cohort was 2.85 years over the course of their lifetime. Those workers with higher exposure to SF were found to have poorer short-term memory and reduced ability to detect smell than individuals who were unexposed (the "referent" or control group). Researchers also found that structural fumigation workers had statistically nonsignificant lower peripheral nerve activity (i.e., nerves beyond the brain and spinal cord). The researchers noted that the physically demanding tasks of tent crew workers, such as heavy lifting and repetitive movements, could have contributed to these effects rather than chemical exposure alone. In addition to acting as confounders, they could also act synergistically or cumulatively with SF exposure so that attempting to control for these variables may obscure the true and combined effect on occupational risks faced by tent workers.

Respiratory

Respiratory SF is a low molecular weight, highly volatile gas with the ability to penetrate respiratory tissues, where it can induce severe nasal irritation and inflammation. Epidemiological data show that individuals with underlying respiratory conditions may be highly susceptible to the adverse effects of SF inhalation exposure (Barreau et al., 2019). Toxicological findings demonstrate prolonged SF inhalation exposure in rodents, rabbits, and dogs results in both inflammation of the upper and lower respiratory systems, with significant tissue damage (DPR, 2006; DPR 2020). For example, in animal inhalation studies, rats and rabbits exposed to 300 ppm of Vikane formulations for two weeks exhibited signs of nasal irritation. The study originally planned for rabbits to be exposed to concentrations of 600 ppm, but this was reduced to 300 ppm due to convulsions observed after the ninth exposure. Rats exposed to 600 ppm over a 2-week period exhibited pulmonary edema and hemorrhaging (Eisenbrandt & Nitschke, 1989).

Developmental and Reproductive

A chronic inhalation study of SF exposure in pregnant rats and their offspring did not reveal any teratogenic effects (i.e., developmental malformations of fetus) (Breslin et al., 1990). However, in exposed dams, dental fluorosis, brain vacuoles, and alveolar macrophages in the lungs were observed at 150 ppm, suggesting fluoride ion accumulation and a localized inflammatory or immune response to prolonged SF exposure.

Genotoxicity

DPR's 2006 Risk Characterization Document concluded that SF was not **genotoxic**, based on the weight of evidence from rodent studies that were regarded as acceptable evidence conducted by Dow Chemical Company (Gollapudi et al., 1990a, 1990b, 1991, as cited in DPR, 2020). Based on these earlier results, the EPA also concluded that SF was not likely to be carcinogenic to humans (EPA, 2004). In DPR's 2020 addendum, newer Dow studies were incorporated that found weak positive results at high concentrations, concluding that toxicity of SF was attributed to fluoride ions (Gollapudi et al., 2002 (MRID 48549201); Gollapudi et al., 2005 (MRID 48549202)). While this existing evidence from more recent studies indicates that SF may have potential to be genotoxic, additional studies are warranted to better characterize its carcinogenicity, particularly in the context of long-term exposure. SF exposure—particularly its fluoride mediated mechanisms—has not been comprehensively evaluated by any public health agency.

From DPR's 2006 report, in an **Ames test** using four strains of *Salmonella typhimurium* (A98, TA100, TA1535, and TA1537), SF with a purity of 96.5% did not induce mutations at the highest concentration of 30,000 ppm, although slight cytotoxicity (cell death) was noted at this high dose (Gollapudi et al., 1990a, as cited in DPR, 2020). While cytotoxicity is often assessed in studies of genotoxicity, DNA damage at doses high enough to cause cytotoxicity may have resulted from the cell death itself rather than genotoxicity of the substance (Azqueta et al., 2022). In a separate study of micronucleus assay, mice exposed to SF (purity 99.6%) for 4 hours in chambers at concentrations of 50 ppm, 175 ppm, and 520 ppm showed no chromosomal damage in bone marrow after 3 days (Gollapudi et al., 1990b as cited in DPR, 2020). Another study used an **unscheduled DNA synthesis assay** where rat liver cells were exposed to SF (purity 97.4%) for 18–19 hours. No clear evidence of DNA repair activity (indicative of genotoxic damage) was observed. However, slight cytotoxicity at 1,020 ppm, and overt toxicity at 1,530 ppm in subsequent trials, was noted (Gollapudi et al., 1991, as cited in DPR, 2020).

According to DPR's 2020 addendum, SF has not demonstrated consistent genotoxic effects in two additional studies, and fluoride ions (one of SF's **degradants**) may be responsible for the observed genotoxic damage from SF exposure (DPR, 2020). In a **mouse lymphoma assay** (L5178Y), cells exposed to SF (purity 99.8%) for 4 hours showed a weak increase in mutation frequency at concentrations of 2,000 ppm and 4,000 ppm (Gollapudi et al., 2002, as cited in DPR, 2020). In an in vitro study, primary lymphocyte cultures derived from male rats were exposed to SF concentrations ranging from 100 ppm to 50,000 ppm for 4 hours and exhibited increases in chromosomal aberrations at 15,000 ppm to 25,000 ppm (Gollapudi et al., 2005 as cited in DPR, 2020). These studies implicate fluoride as a plausible genotoxic ion. However, its role in mediating DNA damage from SF exposure requires further investigation. In short, the mechanism of action of SF in humans is not fully understood and warrants further study.

Overall, the science on the human health effects from SF exposure from structural fumigations remains sparse, particularly for long-term health and neurological and respiratory outcomes. Most available evidence hails from registrant-sponsored studies, with limited independent, peer-reviewed information about interactions with other formulations (i.e., chloropicrin) and the cumulative effects of multiple other toxicants. In California, certain subpopulations are disproportionately exposed to environmental pollutants. Race/ethnicity, geography, and socioeconomic status have all been shown to be correlated with the degree of environmental exposure (Cushing et al., 2015). Data are lacking on the public health implications of SF exposure in combination with other household and commercial pesticides, as well as nonchemical stressors (i.e., low-income housing). Addressing these gaps in knowledge can inform better public health protections.

> 30. **FINDING:** Sulfuryl fluoride is a highly toxic fumigant with documented adverse neurotoxic and respiratory effects, and emerging evidence suggests potential genotoxicity.

> 31. **FINDING:** Licensed fumigation workers who handle, store, and apply sulfuryl fluoride are the most at risk for acute and chronic inhalation exposures. However, only two studies to date have examined sulfuryl fluoride exposure in occupational settings, both of which were conducted more than 25 years ago and in contexts that would no longer be permissible in California today due to the changes in regulation on permissible reentry levels.

> 32. **CONCLUSION:** An additional study of the chronic health impacts of sulfuryl fluoride exposure in occupational studies is warranted given the paucity of research on this subject as well as the differences in exposure today compared with when the only two studies in the United States were conducted.

> 33. **FINDING:** The majority of the toxicological data on sulfuryl fluoride exposure comes from registrant-submitted studies conducted by its manufacturer, Dow Chemical Company. These studies, along with published peer-reviewed studies, show that inhalation—whether from acute exposure, intermediate exposure, or chronic exposure—may lead to adverse neurotoxic and respiratory effects.

34. **FINDING:** While existing evidence indicates that SF has genotoxic potential, further research is warranted to characterize its carcinogenicity, particularly in the context of long-term exposure. This potential has not been independently evaluated outside of industry-sponsored studies, and the fluoride-mediated mechanisms of SF toxicity remain poorly understood.

35. **CONCLUSION:** To advance the scientific understanding of potential genotoxic or carcinogenic effects from sulfuryl fluoride exposure, including its mechanisms of toxicity, additional research from peer-reviewed, academic, and independent sources is needed. Broadening the current body of industry-sponsored studies will help ensure a more comprehensive understanding to support informed public health decision-making.

36. **FINDING:** According to publicly available data from the Pesticide Illness Surveillance Program in California, reentry or residue from fumigated structures using sulfuryl fluoride was the leading cause of injuries and illnesses. These incidents primarily involved residents returning to fumigated homes and employees returning to fumigated workspaces.

37. **FINDING:** PISP data shows some inconsistencies in enforcement and in addition, it is likely that some violations are not reported.

38. **CONCLUSION:** Greater oversight of pre- and post-fumigation protocols could help mitigate the number of injuries and illnesses caused by sulfuryl fluoride exposure. Such actions could include proper and accurate calibration of clearance devices and routine compliance inspections to improve the aeration process post-fumigation in treated homes.

39. **FINDING:** The EPA has established a false negative tolerance level of 30% for clearance devices (i.e., so long as false negative rates are less than 30%, these devices are deemed acceptable). However, the EPA does not directly regulate specific clearance devices, posing a public health concern for workers and occupants.

40. **CONCLUSION:** Given the established risks associated with sulfuryl fluoride exposure, the EPA's 30% tolerance level warrants critical evaluation to determine whether it is sufficiently protective for occupants returning to treated structures.

41. **FINDING:** When tested for their ability to reliably detect whether SF concentrations exceed the federally and state-mandated clearance level of 1 ppm in ambient air, two popular clearance devices were found to have false negative rates of 100% and 80%.

42. **CONCLUSION:** Faulty clearance devices could explain some of the injuries and illnesses reported to the Pesticide Illness Surveillance Program.

43. **RECOMMENDATION:** Relevant California state agencies should consider independently evaluating the reliability of clearance devices and imposing stricter state-level reliability standards and certifications.

44. **FINDING:** Preliminary data suggest that sulfuryl fluoride-related accidents and illnesses following structural fumigations continue in California despite the implementation of the California Aeriation Plan. Some of these incidents may have resulted from faulty clearance devices, rather than flaws in the design of the plan itself.

45. **CONCLUSION:** Given the continued risk of exposure, a review and update of the plan may be warranted to strengthen safety measures.

Exposure in California

This section provides an overview of regulatory and advisory exposure levels established in California, outlining how health-based guidelines are designed to protect workers and the general public.

Regulatory and Advisory Exposure Levels

Risk assessment is a scientific process used by regulatory agencies to evaluate and characterize the frequency and magnitude of potential ecological and human health risks, following exposure (contact) to an environmental stressor. Risk assessments are the foundation for setting regulatory based health protections. When sufficient toxicological information exists (and when epidemiological data are limited), reference values from risk assessments are used in **environmental epidemiology** to characterize and quantify risk in real-world settings (e.g., workplace, neighborhood). Reference values are derived by regulatory (e.g., the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA)) and advisory (e.g., the National Institute for Occupational Health and Safety) agencies and are based primarily on animal models due to the lack of human data. Reference values are not established when data are lacking. Reference values from federal and state regulatory agencies are enforceable when legally mandated. These values are subject to change when new scientific information becomes available. However, regulatory agencies must abide by the rulemaking process and public funding to update reference values. For regulatory agencies, this often leads to disparate and conservative reference values compared with those established by scientific advisory agencies. Advisory agencies are not bound by legal procedures, such that reference values are readily updated by incorporating the most recent studies. Consequently, differences in guidelines often reflect varying methods of exposure assessment and assumptions about real-world conditions (Vandenberg et al., 2022). For instance, in a study of workplace fatalities, reconstructed exposure estimates based on conservative assumptions were found to underestimate true exposure levels, likely due to real-world conditions, including inconsistent or ineffective use of respiratory protective equipment (Tustin & Cannon, 2022).

U.S. laws and regulations include protections for sensitive or susceptible subpopulations, which are incorporated into human health risk assessments. To account for differences in human susceptibility, whether biological or external (e.g., poverty), regulatory agencies typically apply default adjustment factors or uncertainty factors to risk assessments These uncertainty factors are typically a 10-fold factor to account for potential greater human susceptibility relative to test animals and a 10-fold factor to protect more sensitive individuals within the human population. Combined, these uncertainty factors are intended to provide a safety margin, but research shows that the default 10-fold safety factor underestimates the risks posed to fetuses, children, pregnant individuals, senior adults, and those with disabilities or comorbidities (Varshavsky et al., 2023; WHO, 2017).

Under the Food Quality Protection Act (FQPA), the EPA must apply an additional 10-fold safety factor to protect children unless sufficient data justify its removal. Yet this margin is often reduced or omitted, even when data are limited, undermining FQPA's intent (Donley et al., 2022). These safety margins often rely on default assumptions, and do not capture sensitive windows of growth (e.g., prenatal development, infancy, puberty) or other external vulnerabilities such as poverty. There is growing consensus among scientists and health agencies, such as the World Health Organization, that regulatory agencies should move beyond the default safety factors and instead use chemical-specific data to inform risk assessments (WHO, 2017). For example, the California Office of Environmental Health Hazard Assessment has used chemical-specific data for several hazardous air pollutants to improve risk assessment methods by measuring how a chemical's absorption, distribution, metabolism, and excretion varies across age groups to understand of age-related susceptibility in California. Adjustments to account for human variability to pesticide exposures remain rare and represent missed opportunities to address health inequities (Bhat et al., 2017; Varshansky et al., 2023).

New methods and computational techniques, combined with insights from epidemiological studies, can strengthen human health risk assessment by producing more relevant and potentially more protective models while reducing reliance on default adjustment factors and animal testing (Lu et al., 2025). However, their adoption by regulatory agencies into routine risk assessments has been slow. Additionally, there is growing consensus among research scientists urging caution about relying solely on industry-sponsored studies due to inherent conflicts of interest. Indeed, it has been documented that industry-funded research often produces findings that support regulatory outcomes favorable to the sponsoring entities (Legg et al., 2021; Schölin et al., 2025). To strengthen the evidence base and ensure unbiased risk assessments, human health studies must be corroborated by independent researchers or public health agencies. At the same time, ongoing public concern persists that regulatory agencies face pressure from industry, potentially leading to insufficient protection for vulnerable populations and failure to uphold the precautionary principle of doing no harm (Schwartz et al., 2011; Fabbri et al., 2018; Donley et al., 2022).

Another major challenge in risk assessments is selecting which health impacts or symptoms qualify as **critical endpoints**, the adverse effect associated with the lowest administered dose, versus symptoms that show evidence of exposure without evidence of harm. Critical endpoints can include developmental, reproductive, cancer, or respiratory issues. For many fumigants, it can be challenging to determine which biological changes or metabolic patterns are related to adverse health outcomes. Therefore, the evaluation of observed effects is crucial to accurately assess human health risks even in the absence of complete mechanistic understanding about how fumigants harm human health.

In California, pest control companies must adhere to both federal and state reference guidelines for exposure levels. OSHA has set a permissible exposure limit (PEL) of 5 ppm over an 8-hour workday, with a short-term exposure limit (STEL) of 10 ppm. The California Division of Occupational Safety and Health adopted the same 5 ppm 8-hour PEL as federal OSHA. In California, additional workplace safety requirements, such as more frequent air monitoring and stricter requirements for fumigation workers may be required. In addition to workplace standards, DPR has set more protective air concentration reference levels for ambient SF exposure than the EPA. These levels—intended for residential bystanders and the general public—are often significantly lower than occupational limits to better protect sensitive populations, such as children. Reference levels set by DPR include an acute exposure level of 0.41 ppm, a short-term level of 0.013 ppm, a subchronic level of 0.018 ppm, and a chronic level of 0.012 ppm.

Fumigation workers are at risk from both acute and chronic exposures. ***Table 1.17*** provides the reference values for SF exposure via inhalation for people who may be in close proximity to structural fumigation (i.e., bystanders) and for individuals exposed occupationally. In 2017, DPR proposed SF reference concentrations (RfCs) to reduce female worker exposures, specifically 2.6 ppm for 8-hour exposures and 0.13 ppm for short-term (1–2 weeks) and chronic exposures (Dong, 2017). Both state and federal laws set the SF clearance level at 1 ppm or less before occupants may reenter a fumigated space (DPR, 2020). During active fumigation, estimated indoor levels are estimated to be approximately 1,000 ppm, while ambient air levels around the fumigation site can exceed 1 ppm (Hayes & Krippendorff, 2007). Additionally, when a fumigated structure is aerated, 90% of the indoor SF escapes into the atmosphere within the first 2 hours (Tao, 2019). DPR also updated its acute reference targets for air concentrations of SF for residential bystanders to mitigate residential and community exposures (DPR, 2020).

Air Monitoring

In 2013, the CAP was updated to improve aeration and ventilation procedures of fumigated structures. A study conducted by Barnekow and Rotondaro (2015) sought to assess fumigation worker and residential bystander/neighbor SF levels using the revised CAP at maximum rates to control powderpost beetles, and 10 times the rate to control termites. Fumigation was conducted in three family homes at rates of 40, 52, and 63 oz/1,000 ft^3 with mean application rate of 52 oz/1,000 ft^3. Additionally, researchers increased the holding time to 48 hours for fumigation phases and increased the aeration time to 21 hours. Stationary indoor and outdoor air monitors were located in the three treated homes and inside a neighbor's home to mimic residential exposures. ***Table 1.18*** presents the occupational exposure results from this study, which found that occupational exposures were all less than RfC target values for acute (2.6 ppm) and chronic (0.13 ppm) exposures, including the more protective reference values for female workers (acute RfC = 2.57 ppm, and short-term RfC = 0.13 ppm) (Dong et al., 2017; Stefanova-Wilbur, 2017 as cited in DPR, 2020).

While worker safety thresholds were met, residential exposures for nearby neighbors and returning occupant levels exceeded recommended safety limits, raising public health concerns (***Table 1.19***). For bystanders and neighbors, the 24-hour average exposures of 0.48 ppm and 0.67 ppm exceeded the RfC of 0.41 ppm for the first (0-24 hours) and second (24-48 hour) monitoring intervals. Additionally, an air monitoring study by Wright et al. (2003) found that ambient concentrations of SF exposure were detected 5–50 feet away from the treated homes and dissipated after clearance, with the highest levels detected during the aeration phase (DPR, 2020). Similarly, occupants who reentered fumigated and aerated structures during the post-clearance phase were exposed to higher SF levels of 1.14 ppm and 0.72 ppm (24-hr TWA), both exceeding the RfC of 0.41 ppm for both first and second 24-hr intervals (Stefanova-Wilbur, 2017). Earlier monitoring studies detected measurable levels of SF in homes for up to 48 hours after the 5 ppm clearance level had been met, indicating ongoing exposure risk to occupants even after structures met the 5 ppm clearance level (Shurdut, 1995). Using Shurdut's data, DPR's ambient modeling found that SF could persist in homes for up to 7 days before approaching 0 ppm. These findings, together with subsequent work from Barnekow and Rotondaro (2015), supported concerns that a 5-ppm clearance level was insufficiently protective, and informed the regulatory move toward a stricter reentry standard of 1 ppm.

Table 1.17. Reference levels and guidelines for human health risk assessment for SF inhalation.

Reference (agency)	Reference value	Definition	Setting	Dose (ppm)[a]
NOAEL (EPA / ATSDR)	No observed adverse effect level	Highest dose where no adverse effects were observed	Non-occupational	Acute: NA Short-term: 100[b] Subchronic: 30[c] Chronic: 30[c]
NOEL (DPR)	No observed effect level	Highest dose at which no effects (whether adverse or not) were observed	Non-occupational	Acute: 300[d] Short-term: 5[e] Subchronic: 30[f] Chronic: 20[g]
LOAEL (EPA / ATSDR)	Lowest observed adverse effect level	Lowest dose where no adverse effects were observed	Non-occupational	Acute: NA Short-term: 300[b] Subchronic: 100[c] Chronic: 100[c]
LOEL (DPR)	Lowest observed effect level	Lowest dose at which no effects (whether adverse or not) were observed	Non-occupational	Acute: N/A Short-term: 20[e] Subchronic: 100[f] Chronic: 80 or 150 (maternal)[g]
RfC (DPR)	Reference concentration	Continuous inhalation exposure with no harm over a lifetime time-weighted average (TWA)	Ambient residential	Acute: 0.41 [range: 0.25–0.75][d] Short-term: 0.013[e] Subchronic: 0.018[f] Chronic: 0.012[g]
HEC (DPR)	Human equivalent concentration	Animal dose adjusted for safe human levels	Non-occupational	Acute: 75[d] Short-term: 1.25[e] Subchronic: 5.4[f] Chronic: 3.57[g]
RfC (DPR)	Reference concentration	Worker levels without adverse effects	Occupational	Acute (24hr TWA): 2.57 Seasonal: 0.14 Chronic: 0.04 Acute, female: 2.6 Short-term, female: 0.13 Chronic, female: 0.13
Post-clearance indoor ambient air concentration (OEHHA)	Reference exposure level	Exposure limits for public health	Ambient Indoor	< 1
STEL (OSHA / NIOSH)	Short-term exposure level	Worker exposure without adverse effects (15 min)	Occupational	Short-term: 10
PEL (OSHA / NIOSH)	Permissible exposure level	Worker exposure without adverse effects (8-hr workday)	Occupational	Chronic: 5
TLV (ACGIH)	Threshold limit value	Worker exposure levels without adverse effects 8-hour TWA	Occupational	Chronic: 5
PEL (OSHA / NIOSH)	Immediate danger to life or health	Acute inhalation toxicity in a 30-minute period	Occupational	Acute: 200

[a] Acute exposure less than 9 days; short-term 10–14 days; subchronic 15–89 days; chronic greater than 90 days (vs. humans > 1 year).
[b] Eisenbrandt et al., (1985).
[c] Nitschke et al. (1987).
[d] Albee et al. (1993) as cited in DPR (2020).
[e] Marty et al., (2015) as cited in DPR (2020).
[f] Nitschke and Quast (1993), Nitschke et al. (1987b), and Mattsson et al. (1988) as cited in DPR (2020)
[g] Quast et al. (1993b,c) and Breslin et al. (1992) as cited in DPR (2020).

Table 1.18. Estimated SF exposures to powderpost beetle fumigations among workers.

	Exposure levels (ppm)			
Work activities	Short-term[a]	Seasonal[b]	Annual	Lifetime
Fumigator	0.17	0.05	0.02	0.01
Tent crew	0.12	0.04	0.02	0.01
Fumigator, tent, clearance	0.15	0.04	0.02	0.01

Note: Adapted from Barnekow and Rotandaro (2015)
[a] Short-term exposure is exposure that lasts between 1 day and 7 days.
[b] Seasonal exposure is exposure that lasts between 1 week and 1 year.

Table 1.19. Estimated ambient SF exposures to powderpost beetle fumigations among residents and neighbors

	Short-term exposure (ppm)		
	0–24 hours, 24-hr TWA	**24–48 hours, 24-hr TWA**	**Aeration phase, 22-hr TWA**
Neighbors or bystanders residing in adjacent structures	0.48	0.67	0.23
Residents reentering aerated structures	1.14	0.72	NA

Note: Adapted from Barnekow and Rotandaro (2015)

46. **FINDING:** Individuals living in close proximity to fumigated structures and occupants reentering treated structures may be at risk for neurotoxic effects of SF. Studies have reported incidences where residential exposures for returning occupants and neighbors exceeded recommended safety limits, raising public health concerns. SF concentrations can remain elevated in homes for 7 days post-clearance before levels drop to zero.

Section 1.8: Environmental and Ecological Concerns

SF is not an **ozone**-depleting substance, but it is a potent GHG with an atmospheric half-life of 36 years that represents a **global warming potential** (GWP) of 4,630 times that of CO_2 (over a 100-year time frame) (Tsai, 2010; Papadimitriou et al., 2008; IPCC, 2024). Thus, for every ton of SF emitted, the impact on the climate over 100 years is equivalent to having emitted 4,630 tons of CO_2. The 20-year GWP of SF is even higher, wherein 1 ton of SF is equivalent to 7,510 tons of CO_2 (IPCC, 2024). The 20-year GWP is typically used to describe the climate impacts of gases that have shorter atmospheric lifespans, such as methane and SF.

From 2007 to 2023, structures in California were fumigated with an average of approximately 25.8 pounds of SF per structure (***Section 1.5***; DPR, 2024). Given the 100-year GWP of SF, the average fumigation is equivalent to adding roughly 119,500 pounds (or 54.4 metric tons) of CO_2 to the atmosphere. Adding 54.4 metric tons of CO_2 to the atmosphere is the same as driving a typical passenger vehicle 135,510 miles (assuming 400 grams of CO_2 per mile, as suggested by the EPA) (EPA, 2025c). For context, the average U.S. citizen contributes the equivalent of 14.4 tons of CO_2 annually from all sources, including transportation, diet, and energy use (European Commission, 2023). Thus, on average, a person who chooses to fumigate their household more than quadruples their per capita GHG impact that year. It should be noted, however, that these estimates of the climate impacts of fumigating with SF assume that all SF used during the fumigation is ultimately released to the environment when, in fact, some SF may be destroyed or permanently absorbed during the process (Gaeta et al., 2024; Mühle et al., 2009).

While SF is a GHG, it is not currently regulated by the California Air Resources Board the way that other common GHGs are and is not subject to restrictions imposed by the GHG emissions inventory and related emissions reduction laws in California (e.g., Assembly Bill 32, 2006, and Assembly Bill 1279, 2022).

Radiative forcing (RF) is another indicator of the impact of a substance on the Earth's climate and a means to compare the contributions of various gases to global warming. Unlike GWP, which compares the effect of equal masses of different gases, radiative forcing reflects the impact of the current atmospheric concentration of a gas on Earth's climate, allowing for comparison of the current contributions of various gases to global warming. A positive RF value indicates that the substance absorbs radiation emitted from the Earth's surface (leading to a warmer atmosphere) while a negative RF value indicates the substance reflects or reduces the amount of incoming solar radiation reaching the surface (leading to a cooler atmosphere). All GHGs have positive RF values. The RF value of a gas will depend on its existing concentration in the atmosphere, the wavelengths at which the gas absorbs and emits radiation, and how effectively the molecule absorbs radiation at those wavelengths. Because it varies with concentration, RF values can change over time. In contrast to GWP, radiative forcing provides an indicator of a substance's immediate impact on the earth's climate (as opposed to over a longer time horizon), although it is worth noting that the two values are related as the GWP of a substance is derived from its RF value. The concentration of SF has been increasing in the atmosphere, thus so has its RF value: the RF value of SF was 0.0003 in 2011 (Myhre et al., 2013) and 0.00046 in 2023 (Shine & Kang, 2023). For comparison, in 2023, the RF values for CO_2, methane, and nitrous oxide—the three most abundant GHGs in the Earth's atmosphere, besides water vapor—were 2.29, 0.57, and 0.22, respectively (EPA, 2025d). Even though the RF values are very low for SF compared with CO_2, the values have increased in the past decade, and that should be of concern. Further, a low RF value does not diminish the importance of a high GWP value for SF because the RF of a gas is determined, in part, by the concentration of that gas in the atmosphere. Thus, even if gases are extremely efficient at trapping heat (high GWP), if they exist in low concentrations in the atmosphere, they will have a low RF value.

SF is not very soluble in water at ambient temperature, and in alkaline (basic) solutions (having a pH greater than 7), it quickly breaks down to form fluorosulfate (SO_3 F-) and decomposes to sulfate and fluoride (Cady & Misca, 1974). As the alkalinity or pH increases, the rate of break down increases. Thus, alkaline water bodies (e.g., the ocean) have been proposed as a trap (sink) for SF in the environment. Indeed, the uptake half-life of the ocean for SF is 40 years, while all other atmospheric pathways for SF destruction are greater than 600 years. The hydroxyl radical (OH) destruction is negligible compared with the ocean uptake. Thus, the ocean is the dominant sink by several orders of magnitude (Mühle et al., 2009).

In the troposphere, SF is stable and does not degrade with highly oxidative species such as ozone and hydroxyl radicals (OH) (Mühle et al., 2009; Papadimitriou et al., 2008). Under extreme conditions such as electrical discharge, hydrolysis, and combustion, SF can break down into several toxic compounds such as HF, sulfuric acid (H_2SO_4), nitrogen fluoride (NF_3), sulfur dioxide (SO_2), and sulfur pentafluoride (SF_5). This will be an important consideration in any effort to scrub SF exhaust before its release into the atmosphere.

A global increase of SF mole fraction from 0.3 to 2.5 parts per trillion (ppt), along with a global increase in emissions from 0.5 Gg per year to 2.9 Gg per year, occurred from 1978 to 2019 (***Figure 1.10***) (Gressent et al., 2021). This is the first time global atmospheric measurements from the Advanced Global Atmospheric Gases Experiment (AGAGE) network were used to estimate SF emissions. Gressent et al. (2021) concluded that the global emissions increase is driven by the growing use of SF in structural fumigation in North America and in postharvest treatment of grains and other agricultural products worldwide.

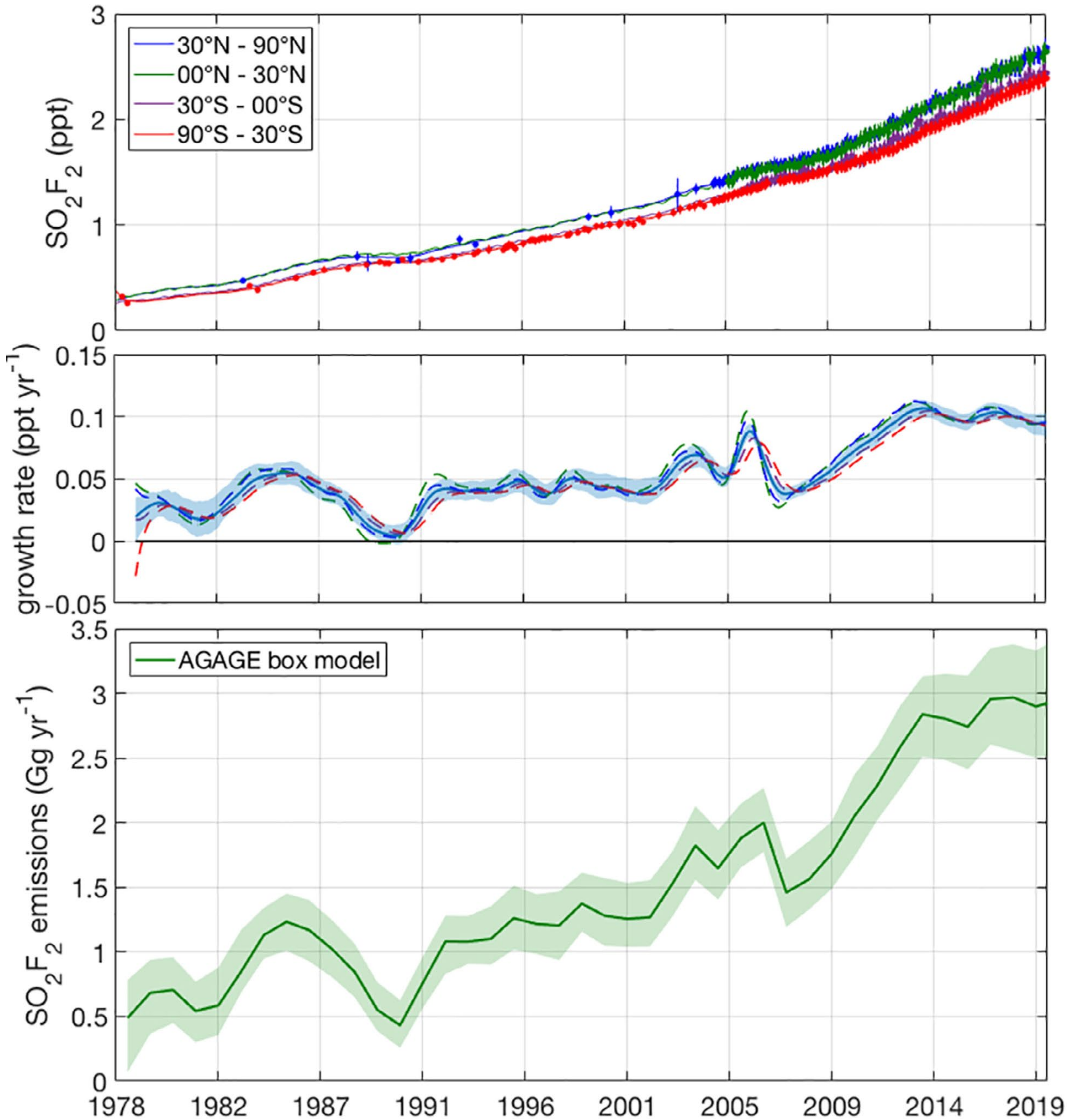

Figure 1.10. Global atmospheric concentrations (top) and emissions of SF (bottom) have both increased since 1978. Year over year growth rates in atmospheric concentrations are shown in the middle plot. Reprinted from Gressent et al. (2021). Used under Creative Commons Attribution License.

In the United States, the greatest amount of SF is emitted in California, at a rate of approximately 0.26 Gg per year. This is a top-down estimate based on atmospheric measurements from the National Oceanic and Atmospheric Administration's (NOAA's) Global Greenhouse Gas Reference Network (Gaeta et al., 2024). This amounts to 60% to 85% of SF emissions in the United States and 5.5%–12% of global SF emissions. The highest emissions are in Los Angeles, Orange, and San Diego Counties (***Figure 1.11***). These top-down models have an important limitation in that no atmospheric monitoring stations are located in Florida, which also commonly fumigates structures with SF to control drywood termites. The lack of monitoring stations in Florida makes it difficult to directly compare the emissions between these two states. Limited data from Florida suggest that California performs more structural fumigations (91,976 on average in California versus an estimated 60,000 annually in Florida; ***Section 1.9***), although the pounds of SF used per fumigation in Florida cannot be determined from the available data. The estimated rate of emissions for the United States is 0.3 Gg per year, although, as noted, data are sparse in the southeastern United States, particularly Florida, and this may be an underestimate.

Gaeta et al. (2024) found disagreement between the top-down model estimates of emissions of SF in California and the use of SF reported to DPR: The emission estimates were only 10% to 25% of what reported SF use would imply. This suggests that either 1) not all of the SF used during fumigations is ultimately emitted to the atmosphere, or 2) the calculated emissions based on the atmospheric modeling are underestimates. More studies on the fate of SF applied during structural fumigations could provide further illumination on this matter.

Beyond published studies, continuous SF measurements from NOAA and the AGAGE network provide an ongoing record of atmospheric concentrations in California. AGAGE operates sites in La Jolla and Trinidad Head, and NOAA operates five locations across the state, including both urban and remote stations. These high-frequency datasets, available to the public after quality assurance and quality control review, are a valuable resource for tracking changes in SF over time.

> 47. **FINDING:** Sulfuryl fluoride is a potent greenhouse gas that is released into the atmosphere following structural fumigations. Global atmospheric concentrations of sulfuryl fluoride have increased more than eightfold since 1978.

> 48. **FINDING:** Structural fumigations in Southern California are an important source of atmospheric sulfuryl fluoride.

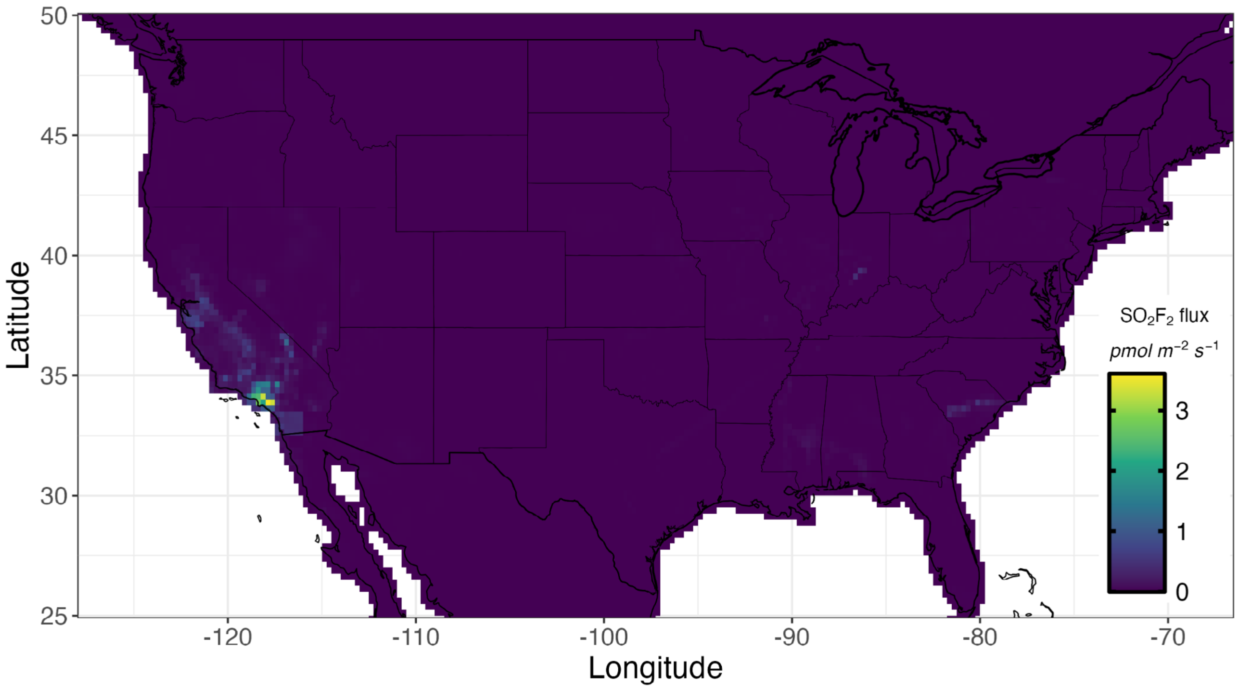

Figure 1.11. Estimates of SF emissions from 2015 to 2019 in the United States. Image adapted from Gaeta et al. (2024) and provided courtesy of D. Gaeta.

SF is not considered to be a groundwater pollutant (DPR, 2025c). No known studies have evaluated the potential impacts of SF venting on nearby nontarget insects nor on wildlife. While SF has a higher vapor density than air, there is no evidence of vented SF accumulating in the surrounding areas. Its gaseous state means that it will disperse rapidly in the broader environment. "Pooling" would only be expected to occur within enclosed spaces of the fumigated structure (this is why the label requires that cabinets, drawers, closets, etc. be opened during fumigation).

Section 1.9: Sulfuryl Fluoride Use in Other States and Countries

The amount of SF used in structural pest control is only maintained and available for California. As established in ***Section 1.3***, Hawaii and Florida also have drywood termites of structural concern; however, the amounts of SF used in Florida and Hawaii to treat these and other wood-destroying pests are unknown. An estimated 58,000 drywood termite fumigations are conducted annually in Florida (Zilberman & Lewis, 2024). Another source reports that more than 60,000 structures are fumigated in Florida annually (FFM, 2021).

Publicly available data concerning the use of fumigants to control structural pests worldwide is lacking, although market data regarding the current and projected use of SF worldwide are available for purchase. Wood-destroying beetles are a major pest in Europe, yet the first fumigation of a structure in Europe with SF was not conducted until 1992 (Binker, 1993). In Queensland, Australia, from 1968 to 2021, 898 structures were fumigated to control *C. brevis* (Haigh et al., 2022). Methyl bromide was the main fumigant used from 1978 to 1990 to eradicate *C. brevis* (Peters, 1990). The number of structures fumigated with SF was not reported.

In the Azores, Portugal, SF was used in a demonstration/research project to treat two structures infested with *C. brevis* (Scheffrahn et al., 2006). At that time, a commercialization plan was established to train PMPs. There are no data available concerning the number of structures fumigated with SF in the Azores.

The entire fumigation process is expensive. The wholesale cost of fumigating a typical structure of 600 m^3 (21,189 ft^3) ranges from $1,590 to $2,648. The retail costs range from $2,000 to $5,000 (Zilberman & Lewis, 2024). The residents must also find lodging for themselves and their pets for 2–3 days during the fumigation. The expenses incurred by the occupant or homeowner during the fumigation can easily exceed $500. In addition, equipment expenses including tarps, gas detectors, fans, and self-contained breathing apparatuses make fumigation prohibitive in many countries.

> 49. **FINDING:** The amount of sulfuryl fluoride used to control structural pests outside California is unknown. However, estimates suggest that more than 60,000 structural fumigations are conducted in Florida annually. There are no publicly available data on the number of structures fumigated in Hawaii.

> 50. **FINDING:** The use of sulfuryl fluoride in structural pest control is dictated by the importance of drywood termites in that county, state, or country. Since fumigation is costly and requires special equipment and training, economic factors will also dictate where it will be used to control drywood termites.

> 51. **CONCLUSION:** Greater surveillance of sulfuryl fluoride is needed, especially in Florida and Hawaii, where thousands of fumigations are also performed.

Section 1.10: Tradeoffs Related to Using Sulfuryl Fluoride

Benefits

By ensuring the complete eradication of drywood termites throughout a structure, SF helps prevent potentially irreparable damage to homes when termite infestations are discovered. This is particularly important in housing-constrained regions such as Los Angeles and the Bay Area, where termite pressure overlaps with some of the most competitive and least flexible real estate markets in California. One of the key advantages of SF is its ability to penetrate inaccessible areas of a structure, allowing PMPs to eliminate infestations without needing to expose termite galleries by opening walls or ceilings. Further, in heavily infested properties, it allows PMPs to eliminate all possible infestations—even those within the structure for which visual confirmation of termite presence would not be possible.

Drawbacks

Historically, one pesticide has needed to be replaced by another when the earlier one stops working or is found to generate other health or environmental problems. SF was preceded by hydrogen cyanide, chloropicrin, and then methyl bromide. Its continued use perpetuates a pattern of overreliance on chemicals to resolve our pest problems in ways that potentially stall innovation into less toxic or nonchemical alternatives.

This report considered the health and environmental impacts associated with the use of SF. It should be noted, however, that both the health and environmental risks of SF extend beyond its use to include its production, transportation, and disposal. Ideally, the entire chemical life cycle should be considered in assessing its risks (Galt, 2008; Mansfield et al., 2024).

SF is a potent GHG. While SF is not currently regulated as such under California law, its regulatory status likely has more to do with the timing of its discovery as a GHG than its climate impact. Recent findings of high emissions from SF fumigations warrant closer examination of possible efficiencies in the deployment and use of SF, particularly in light of the state's overarching commitment to achieving net-zero GHG emissions. Although it is used in relatively small quantities compared with other GHGs, its high GWP means that it has an outsize impact on climate change on a per-ton basis.

SF is a toxic chemical that must be handled with great caution, and there are inherent risks to human health associated with the use of SF. Reentry into improperly cleared structures (whether due to faulty clearance devices, lack of awareness about the fumigation, or willful criminal entry) poses severe acute risks to health, including death. Toxicological studies show that inhalation of SF has neurotoxic and respiratory impacts, as well as potential genotoxic impacts. While PMPs are at highest risk of exposure to SF, data from California's PISP suggest that the fumigation of structures with SF can also affect bystanders in surrounding areas upon ventilation.

From the homeowner perspective, one of the major drawbacks in the use of SF to fumigate structures is that the structure must be evacuated for several days. The concentration of SF required to kill drywood termites under the tarp is lethal to humans, pets, animals, and plants. Time is required to prepare the structure for fumigation, to fumigate (typically 22–24 hours), and to clear the structure of SF (typically another 24 hours) (FFM, 2021; SPCB, 2021). Residents are required to bag food, drugs, and medicinal items not in their original plastic, glass, or metal containers with the manufacturer's airtight seal intact and remove plants and pets from the structure. Any mattress encased in plastic needs to be removed, with exceptions of water beds and vented or opened casing mattresses. Plants and other landscaping material must be removed from around the exterior of the structure as well so that the tarps can make contact with the ground.

Security of structures during the fumigation process has become an important issue in recent years. The cities of Lakewood and Cerritos, California, have websites discussing measures to prevent fumigated structures from being burglarized (Cerritos, 2012; Lakewood, 2025).

Fumigating with SF could theoretically be weighed through a cost-benefit analysis, but there are numerous limitations to such an approach (Ackerman, 2006). In fact, the process of assigning economic values to environmental and human health costs is notoriously fraught, which is why attempts at modeling even simple concerns yield inconsistent and often contested results (DuPuis, 2004). Further, some argue that the values of human health and environmental sustainability are virtually impossible to quantify (Schröter et al., 2014; Loos et al. 2023). Attempting to assign them economic values evades what are inherently political questions and deeply conflicts with some people's religious and cultural values (Conniff, 2012; Liboiron, 2021).

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Chapter 2: Alternatives to Sulfuryl Fluoride

Section 2.1: Chapter Overview

This chapter focuses on alternatives to sulfuryl fluoride (SF) for controlling wood-destroying insects in California, with an emphasis on drywood termites. Section 2.2 provides important context about the different categories of alternative treatments, both whole-structure and localized, and their development. Section 2.3 discusses preventive treatments. Section 2.4 describes several devices marketed to detect termite infestations in structures, especially in hidden and inaccessible areas. Section 2.5 examines whole-structure heat treatment—the only whole-structure alternative to SF fumigation. Sections 2.6 through 2.12 discuss localized treatment alternatives to SF fumigation, including chemical treatments (Section 2.6), heat treatments (Section 2.7), cold treatments (Section 2.8), electrocution (Section 2.9), microwaves (Section 2.10), biological treatments (Section 2.11), and wood removal (Section 2.12). Section 2.13 reviews no treatment, Section 2.14 explores alternative treatments used in other countries, Section 2.15 considers any potential negative consequences for an even broader adoption of alternative treatments, while Section 2.16 discusses the potential benefits. Finally, Section 2.17 presents treatment alternatives with the best tradeoff to SF fumigation.

To simplify cost comparisons among the different alternative treatments covered in this chapter, pest management professionals (PMPs) at several companies were given a hypothetical home (single story with a volume of approximately 29,000 ft^3) and asked to estimate the cost of services to fumigate or provide one of the alternative treatments (***Appendix VI***). For context, PMPs estimated the wholesale costs to fumigate the sample structure would be $1,250, and the retail costs would range from $1,750 to $4,000 (L. Whitmore, pers. commun., 7/30/2025; D. Wadleigh, pers. commun., 5/1/2025; D. Belle, pers. commun., 7/29/2025).

Chapter 2 contains 27 FCRs: 20 Findings, 5 Conclusions, and 2 Recommendations.[5]

Section 2.2: Background

Hydrogen cyanide and chloropicrin were the first fumigants marketed to control drywood termites (Randall et al., 1934). However, neither compound was widely adopted because they could not effectively penetrate wood, and both required long exposure periods to kill drywood termites. A more effective early option was localized treatment with arsenical dust

[5] 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.

with Paris green and calcium arsenate, and sodium fluosilicate (Randall et al., 1934). However, in addition to being toxic to termites, arsenical dusts are also toxic to humans. SF and methyl bromide were introduced as structural fumigants in 1959 and 1961, respectively. Methyl bromide fumigation for structural pests was phased out by 2005 because it harmed the atmosphere's protective ozone layer.

SF fumigation and heat are the only two whole-structure treatments currently approved in California (SPCB, 1998). A benefit of treating entire structures is that finding all active infestations, even those in inaccessible or hidden locations such as wall voids and crawl spaces, is not necessary to ensure all wood-destroying pests are killed. However, neither SF fumigation nor heat treatment can prevent future reinfestation.

Drywood termites can quickly replace reproducing queens and kings and re-establish colonies within structures. Older larval and nymphal termites of drywood termite species found in California, including *Cryptotermes brevis*, *Incisitermes minor,* and *Incistitermes snyderi*, will develop into **neotenic** or supplementary reproductives if a king or queen dies or when a group of termites is cut off from the main colony (Harvey, 1934; Lenz et al., 1982). The new neotenic queens and kings can mate, lay eggs, and maintain the colony. New, reproducing colonies of *I. minor* can appear within 4 months (T. Atkinson, pers. commun., 2/5/2025). Consequently, new colonies may appear if localized treatments fail to kill 100% of termites, especially when those treatments do not provide any residual protection.

Whole-structure treatments are often justified when there are multiple infestations in hard-to-reach locations. The risk of having several infestations in hard-to-reach areas rises once there is evidence of swarming (i.e., there are winged reproductive individuals) within a structure. The California Structural Pest Control Act (SPCA) (Section 1991.8, SPCB, 2021) requires that PMPs recommend an all-encompassing treatment (SF fumigation or heat) or expose the infested area(s) for local treatment if there is evidence of an infestation extending into an inaccessible area. Homeowners and property owners typically choose SF fumigation in this situation.

Alternative treatment strategies for the control of drywood termites have been extensively reviewed (Scheffrahn & Su, 1994, 1997; Lewis, 1997, 2003; Verma et al., 2009; Lewis & Forschler, 2014). Some of the advantages and disadvantages of each treatment are provided in ***Table 2.1***. No alternative treatments exist elsewhere in the United States or abroad that have not also been tried in California.

Localized treatments are the most common alternative to SF fumigation. These treatments can be either physical or chemical, including heat, cold, electrocution, microwaves, wood removal, drill-and-inject chemicals, and borate surface sprays. Localized treatments may or may not provide residual activity that prevents reinfestations. Limited information exists regarding the effectiveness of most alternative treatments under laboratory or field conditions. A review of alternative treatments for controlling drywood termites concluded that the effectiveness of alternative treatments ranged from 0% to 100%, with no guarantees that colonies are eliminated (Lewis, 2003).

Companies also market a variety of devices to prevent, eliminate, repel, or kill drywood termites, subterranean termites, carpenter ants, and powderpost beetles. Any device must be registered with the California Department of Pesticide Regulation (DPR, 2025a). The definition of a device is any method, instrument, or contrivance that is intended to control or mitigate any wood-destroying pest. Devices typically use heat, electricity, or microwaves. DPR registration requires that companies submit information regarding the principles of operation, effectiveness data, human and animal safety, and the structural integrity of each device.

The inconspicuous nature of drywood termite infestations and their ability to replace reproductive kings and queens must both be considered when choosing alternative treatments. Drywood termites feed and live within single pieces of wood, but colonies can extend into adjacent pieces of lumber within a structure. If their galleries (i.e., tunnel systems) extend into inaccessible areas, the colonies are no longer accessible to PMPs nor amenable to localized treatments.

There is limited data on the comparative rates with which SF fumigation or alternative treatments are conducted in California. Indeed, the most recent estimates are from the early 1990s. While faculty at UC Riverside, T. Atkinson (pers. commun., 2/5/2025) surveyed structural pest inspection reports and completion notices filed with the SPCB from Orange, Riverside, and San Bernardino counties from 1992 to 1993. Of the structures treated, 72% were injected with the organophosphate insecticide chlorpyrifos, 22% were fumigated with SF, and 6% had nonchemical treatments. The nonchemical treatments, in order of decreasing frequency of use, were Electro-Gun, microwave, wood replacement, heat, and cold.

Table 2.1. Treatment options for the control of drywood termite infestations.

Treatment	Localized (L) or whole structure (WS)	Remedial (R) or preventive (P)	Residual activity	Treatment time	Key strengths	Key drawbacks	Costs per structure[d]
SF Fumigation	WS	R	No	2–3 days	Treats exposed and hidden infestations. Guarantee	Greenhouse gas Category I insecticide	$$$ Depends on cubic volumee Living expenses 2–3 days
Heat	WS	R	No	12 hours	Treats exposed and hidden infestations. Guarantee	Heat-sensitive items	$$$ At least 50% more expensive than fumigation. Rarely done
Heat	L	R	No	4–12 hours	Limited to boards/spots in structure	Heat-sensitive items	$$ Depends on volume treated
Cold	L	No longer registered in CA					
Electrocution	L	R	No	30–60 minutes	A nonchemical method	Limited to exposed and accessible boards	$$
Microwaves	L	R	No	10–30 minutes	A nonchemical method	Limited to exposed and accessible boards	$$
Drill-and-inject	L	R or P	Yes[b]	5–20 minutes	Provides targeted residual and prevention	Limited to finding accessible galleries. Drilling holes and patching of unsightly boards Category II–IV insecticides	$$–$$$
Surface sprays	L	P or R	Yes[b]	10 minutes–2 hours	Provides residual and prevention	Limited to exposed and accessible boards Category II–IV insecticides	$–$$ Cheapest when only surface is treated
Wood replacement	L	R	Yes[c]	Variable	Infestation source removed	Wood replacement is costly. If lead paint and asbestos are involved, additional costs	$–$$$ Depends on scope, can be very expensive

[a] Adapted from Scheffrahn & Su (1997), Lewis (1997), and Lewis & Forschler (2014).
[b] Depends on the active ingredient.
[c] Depends if wood has been treated with wood preservatives, composite lumber, or a highly resistant wood.
[d] Data from Zilberman and Lewis (2024). $ = less than $200, $$ = $200–$1,000, $$$ = greater than $1,000.
[e] 29,000 ft^3 home fumigated with sulfuryl fluoride costs the consumer from $1,875 to $ 3,125.

Section 2.3: Preventive Measures

Section 2.3.1: Background

Effective chemical and nonchemical preventive measures to prevent termite infestations have been sought since the early 1900s. Limited research has investigated the effectiveness of surface treatments at deterring termite feeding. However, there is limited data regarding the long-term effectiveness of preventive treatments for drywood termites.

Current methods for termite prevention are similar to those proposed nearly 100 years ago. Brown et al. (1934) recommended deterring termites by covering wood with paint, placing cover screens over attic openings, and sealing cracks and small openings in exterior walls. Additional measures included using wood treated with preservatives, choosing seasoned heartwoods of trees unpalatable to termites, and locating and treating colonies before they extend throughout a structure.

Existing preventive measures include wood preservatives; surface application of silica gels or borates to prevent **alates** (winged reproductive individuals) from establishing new colonies; and noninsecticidal approaches such as paints, wood coatings, and termite-resistant wood (Scheffrahn & Su, 1994; Lewis, 2003; Lewis & Forschler, 2014). However, not all paints and coatings are protective. For example, one or two coats of oil-based enamel and shellac on Douglas fir prevented *I. minor* feeding but water-based latex paint did not. None of the paint coatings were toxic to termites (Rust & Scheffrahn, 1980).

Wood preservatives prevent wood degradation due to fungi, stain, molds, wood-destroying insects, crustaceans, and mollusks (EPA, 2024b). Many of the older wood preservatives, such as creosote, chromated arsenicals, and pentachlorophenol, have had their use prohibited or dramatically restricted due to human and environmental health risks. Newer wood preservatives approved for residential use against drywood termites include alkaline copper quaternary, borates, copper azole, and copper naphthenate.

California building codes require that wood treated with preservatives be used during construction under certain circumstances, primarily to prevent fungi and subterranean termites (CBC, 2022). These include any time wood is in contact with soil or fresh water; when wood joists or wood floors are within 18 inches of the ground, posts, or columns that support the structure are in contact with the ground; when wood is used for exterior decks and balconies; and when wood framing material is 8 inches from exposed earth.

Borate formulations such as disodium octaborate tetrahydrate (DOT) have been widely used to deter wood-destroying insects. One company estimates that to date nearly 2 million homes across the United States have been treated with a 2-foot band of DOT along the bottom of the structure at the time of construction to replace conventional insecticide soil treatments to prevent subterranean termites (J. Lloyd, pers. commun., 8/14/2025). However, the number of structures in which all interior wood surfaces have been sprayed is unknown. All wooden surfaces would have to be thoroughly treated with DOT for it to be effective against drywood termites.

Simulated field studies by Gillenwaters et al. (2018) and laboratory tests by Rust & Venturina (2009) clearly indicate that surfaces treated with liquid borates are not highly toxic to drywood termites by contact. However, they do prevent feeding and penetration by **alates** and workers. To be effective, the surface must be thoroughly treated.

Although liquid formulations of DOT fail to kill drywood termites on contact, dust deposits are toxic. Other dust compounds toxic to the drywood termite *C. brevis* include chlorpyrifos, spinosad, and calcium arsenate applied to boards (Scheffrahn et al., 1997a). Rust & Venturina (2009) investigated the activity of two formulations of DOT, as well as thiamethoxam and imidacloprid foam, and fipronil and d-limonene, against *I. minor*. Deposits of DOT, fipronil, and thiamethoxam were lethal to drywood termites on both continuous and brief exposures. The active ingredients were readily available from the treated surfaces. Deposits of DOT dust, fipronil liquid, and thiamethoxam foam were not repellent, and lethal doses of active ingredient were readily transferred from treated termites (donors) to untreated termites (recipients). Fresh deposits of d-limonene were extremely toxic to drywood termites. However, the deposits rapidly lost their contact activity within 24–48 hours but were repellent to termites. Vapors of d-limonene and fipronil were toxic to drywood termites. Prolonged exposures of drywood termites on deposits of DOT and imidacloprid foam were required to kill termites, but the nonlethal deposits deterred termite feeding. Nonlethal deposits of d-limonene deterred feeding. DOT dust, fipronil, and thiamethoxam foam consistently provided the best results in the laboratory tests. Dust formulations of DOT, silica gel, and imidacloprid prevented *C. brevis* alates from establishing new colonies in a simulated laboratory study (Scheffrahn et al., 2001). Liquid and dust deposits of DOT and silica gel at label rates prevented alates of *C. brevis* from establishing colonies in treated wood (Gillenwaters et al., 2018).

Wood blocks dipped or vacuum treated with 0.1% to 1.0% solutions of DOT were tested as preservatives against *I. minor* **pseudergates** (immature termite workers) (Kartal et al., 2020). Vacuum-treated wood consistently provided greater kill of drywood termites at 6 weeks. Concentrations greater than 0.5% prevented feeding on the treated wood. The depth of penetration of two formulations of DOT sprayed on framing lumber increased over 26 weeks (Lebow et al., 2013). The DOT penetrated 5–6 mm, 6–9 mm, and 9–11 mm at week 6, 13, and 26, respectively. Moisture content of the wood may greatly affect the depth of penetration.

In laboratory studies, fipronil foams provided faster contact activity against *C. brevis* than did imidacloprid foams (Hassan et al., 2023). Deposits of the fipronil foam were not repellent, and fipronil was readily transferred from donor to recipient termites.

The application of recycled paper treated with orthoboric acid (TAP Pest Control Insulation) is **registered** for new and retrofit construction. Cellulose insulation treated with boric acid in wall voids killed and prevented subterranean termites from penetrating it (Mankowski & Grace, 2004). Liquid deposits of DOT and orthoboric acid on cellulose surfaces are not very toxic to drywood termites, and long exposures are required (Scheffrahn, et al. 1997a; Rust & Venturia, 2009). The effectiveness of these treated insulation materials against drywood termites has never been studied or published.

> 52. **FINDING:** Borate formulations applied to wood surfaces can deter drywood termites. These surface treatments are applied during construction as preventive treatments for subterranean termites and have proven effective. A preliminary cost analysis suggests surface treatment is no more costly than a fumigation or localized treatment and could provide protection for at least 30 years.

> 53. **CONCLUSION:** Borate formulations applied during construction could be an effective method for preventing drywood termite infestation. However, additional research is needed to determine the long-term effectiveness of this approach.

> 54. **RECOMMENDATION:** DPR and other relevant agencies should consider providing financial support for long-term field research (5–15 years if conducted in areas with heavy drywood termite presence) to determine if current borate treatments for subterranean termites could be expanded to include drywood termites.

Section 2.3.2. Scale of Use of Preventive Measures

Data regarding the use of preventive measures for deterring drywood termites in California are scarce. Several companies in California provide borate formulations (DOT) for spray treating wood during construction, but the treatment is primarily to prevent subterranean termites. There is no data on whether DOT is applied to structures undergoing construction in California to prevent drywood termites and wood-destroying beetles. The amount of surface applications of insecticidal sprays and dust registered for drywood termite control (***Table 2.2***) is also unknown, as is the degree to which companies and homeowners apply nonchemical preventive treatments.

Cover screens are required to cover air vents for attics and crawl spaces beneath structures in California. California Building Code (CBC) requires that attic vents be covered with 1⁄16- to 1/4-inch screen mesh (CBC, 2025). Additionally, CBC Chapter 7, Section 706A requires fire-resistant vents with 1/16-inch mesh in all construction in areas designated as moderate, high, or very high risk of wildfires. The screens have been proposed as a preventive measure against wood-destroying insects. Drywood termite **alates** have an average head capsule width of 0.065 inches (personal observation, n=5). While termite bodies can be compressed to squeeze through narrow openings, the head cannot. Alates should be able to enter or escape vents covered with 1/4-inch mesh screen, but 1/16-inch mesh should exclude most termites. The effectiveness of the current code requirement for cover screens is unknown.

> 55. **FINDING:** Fire-resistant vents and screens may have the added benefit of excluding most drywood termites, although this has never been directly evaluated.

> 56. **CONCLUSION:** The effectiveness of fire-resistant vents and screens in excluding drywood termites should be evaluated.

Section 2.3.3: Effectiveness and Duration of Pest Control

There is little data on the long-term effectiveness of chemical and nonchemical preventive treatments for drywood termites. Many of the newer composite building materials have not been tested against drywood termites.

One study evaluated the long-term effectiveness of chemical surface sprays applied to wood while a structure is in the framing stage (Hunt, 1959). Thirty structures in the framing stage were treated with copper naphthenate in 1947. DDT or lindane was added to copper naphthenate emulsions and applied to 10 of these structures. Reinspections of the structures in 1958 revealed that the sprays had deterred drywood termites; however, there is no mention of infestation rates in control untreated structures.

> 57. **FINDING:** The effectiveness of preventive measures for the long-term protection of structures from termites has never been evaluated.

Section 2.3.4: Costs Associated with Preventive Treatments

The cost of alternative building materials such as composite lumber is approximately $16–$32 per square foot, compared with $2–$5 per square foot for standard materials (Boyce, 2025). Installation of composite materials costs $24–$48 per square foot. However, the composite materials last 30–50 years.

The cost of pressure-treated lumber is approximately 45% more than untreated lumber. Like composite materials, pressure-treated lumber will last considerably longer than untreated wood. Properly maintained pressure-treated lumber can last 20–30 years.

The cost of treating an entire structure in the framing stage or treating attics (***Section 2.3.1***) is unknown. The estimated cost to apply DOT spray to the hypothetical structure presented in ***Appendix VI*** would be approximately $425 in chemicals and approximately $1,000 in labor at the time of construction. The cost to the homeowner might range from $1,000 to $2,000 (J. Lloyd, pers, commun., 8/14/2025). These preventive treatments are expected to remain effective for at least 30 years.

> 58. **FINDING:** No research has been conducted to determine the cost effectiveness of preventive measures to control drywood termites.

> 59. **CONCLUSION:** Additional research is needed to determine which preventive treatments are cost effective and provide value to the property owner.

Section 2.3.5. Additional Requirements for Use

Many of the preventive approaches described in this section should be incorporated during construction, which would require coordination between builders and PMPs. Some preventive treatments, such as spraying borates or applying dust to untreated wood, could be applied after whole-structure treatments to help prevent reinfestation. Not all pest control companies provide such services.

Section 2.3.6: Availability, Ease, and Reliability

To prevent drywood termites and some beetles from infesting structures, exposed surfaces of wood must be thoroughly treated. Treating large areas in attics, crawl spaces, and other voids can require special equipment. Installing composite lumber requires special equipment and is more costly than regular lumber.

Section 2.3.7: Human Health Impacts

Considerable data exists regarding the human and animal health impacts of lumber treated with registered wood preservatives (EPA, 2024b). There is less information about the potential human health impacts of other chemicals used as termite preventives in structures. A comprehensive review of the human health impacts of each of these chemicals is beyond the scope of this report. Instead, this section summarizes the potential human health impacts of the most commonly used termite preventive treatments for structural lumber.

The most widely used chemical preventive and remedial treatment of structural lumber is DOT, the toxic ingredient of which is boron (***Section 2.3.1***). DOT is typically applied to furnishings and interior construction, such as framing, sheathing, sill plates, furring strips, trusses, and joists (EPA, 2024b). DOT has oral (Category III), dermal (Category III), and acute inhalation (Category II) toxicity (EPA, 1993). However, as long as applicators follow label instructions, applicators and occupants will have minimal exposure. Dermal absorption is only a concern if DOT gets in open wounds or abrasions (Bernard et al., 2010; Harper et al., 2012). No data exist concerning the indoor fate of DOT (i.e., what happens to the chemical once it is applied in indoor settings) (Harper et al., 2012).

Section 2.3.8: Environmental and Ecological Concerns

The environmental impact of wood preservatives has been intensively reviewed (EPA, 2024b). In California, wood treated with preservatives containing arsenic, chromium, copper, pentachlorophenol, and creosotes is considered toxic waste and must be disposed of accordingly (DTSC, 2021). Lumber treated with these preservatives was primarily limited to structural areas (including in older homes) with earth-wood contacts, sill plates contacting concrete, and excessive moisture.

DOT poses minimal risk to birds, fish, aquatic invertebrates, and other wildlife (EPA, 1993). There are many sources of boron in the environment, including wood and coal burning and rock weathering. The natural background levels of boron in public water supplies is approximately 0.17 mg per liter of water (Bernard et al., 2010). Boron is required by plants for growth, but too much can be toxic (Harper et al., 2012). DOT can leach boron into water, so treated wood should not remain in constant contact with water.

Section 2.4: Detection of Drywood Termite Infestations

Successfully using alternative localized treatments against drywood termites and other wood-destroying insects usually requires knowing the exact location and size of an active infestation. PMPs or customers must also reinspect treated areas to detect survivors and ensure control was achieved. However, in practice reinspections rarely take place unless customers report concerns.

Determining the presence of active termite infestations is difficult. Drywood termites create their nest and gallery system within pieces of wood as they tunnel and forage. The only external sign of an active infestation may be the small entrance hole that alate reproductives created when they entered the wood. The **alates** prefer concealed locations to construct their entrance gallery (Scheffrahn et al., 1998). Fecal pellets may not appear in a structure until after 4–5 years, when mature colonies begin to produce reproductive alates and emergence holes (kick-out holes) (Ebeling, 1975). In older colonies, there may be visible signs of feeding damage along board surfaces.

An inspection by a licensed PMP or field representative is required prior to any pest control recommendations and before work may begin (SPCB, 2021). Detection is part of this larger structural inspection. PMPs typically rely on visual inspections aided by flashlights, probes, ladders, and mirrors. Visual inspections may reveal evidence of wood-destroying pests such as feeding damage, emergence holes, fecal pellets (***Figure 2.1***), and wings from alates, but not necessarily live insects. The presence of live insects is not required to recommend treatment.

In some cases, destructive sampling is the only way to confirm the presence of an active infestation (SPCB, 2021). This can include removing sheetrock, paneling, siding, stucco, and roofing materials to expose infested lumber. However, destructive sampling is not commonly included in inspections. Instead, concealed areas with suspected termites are often marked in reports as "inaccessible." After treatment, the SPCA recommends that PMPs cover and remove all accessible pellets and **frass** so the material will not be reported in future inspections (SPCB, 2021).

Figure 2.1. Six-sided fecal pellets are a telltale sign of western drywood termite infestation. Main photo credit: V. Lewis. Inset photo credit: W. Ebeling.

Termite monitoring devices can indicate the possible presence or absence of termites (Section 1993.4; SPCB, 2021). They do not provide positive identification of an infestation and do not eliminate the need for inspection by a licensed PMP or field representative.

Technologies have been developed to aid termite inspections including borescopes (fiber optic devices); x-rays and computerized tomography (CT); and acoustic emission, microwave, and infrared detectors. Dogs have also been trained to detect termites in structures. In previous literature reviews, none of the inspection aids were considered standard equipment or procedure for inspectors (Lewis, 2006, 2009a; Lewis & Forschler, 2014).

PMPs may use borescopes to look inside wall voids for evidence of termites or their damage. A technician with a borescope was 80% accurate in identifying drywood termites in the laboratory and 36% to 79% accurate in the field (Hassan & Nada, 2024). Vision can be limited by insulation and other materials in the wall voids. Borescopes are time-consuming and require PMPs to drill holes in the wall (Sutherland et al., 2014).

Attempts to detect termites using early acoustic systems were conducted in the 1930s (Barton, 1934), but excessive noise interference prevented their use. Modern acoustic-detection devices transform the vibrations from termites feeding, excavating, or pulling on wood into electric signals (Hassan & Nada, 2024). These electric signals result in acoustic emissions, and acoustic emission counts (AEC) are proxies for termite activity. The sensors focus on frequency bands greater than 20 kHz.

Factors that can affect the accuracy of an acoustic device for detecting termites include the sensor type and frequency range, substrate structure, the interface between sensor and substrate, termite size and behavior, and distance between termite and sensor (Hassan & Nada, 2024). For example, termite detection is affected by whether a sensor is located along the grain of the wood or across the grain. Termites can be detected as far away as 80 cm (31.5 in.) with a sensor placed along the grain and 8 cm (3.2 in.) across the grain (Scheffrahn et al., 1993; Lewis, 2009a). Irrespective of position, the device successfully detected termites 50% of the time when insects were 50 cm (20 in.) away (Scheffrahn et al., 1993). Despite the imperfect data generated by these acoustic devices, they are often relied upon in studies to determine the effectiveness of treatment methods in reducing termite activity.

Excessive background noises can be reduced by using higher transducer frequencies (60 kHz) (Lemaster et al., 1997). In a comparative study, the sensitivity and specificity for PMPs using the acoustic emission device AED 2000L to detect wood-destroying termites and beetles were 80% (Zahid et al., 2012).

Microwave detectors rely on radar fluctuations caused by insect movement. The Termatrac™ was commercialized in 1999, and several studies have evaluated its ability to detect drywood termites. In a laboratory investigation, the Termatrac detected *I. minor* within small logs with 1.8% false positives and 3.8% false negatives (Indrayani et al., 2006). In a comparative study, Termatrac sensitivity and specificity was 56% and 69%, respectively, in detecting termites and beetles in naturally infested branches (Zahid et al., 2012).

At the highest sensitivity, Termatrac detected 97% of termite-infested wood with minimal 22% false positives (McDonald et al., 2022a). The sensitivity settings on the device affected the number of false positives and negatives. The highest sensitivity resulted in 22% false positives, and the lowest sensitivity resulted in 2.9%. Its effectiveness was impacted by the type of wood, moisture content, density, grain orientation, wall coverings, and motion (Lewis, 2009a; Taravati, 2018; McDonald et al., 2022a). Colony size did not affect its detection capability (Hickman & Forschler, 2012; Taravati, 2018; McDonald et al., 2022a). Drywood termites were reliably detected 5 cm (2 in.) beneath drywall (Taravati, 2018). One limitation of the device is that the reliable detection area (5 × 6.5 cm or) is very small (Lewis, 2009a).

X-rays and CT have been used to examine the nesting and tunneling behavior of drywood termites (Fuchs et al., 2004; Himmi et al., 2016). The extent and severity of a drywood termite and powderpost beetle infestation in a museum storage vault and in musical instruments were determined using CT (Bentivoglio-Ravasio et al., 2011; Arbat et al., 2021). Several factors limit this technology, including the high cost of the equipment and the need for trained radiographers and expert interpretation of results (Hassan & Nanda, 2024).

Dogs were 89% successful in detecting the southeastern drywood termite, *I. synderi*, hidden in plastic containers in one study (Brooks et al., 2003). The minimum number of termites tested was 40. Considering the small number of termites in drywood termite colonies (300-500 termites) and their propensity to aggregate in small groups, this might be an issue, especially with small colonies of *C. brevis*. Inspection of attic spaces, fascia boards, and rafters may also present problems for canine inspectors. In a study using infested tree branches (diameters of 1–8 cm or 0.4–3.2 in.), dogs were 100% effective in detecting subterranean termites in naturally infested logs but were unable to detect small numbers of termites in artificially infested boards (Zahid et al., 2012). Dogs failed to detect powderpost beetles in artificially infested boards.

In a review of various detection strategies, Lewis (2009a) concluded that a highly skilled and trained PMP is the best inspection option for drywood termite or any other wood-destroying insect. Whether or not PMPs use the inspection tools described in this section will depend on cost, ease of use, time required to conduct an inspection, and their ability to detect drywood termites in inaccessible locations. Data are not available on how often these inspection devices are used.

60. **FINDING:** None of the available devices and inspection aids can reliably detect the presence of termites and other wood-destroying insects within structures.

61. **CONCLUSION:** Devices and inspection aids do not replace the need for highly trained and experienced pest management professionals.

Section 2.5: Whole-Structure Heat Treatments

Section 2.5.1: Background

Brief exposures to temperatures in excess of 46°C (115°F) are typically lethal to many insects. Grain producers have long used dry heat to control insects infesting grain milling and storage facilities, but controlling wood-destroying insects in residential structures wasn't commercialized until the 1980s (Forbes & Ebeling, 1987). The temperatures required to kill various wood-destroying insects varies among pest species, the type of wood, and conditions of the heat treatment. The first commercial standards for heat treatment recommended core wood temperatures of 48.9°C (120°F) for 30 minutes to kill drywood termites (Ebeling, 1997). Several species of drywood termites have been tested for their heat tolerance (***Table 2.2***). A higher exposure of 54.4°C (120°F) for 60 minutes for nearby pieces of wood was recommended in situations where internal wood temperature of suspected infestations cannot be monitored (Scheffrahn et al., 1997b). The current international standard for heat treating wood packing materials is 56°C (133°F) for at least 30 continuous minutes to ensure all termites and wood-destroying beetles are killed (FAO, 2019).

Table 2.2. Temperature and exposure periods required to kill 100% of drywood termites.

Species	Temperature	Exposure period (min)	Reference
Cryptotermes brevis	45°C (113°F)	45	McDonald et al. (1997b)
	46°C (115°F)	60	Woodrow & Grace (1998b)
	49°C (120°F)	30	Woodrow & Grace (1998b)
	50°C (122°F)	3	McDonald et al. (1997b)
	55°C (131°F)	2	McDonald et al. (1997b)
Incisitermes immigrans	46°C (115°F)	20	Woodrow & Grace (1998b)
	48°C (118°F)	30	Woodrow & Grace (1998b)
Incisitermes minor	46°C (115°F)	265	Forbes & Ebeling (1987)
	51.7°C (125°F)	15	Rust & Reierson (1998)
	54°C (129°F)	6	Forbes & Ebeling (1987)
Incisitermes synderi	50°C (122°F)	15	Scheffrahn et al. (1997b)

There are five heat treatment devices registered with DPR in California (DPR 2025b). The products include 1) Dewey Heat by Dewey Services Inc; 2) Greentech Heat Solutions Titan by Green Tech Solutions; 3) Heat Blast by Team Termite & Pest Control Inc.; 4) Safe-Heat Model 500 Thermal Pest Eradication Device by Topp Portable Air; and 5) ThermaPureHeat by TPE Associates, LLC.

Section 2.5.2: Scale of Use of Whole-Structure Heat Treatments

Whole-structure heat treatments are rare in California due to technical and procedural difficulties (L. Whitmore, pers. commun., 2/12/2025). However, the exact number of whole-structure heat treatments conducted for wood-destroying pests in California is unknown. Heat treatments are often limited to small structures or structural compartments to prevent structural damage. Conversely, under-heating may result in incomplete termite control (Scheffrahn et al., 2006). Whole-structure heat treatments are reserved for situations that make SF fumigation challenging or nonviable (Scheffrahn & Su, 1997; L. Whitmore, pers. commun., 2/12/2025).

Section 2.5.3: Effectiveness and Duration of Pest Control

There is limited information regarding the effectiveness of whole-structure heat treatments. In a simulated field study, heat treatments to the entire structure provided 100% kill on artificially infested boards in all areas except the crawl space (91.1%) and 100% kill of all termites in naturally infested boards (Lewis & Haverty, 1996). Temperature readings throughout the structure recorded 50°C (122°F) for 1 hour. In a repeat of this experiment, the maximum air temperature reached 87.2°C (189°F), and a few termites in the crawl space still survived. In a separate study, failure to kill all the drywood termites was attributed to heat sinks near the infested wood (Perry & Choe, 2020). Once temperatures return to normal, there is no residual activity, and the structure can be reinfested.

Section 2.5.4: Costs Associated with Whole-Structure Heat Treatments

The average cost of heat-treating a home is $5,000 in the United States, with treatments ranging from $1,000 to $12,000. These prices vary depending on the geographic location of the structure (Graham & Pomares, 2025). In California, PMPs estimated that a wholesale volumetric heat treatment of this report's hypothetical structure (***Appendix VI***) would cost $1,275–$2,030 and a retail heat treatment would cost $2,175–$6,090 (L. Whitmore, pers. commun., 7/30/2025; D. Wadleigh, pers. commun., 5/1/2025). These estimates are approximately 60% more than those received for SF fumigation.

Section 2.5.5: Additional Requirements for Use

Heating wood within structures presents many challenges. Wood has much lower thermal conductivity and diffusivity than metal, brick, or stone (Glass & Zelinka, 2021). Large structures such as flour mills are often treated in sections to ensure proper temperatures are obtained (Hammond, 2015). Achieving the duration and temperature needed to kill termites can require significant time and energy (Tay & James, 2021).

Additional factors that affect treatment are ambient conditions outdoors and configuration of the area to be heated. The conductivity of heat along the grain of wood is 1.5–2.8 times greater than across the grain. The species of wood, its density and moisture content, and the presence of structural irregularities such as checks and knots affect conductivity. Thermal conductivity increases as density, moisture content, temperature, or extractive content of the wood increases

(Glass & Zelinka, 2021). Heating time and distance of the termites to the heated surface affect survival (Kumar et al., 2024).

It is essential that the thickest wood members in the structure and those that are thermally protected by concrete or bricks be monitored with temperature probes because wood is a heterogeneous matrix and has low heat conductivity (Ebeling, 1994; Woodrow & Grace, 1998b). In one study of heat treatments, the goal was to achieve a wood core temperature of 49°C (120°F) for 30 minutes in each of nine separate structures that were heat treated in Hawaii to control *C. brevis* (Woodrow & Grace, 1998a). The mean maximum wood core and ambient temperatures were 55.1°C (131°F) and 68.1°C (155°F), respectively. The time required to achieve a wood core temperature of 49°C (120°F) ranged from 33 minutes to 300 minutes depending upon the size and configuration of the areas heated. The ambient temperature inside the structures ranged from 51.8°C (125°F) to 85.1°C (185°F).

Section 2.5.6: Availability, Ease, and Reliability

Select PMPs in California can provide the necessary equipment and services for whole-structure heat treatment. Typically a full working day is required to treat an entire structure (L. Whitmore, pers. comm., 2/12/2025). The heating process requires heating equipment (electric or propane heaters), heat duct tubing, tarping materials, fans, and temperature recording equipment. A 60,000-ft^3 structure requires 12–16 heaters and would be monitored for 12 hours or longer.

Heat treatment can damage certain heat-sensitive items within the structure, including freshly painted surfaces, newly installed wood flooring, molding, baseboards made of vinyl, vinyl flooring, and furniture. Formica cabinets and countertops, and thermal foil cabinets commonly used in kitchens may also be damaged with excessive heat. If the structure has a sprinkler system, it must be removed and capped prior to the heat treatment. It can cost $100 per sprinkler head to protect and then bring back it to operating condition (L. Whitmore, pers. commun., 2/12/2025).

Section 2.5.7: Human Health Impacts

It is highly unlikely that exposure to heated air after the structure is cooling presents a significant health threat to humans. No health hazards or precautionary statements are listed on registrations for heat treatment devices (DPR, 2025b). However, it is possible that treatment could exacerbate existing indoor pollution from certain building materials. In a study of volatile organic compounds (VOCs) levels in homes, new homes were found to have considerably higher levels than older homes, especially formaldehyde and α-pinene (Park & Ikeda, 2006). New homes emitted an average of 328 $\mu g/m^3$, declining to 169 $\mu g/m^3$ after three years. Old homes emitted an average of 88 $\mu g/m^3$. For context, the World Health Organization standard is 100 $\mu g/m^3$ for preventing sensory irritation (WHO, 2010). Heating an entire structure may contribute to excessive amounts of formaldehyde in the air (Park et al., 2004). Inhaled formaldehyde can cause health effects in humans, most notably respiratory effects, and it is carcinogenic to humans by the inhalation route of exposure (EPA, 2024a). However, it is unclear to what extent any excess formaldehyde and other VOCs generated during heat treatments would remain within the structure and if heat-treating materials has any lasting impact on emissions. Heating a building for a prolonged period followed by a thorough flush with outdoor air may lead to a "modest and temporary reduction" in the emission of these indoor contaminants but levels rebound within a matter of weeks (Ander et al., 1994). Similarly, a 10-day "bake-out" could reduce indoor air contaminants, but only if the units were thoroughly and consistently ventilated during the process (Park et al., 2004). Units that received less or no ventilation had higher levels of VOCs and formaldehyde. Minimal ventilation is expected to occur during heat treatments.

Section 2.5.8: Environmental and Ecological Concerns

Heating structures to 50°C (122°F) require a considerable amount of energy, especially with large structures. The heat is generated by electricity or burning propane. While the general GHG impacts of propane are well understood, there is no data on the volume of emissions that result from heat treatment. There are no other suspected environmental concerns or hazards (DPR, 2025b).

Section 2.6: Localized Chemical Treatments

Section 2.6.1: Background

Localized chemical treatments are the standard industry practice for controlling drywood termites and wood-destroying insect in California. Localized chemical treatments are either applied to the surface of boards or wood materials or injected into the termite galleries in infested wood. Some of the first insecticide dust formulations included Paris green (copper aceto arsenite), calcium arsenate, sodium fluosilicate, and calomel (mercurous chloride) (Randall & Doody, 1934). Even though many of these early formulations were effective, they are toxic to humans and animals. These formulations were replaced by various organochlorine, carbamate, and organophosphate insecticides (Scheffrahn & Su, 1994). Again, due to human and environmental health risks, many of these compounds are no longer approved for pest control in urban settings. For example, chlorpyrifos (an organophosphate insecticide) was widely used in the 1990s but is no longer registered for drywood termite control. Newer insecticides such as spinosad (a natural substance made by a soil bacterium) and fipronil have shown promise as localized treatments (Scheffrahn et al., 1997a; Hickman & Forschler, 2012). However, it should be noted that there is evidence that fipronil affects water quality.

Table 2.3 contains a representative list of insecticides registered to control drywood termites. Insecticides registered to control wood-destroying beetles are listed in Chapter 1 (***Table 1.8***, ***Table 1.10***, and ***Table 1.11***).

Table 2.3. Representative list of products and active ingredients registered in California for drywood termite control.

Product	IRAC[a]	Class	Active ingredient(s)	Formulation
Advion WDG	22A	Oxadiazine	indoxacarb	WG
Bora-Care	8D	Borate	disodium octaborate tetrahydrate	WS
CimeXa		Inorganic	silica gel	D
Cyper TC	3A	Pyrethroid	cypermethrin	EC
D-Fense NXT	15	CSI	novaluron	A
	3A	Pyrethroid	deltamethrin	
	7C	JH	pyriproxyfen	
D-Force	3A	Pyrethroid	deltamethrin	A
Dominion 2L	4A	Neonicotinoid	imidacloprid	EC
Drione	3A	Pyrethrin	pyrethrin PBO	D
		Inorganic	silica gel	
EcoPco AR-X	3A	Pyrethroid	pyrethrin	A
			2-phenethyl propionate	
Fendona CS	3A	Pyrethroid	α-cypermethrin	CS
Fi-Pro Aerosol	13	Phenylpyrazole	fipronil	A
Fuse	13	Phenylpyrazole	fipronil	SC
	4A	Neonicotinoid	imidacloprid	
Fuse Foam	13	Phenylpyrazole	fipronil	RTU Foam
	4A	Neonicotinoid	imidacloprid	
Premise 2	4A	Neonicotinoid	imidacloprid	SC
Premise Foam	4A	Neonicotinoid	imidacloprid	RTU Foam
Spectracide Terminate	13	Pyrethroid	λ-cyhalothrin	SC
Tarus Dry	13	Phenylpyrazole	fipronil	D
Tarus SC	13	Phenylpyrazole	fipronil	SC
Tempo 1% Dust	3A	Pyrethroid	cyfluthrin	D
Tempo Ultra	3A	Pyrethroid	β-cyfluthrin	WSP
Temprid FX	4A	Neonicotinoid	imidacloprid	SC
	3A	Pyrethroid	β-cyfluthrin	
Termidor SC	13	Phenylpyrazole	fipronil	RTU Foam
Termidor Foam	13	Phenylpyrazole	fipronil	RTU Foam
Tim-bor	8D	Borate	disodium octaborate tetrahydrate	WS
Totality Wood Treatment	3A	Pyrethroid	bifenthrin	EC

[a]Insecticide Resistance Action Committee categorization of active ingredients according to their mode of action.
[b]A – aerosol, CS – capsule suspension, D – dust, EC – emulsifiable concentrate, SC – suspended concentrate, RTU – ready to use, WG – water dispersible granule, WS – water soluble, WSP – water soluble packets.

Section 2.6.2: Scale of Use

Localized insecticide treatments to control drywood termites have long been a popular treatment option. In a survey of completion notices filed with the SPCB in 1992–1993, 72% of the alternative treatments to SF fumigation were the localized injection of chlorpyrifos into termite galleries (T. Atkinson. pers. commun., 2/5/2025). Data regarding the frequency of localized insecticide treatments to control drywood termites are available on completion notices filed with the SPCB. There is no published record of these data being collated and analyzed. It is impossible to determine the amount of insecticide applied for localized drywood termite control from the DPR pesticide use reports.

Section 2.6.3: Effectiveness and Duration of Pest Control

Surface Treatments

The application of insecticides to the surface of lumber is commonly conducted to treat various wood-boring beetle infestations. In laboratory studies, surface applications of DOT killed 96% to 99% of the larval beetles *Hemicoelus gibbicollis* in infested lumber (Soumi & Akre, 1992). DOT treatments did not prevent female beetles from laying eggs on treated surfaces but prevented larvae from feeding on treated boards. Treatment is most effective when adults are emerging from the wood. Penetration of DOT is limited to a few millimeters so it may take a long time to kill all the larvae (Soumi, 2006).

Liquid deposits of DOT failed to kill drywood termites on contact, but dust deposits were lethal. Chlorpyrifos, spinosad, and dust formulations of calcium arsenate applied to boards were toxic to *C. brevis* (Scheffrahn et al., 1997a). Rust & Venturia (2009) investigated the activity of Bora-Care® (DOT), Optigard™ ZT foam (thiamethoxam), Premise® Foam (imidacloprid), Termidor® SC (fipronil), Tim-bor® (DOT), and XT-2000® (d-limonene) against *I. minor*. Deposits of Tim-bor dust, Termidor liquid, and Optigard foam were lethal to drywood termites on both continuous and brief exposures. The active ingredients were released from the treated surfaces and removed by the termites. Deposits of Tim-bor dust, Termidor liquid, and Optigard foam did not repel termites and lethal doses of active ingredient were readily transferred from treated termites (donors) to untreated termites (recipients). Fresh deposits of XT-2000 liquid were extremely toxic to drywood termites. However, the deposits rapidly lost their contact activity within 24–48 hours and were repellent to termites. Vapors of both XT-2000 and Termidor were toxic to drywood termites. Deposits of XT-2000 lost their vapor toxicity within 24 hours. Prolonged exposures of drywood termites on deposits of Tim-bor liquid, Bora-Care, and Premise Foam were necessary to provide kill, and nonlethal deposits deterred termite feeding. Nonlethal deposits of XT-2000 deterred feeding. Tim-bor dust, Termidor liquid, and Optigard foam consistently provided the best results in the laboratory tests.

Dust formulations of DOT, silica gel, and imidacloprid prevented *C. brevis* **alates** from establishing new colonies in a simulated laboratory study (Scheffrahn et al., 2001). In laboratory studies, fipronil foams provided faster contact activity against *C. brevis* than did imidacloprid foams (Hassan et al., 2023). Deposits of the fipronil foam were not repellent, and fipronil was readily transferred from donor to recipient termites.

Surface-only treatments were not as effective as injections of insecticides into termite galleries at controlling drywood termite infestations (Scheffrahn et al., 1998).

Injections into Galleries

To inject dust, liquids, or foam into termite galleries, a technician typically drills a small hole into the infested board to intersect a termite gallery. The drill holes are typically 5–8 inches apart and often in a diamond pattern. Small amounts of dust, liquid insecticide, or insecticidal foams are injected into the termite gallery. The drill holes are then sealed with a small piece of wooden dowelling. This method is known as “drill-in-treat.” For example, the amounts of liquid insecticides injected into an 8-foot board infested with drywood termites ranged from 82 ml to 289 ml depending on the insecticide and the extent of the drywood termite infestation (Lewis, 2009b). The amount of fipronil injected into the infested board was approximately 280 mg. In a field study in Florida, approximately 4.3 drill holes were injected with approximately 60 ml per hole of a 0.5% suspension of spinosad (Thoms, 2000). Approximately 300 mg of spinosad was injected into each infested board. Fipronil dust is injected into termite galleries at a maximum rate of 5 grams of dust (25 mg of fipronil) per 1,000 ft^2.

There is limited data on the effectiveness of drill-in-treat methods compared to fumigation in real-world scenarios. One study from the 1960s examined attics in homes that were drill-in-treated with insecticides (n=322) and that were fumigated (n=195) in Los Angeles County. These homes were reinspected after 2.2–4.8 years (Ebeling & Wagner, 1964). Of the homes that were drill-in-treated, 70.3% were reinfested within 3.5 years. Of those fumigated, 31.7% were reinfested within an average of 3.7 years. However, the authors cautioned that the initial inspections of fumigated homes were often not as thorough as the homes where drill-in-treat was performed. Consequently, evidence of previous infestations may not have been removed in the fumigated homes and thus were counted during reinspection. This may have artificially increased the reinfestation rates in fumigated structures.

There are a limited number of studies in which drywood termite infestations in structures have been monitored and treated with localized treatments. Field tests were conducted with spinosad, chlorpyrifos, DOT, and calcium arsenate against *C. brevis* (Scheffrahn et al., 1997a). Aqueous formulations of DOT were not effective in the laboratory or when applied to the surface of infested wood in the field. Injections of chlorpyrifos into galleries provided mixed results in the laboratory and failed to reduce termite activity in the field (Scheffrahn & Thoms, 1999). Spinosad can be passed among termites and spread from dead termites (Ferster et al., 2001). Single injections of spinosad, chlorpyrifos, and DOT into pallets infested with *C. brevis* provided 58%, 33%, and 30% reductions in AEC at 1 year (Woodrow et al., 2006).

Aerosol formulations may allow for greater penetration through pellet-filled termite galleries than foam formulations. In laboratory studies, boards naturally infested with *I. synderi* were treated with imidacloprid foam and a dry formulation and aerosol formulation of fipronil (Hickman & Forschler, 2012). All three treatments reduced the activity counts from a microwave detector at 65 days post-treatment. There was a 100% mortality of termites in five out of 11 (30%) of the treated boards. Hickman & Forschler attributed the survival of termites to the lack of coverage of the injected insecticides because of the architecture of the termite galleries. Residual deposits of aerosols containing synergized pyrethrin killed *C. brevis* in laboratory studies (Hassan & Fitzgerald, 2023).

In laboratory studies, adding the attractant β-pinene (1 $\mu g/cm^2$) to 10 μl aqueous 0.06% fipronil applied to galleries significantly increased mortality against *I. minor* (Poulos et al., 2024). The β-pinene did not increase the mortality when applied with DOT dust.

Determining the effectiveness and duration of localized chemical treatments is very difficult. While detecting termites in accessible lumber is feasible, quantifying termite numbers in boards is not possible without dissecting the infested wood. In field studies, spinosad and chlorpyrifos injected into termite galleries significantly reduced AEC at 3 months after treatment (Scheffrahn et al., 1997a). Only spinosad provided significant reductions in AEC at 5 months. In another field study, injections of aqueous spinosad into termite galleries provided 98% to 100% kill of *C. brevis* and *I. snyderi* (Scheffrahn & Thoms, 1999). Only the spinosad provided significant reductions in AEC.

In a large field study in California, six insecticides were tested in the field as localized treatments against *I. minor* infestations (Lewis, 2009b). AEC counts of termite activity in infested areas were taken, and then the area was treated. The high variability in AEC between sites, potential seasonal movement of termites, and changing ambient conditions made comparing their effectiveness a challenge. The study was discontinued after 3 months, and there were no definitive conclusions.

> 62. **FINDING:** There are limited data regarding the effectiveness of various localized chemical treatments under field conditions.

> 63. **FINDING:** Some localized chemical treatments provide residual activity and deter termite feeding.

Section 2.6.4: Costs Associated with Localized Treatments

The cost of localized treatments to the homeowner is highly variable depending upon the extent and the accessibility of the infestation, distance travelled to the job site, and the amount of patching and repairs. Estimated supply costs for localized treatments with liquid termiticides are $6 to $8 per square foot (Graham & Pomares, 2025). However, the total treatment cost must also account for one or more visits by a pest control technician, which can range from $300 to $480 per visit. In California, PMPs estimated that a local drill and treat of this report's hypothetical structure (***Appendix VI***) would cost a minimum of $875, and if any sheetrock or plaster were removed, the costs would increase to a minimum of $1,600 (J. Berggren, pers. commun., 7/29/2025). Another estimate ranged from $800 to $2,200 with factors such as the extent of the infestation, the amount of drilling, patching and repairs, and equipment needed increasing the costs (D. Belle, pers. commun., 7/29/2025). The process may cause damage to the structure that will need repair (LOCAL, 2025).

The completion reports retained by the pest control firms in California would have information concerning the extent of the treatment, chemicals used, and costs associated with the localized chemical treatments. These data have never been reported in the scientific literature.

Section 2.6.5: Additional Requirements for Use

Locating and drilling into termite galleries is challenging, especially when treating small colonies or multiple colonies. Termite galleries from different colonies may not intersect one another, requiring extensive patterns of drill holes to ensure all galleries are treated. The architecture of termite galleries and fecal pellets in a gallery can prevent insecticides injected into the galleries from thoroughly dispersing, reducing effectiveness (Hickman & Forschler, 2012). Better detection methods for locating termite galleries in the wood would be extremely useful.

Section 2.6.6: Availability, Ease, and Reliability

Localized chemical treatments are the standard industry practice for controlling drywood termites in California, and numerous products are registered for that use (***Table 2.3***). The most popular surface treatments contain sodium octaborate tetrahydrate and provide approximately 12–14 grams of active ingredient per square foot. Limited data are available regarding the effectiveness of many of the products listed in ***Table 2.3***.

Locating, drilling, and treating drywood termite infestations can be challenging. Experience and knowledge of construction practices can greatly assist in conducting localized treatments. The process may lead to damage requiring repair (LOCAL, 2025).

Section 2.6.7: Human Health Concerns

The toxicity of a representative list of insecticides registered in California to kill drywood termites is provided in ***Table 2.4***. In general, pyrethroid class insecticides have greater oral and contact toxicities than borates, silica aerogels, and chitin synthesis inhibitors. Many of the surface sprays have a signal word (e.g., warning or caution) for dermal and inhalation exposure. There is very little information in the literature regarding localized chemical treatments and their bioavailability, movement within structures, and any potential human health concerns when insecticides are applied within areas of a structure that are physically separated from the living space. The treated surfaces may be sealed within walls or inaccessible to humans.

64. **FINDING:** There is limited information available concerning the potential risks of occupant exposure to localized chemical treatments applied to control drywood termites.

65. **FINDING:** The use of Category II and Category III chemicals, even in localized settings, may still have health impacts for handlers and inhabitants.

Section 2.6.8: Environmental and Ecological Concerns

There are no studies reported in the scientific literature regarding the environmental and ecological concerns of injecting insecticides into termite galleries or treating the surfaces of wood within structures. DOT treatment outdoors or in areas with excessive moisture or water runoff should be avoided because the solubility of DOT in water is 29%.

66. **FINDING:** There is limited information about the environmental or ecological impact of localized chemical treatments.

Table 2.4. Toxicity and signal word for active ingredients in products registered in California for drywood termite control and surface treatments to control wood-destroying beetles.

Insecticide class	Active ingredient	Toxicity category (signal word) Oral	Dermal	Inhalation	References
Pyrethroid	Bifenthrin	II (Warning)	III (Caution)	III (Caution)	Johnson et al. (2010)
	Cyfluthrin	II (Warning)	IV (Caution)	II (Warning)	EPA (1987a)
	Cyhalothrin	II (Warning)	II (Warning)	II (Warning)	NPIC (2001)
	Cypermethrin	II (Warning)	III (Caution)	III (Caution)	EPA (1989)
	Deltamethrin	I–IV[a]	II–III[a]	IV (Caution)	Johnson et al. (2010)
Borate	Boric acid	III (Warning)	III (Warning)	II (Warning)	EPA (1993)
Silica dioxide/silica gel	Silicon dioxide	III (Warning)	III (Warning)	No data	EPA (1991)
Phenylpyrazole	Fipronil	II (Warning)	II-III[b]	II (Caution)	EPA (1996)
Oxadiazine	Indoxacarb[c]	III (Caution)	IV (Caution)	IV Caution)	EPA (2000)
Neonicotinoid	Imidacloprid	II (Warning)	IV (Caution)	II–III[b]	Gervais et al. (2010)
Chitin synthesis inhibitor	Novaluron	IV (Caution)	III (Caution)	IV (Caution)	EPA (2001)
Juvenile hormone	Pyriproxyfen	III (Caution)	III (Caution)	III (Caution)	WHO (2024)
Botanical essence	Limonene	III (Caution)	IV (Caution)	No data	CAN (2023)

[a] Substances used to administer affect the lethal dose.
[b] Depends on the formulation.
[c] Considered a “reduced-risk” insecticide.

Section 2.7: Localized Heat Treatments

Section 2.7.1: Background

Localized heat treatments to kill wood-destroying insects typically encompass attics, rooms, or other areas specifically identified in an inspection (L. Whitmore, pers. commun., 2/5/2025; Scheffrahn & Su, 1997). The principles and concepts for heating whole structures and localized areas are the same. It is the scale of the treatment that differs.

Section 2.7.2: Scale of Use

Although localized heat treatment is widely offered by pest control companies in California, there is no information concerning how frequently it is used to control drywood termites. This information is available from the PMP and is retained for 3 years but has never been analyzed.

Section 2.7.3: Effectiveness and Duration

No studies on the effectiveness or longevity of localized heat treatments have been reported in the scientific literature. As with whole-structure heat treatments, there is no residual lethality following local heat treatment.

Section 2.7.4: Costs Associated with Localized Heat Treatments

Whole-structure heat treatments are between $1,000 and $12,000—localized heat treatments should cost less (L. Whitmore, pers. commun. 2/5/2025). The costs would depend on the number of rooms or the area to be treated.

Section 2.7.5: Additional Requirements for Use

Heat treatment can damage certain heat-sensitive items within the structure, including freshly painted surfaces, newly installed wood flooring, molding, baseboards made of vinyl, vinyl flooring, and furniture. Formica cabinets and countertops and thermal foil cabinets commonly used in kitchens may also be damaged with excessive heat. If the structure has a sprinkler system, it must be removed and capped prior to the heat treatment. It can cost $100 per sprinkler head to protect and then bring back it to operating condition (L. Whitmore, pers. commun., 2/12/2025).

Section 2.7.6: Availability, Ease, and Reliability

Less equipment and preparation should be required to conduct localized treatments compared with whole-structure treatments. The process is essentially the same, and it is simply a matter of scale.

Section 2.7.7: Human Health Impacts

No negative impacts on health are anticipated (see ***Section 2.5.7***)

Section 2.7.8: Environmental and Ecological Concerns

No negative environmental and ecological concerns are anticipated (see ***Section 2.5.8***).

Section 2.8: Cold Treatments

Section 2.8.1: Background

Exposure to extremely low temperatures is lethal to most insects. If the internal temperature of wood infested by drywood termites can be lowered below -20°C (-4°F), it is possible to kill them. For example, the critical thermal minimum (CTM), a momentary exposure that is lethal when the temperature drops at 1°C per minute, for *I. minor* and the powderpost beetle *Lyctus planicollis* eggs are -21.3°C (-6°F) and -35.6°C (-32°F), respectively (Rust et al., 1997).

Using liquid nitrogen to rapidly lower temperatures in wood infested by drywood termites was tested in a mockup structure in 1986 (Forbes & Ebeling, 1986) and approved by DPR in 1987 (DPR, 2025e). Drywood termites exposed to temperatures from -18.5°C to -19.4°C (-2.0°F–0.5°F) for 5 minutes were killed. It took approximately 75 minutes to reduce temperatures in the wall void to lethal levels. The vertical position of the liquid nitrogen release point and the release rate both affected the time to reach CTM. Fiberglass insulation also affected the pattern of cooling. Plumbing and electrical fixtures in the mockup wall were not damaged by liquid nitrogen, but cracks appeared in vinyl floor tiles adjacent to the wall. In the test room, the oxygen level where liquid nitrogen was released rapidly dropped to less than 19.5%, the minimum acceptable level for worker safety. Electronic monitoring should be required to ensure safe oxygen levels exist in the room being treated. It is important to accurately monitor the internal temperature of target wood with thermocouples to ensure that the CTM is achieved (Rust et al., 1997).

Section 2.8.2: Scale of Use

Liquid nitrogen has not been approved for use on wood-destroying pests in California since 2004 (DPR, 2025e). It is uncertain whether cold treatments are being conducted at this time in other states or countries.

> 67. **FINDING:** There are currently no devices using liquid nitrogen for termite control registered in California.

Section 2.8.3: Effectiveness and Duration of Pest Control

Liquid nitrogen applications for 30 minutes at 1.4 kg/min and 15 minutes at 0.9 kg/min to wall voids provided nearly 100% mortality for naturally infested boards (Lewis & Haverty, 1996). The placement of temperature probes was critical for achieving high levels of effectiveness. Cold treatments do not provide any residual protection.

Termites are killed in only the wood members surrounding the void (Rust et al., 1997).

Section 2.8.4: Costs Associated with Cold Treatments

Because cold treatments have not been conducted since 2004, there are no current cost estimates available. However, the process is labor intensive and requires moving cylinders, drilling wall voids, and repairing them. Treating small areas would cost hundreds of dollars.

Section 2.8.5: Additional Requirements for Use

Some damage to wall coverings is possible because of frost formation, and injection holes in the walls must be repaired (Lewis & Haverty, 1996). There have been some concerns about the effects of liquid nitrogen on plumbing connections, even though none were reported in laboratory tests (Rust et al., 1997).

The vacuum-insulated containers (dewars) containing liquid nitrogen are extremely heavy and limit its use. Treating overhead wooden beams and groove ceiling boards would be a challenge with this method.

Section 2.8.6. Availability, Ease, and Reliability

It is uncertain whether cold treatment is used in other states or countries.

Section 2.8.7. Human Health Impacts

Liquid nitrogen is a **restricted-use pesticide** due to the risk of severe cold burns or frostbite on contact with skin or eyes, as well as asphyxiation (EPA, 1987b; DPR, 2025e).

Section 2.8.8. Environmental and Ecological Concerns

There are no known environmental concerns associated with liquid nitrogen.

Section 2.9: Electrocution

Section 2.9.1: Background

The Entermax System employs the Electro-Gun to deliver electrical current to boards infested with termites and beetles (Ebeling, 1983, 1985). The gun produces high frequency (100 kHz), high voltage (90,000 volts), and low current (50 watts) that will penetrate approximately 0.5 inches (1.27 cm) into wood surfaces. The charge will enter and follow along termite galleries for up to 18 inches (45.7 cm). The first units were leased to PMPs in 1980 (Ebeling, 1985). The current Electro-Gun was registered on March 28, 2006 (DPR, 2025c). It is the only device using electric current to kill termites and beetles registered in California.

In laboratory tests with the *I. minor* drywood termite and the confused flour beetle, *Tribolium confusum* (Jacquelin du Val), many of the insects were killed immediately after exposure to electricity (Ebeling, 1983). In other studies, 30- and 60-second exposures to electricity in galleries 0.25-inch and 0.5-inch (0.64 cm and 1.27 cm) deep in pieces of wood killed 4.8% of the beetles at day 12 and 82.7% at day 37 (Ebeling, 1983). The reason for the delayed mortality is unknown.

Section 2.9.2: Scale of Use

It is difficult to determine if the Electro-Gun is being widely used to control drywood termites and wood-destroying beetles. Data regarding the use of Electro-Gun in California to control drywood termites and wood-destroying beetles are available on the inspection report and completion notices retained by pest control firms. However, information on its frequency of use has not been reported since 1993.

The Electro-Gun is currently advertised by pest control firms in Florida and Canada. A pest control firm in Portugal has rights to use it in Europe.

Section 2.9.3: Effectiveness and Duration of Pest Control

Knowing the precise location and extent of the drywood termite infestation is required for successful treatment with the Electro-Gun. In a simulated field study, mortality of *I. minor* nymphs placed in the structure was less than 90% at 4 weeks (Lewis & Haverty, 1996). In a second trial, in which artificially and naturally infested boards were placed away from wire mesh in the stucco and metal supports of a simulated structure, more than 95% of the termites were killed (Lewis & Haverty, 1996). The authors concluded that a drill-and-pin technique of inserting copper wires into termite galleries should be used to achieve reasonable levels of mortality.

In a subsequent study, boards naturally infested and artificially infested with *I. minor* were placed within a specially constructed building to test the effectiveness of Electro-Gun treatments (Lewis & Haverty, 2001). Large pieces of wood and wood behind drywall were treated with a drill-in-pin technique. Small holes were drilled into termite galleries, and small copper wires were inserted. Mortality of termites was less than 50% for all artificially infested boards three days after treatment, except for the boards behind drywall (52% to 62%). At four weeks, the mortality of termites from naturally infested boards ranged from 57% to 100%. The treatment time and the number of holes drilled into the wood and copper wires affected the degree of control.

The use of electrocution to kill wood-destroying insects does not provide any residual control, and treated objects are subject to reinfestation.

> 68. **FINDING:** There is very little data concerning the effectiveness of electrocution under laboratory or field conditions.

Section 2.9.4: Costs Associated With Electrocution

The estimate to treat a "small area" with the Electro-Gun is $1,150 (HOME, 2025). No estimate could be obtained for the hypothetical structure provided in ***Appendix VI***. However, several pest control firms indicated that their minimum charges to visit a structure and conduct localized treatments ranged from $800 to $1,200.

Section 2.9.5: Additional Requirements

Determining the precise location of a drywood termite infestation is important when treating with the Electro-Gun. The technician must have access to the infested wood to apply the electrical charge. The inspection and treatment require a highly trained and experienced PMP (Lewis & Haverty, 1996).

Section 2.9.6: Availability, Ease, and Reliability

In California and Florida, there are pest management firms using the Electro-Gun, a handheld device. Access to the infestation is important because the PMP must make contact between the device probe and the infested wood.

Some damage to wood may occur, and the holes required to place pins in the wood need repair (Lewis & Haverty, 1996). Excessive treatments and holes with copper wires can scorch wood (Lewis & Haverty, 2001). Wood is a nonconductor of electricity, and if the probe is left in place too long, the electricity will carbonize a path to the ground or a good conductor (Ebeling, 1983).

A report by Macron Forensics on the physical effects of the Electro-Gun on typical construction wood members concluded that there was no burn damage to wood members even when treated for 1 minute. There was no correlation between increasing the treatment time and temperature change. There were insufficient temperature increases to result in temperature-related warping stresses. The report concluded that there was no appreciable structural damage to wood when holes were drilled for the drill-in-pin method.

Section 2.9.7: Human Health Impacts

The Electro-Gun produces high-frequency electricity (100 kHz) and high voltage (90,000 volts), but low current (90 watts) (Ebeling, 1983). The electrical current does not penetrate the conductor's entire mass and tends to flow instead on the outer surface of the skin; this is known as the so-called "skin effect." The larger the cross section of the conductor, such as a human, the greater its conductivity and the more pronounced the skin effect. Termites and other insects are too small to receive any benefit from the skin effect (Ebeling, 1983). Additional information may be available on the registration applications filed with DPR (DPR, 2025c).

Section 2.9.8: Environmental and Ecological Concerns

There are no known environmental or ecological concerns associated with the use of electrocution for pest control (DPR, 2025c).

Section 2.10: Microwaves

Section 2.10.1: Background

Using microwaves and radio waves to control insects and fungi in stored grains and foods is widespread and effectively extends the life of grains (Macana & Baik, 2018; El Arroud et al., 2024). Microwaves heat by exciting water molecules and generate heat through friction in the insect and surrounding substrate (Yanagama et al., 2020). One advantage of microwaves is that lethal temperatures are reached more quickly than conventional heating methods. For example, 4 in. × 4 in. × 4 in. green wood blocks reached 60°C (140°F) within 0.5–5 minutes of irradiation, compared with 70–123 minutes with conventional heat treatment (Fleming et al., 2002). The standard for treating packing materials in industrial microwave ovens is 60°C (140ºF) for a continuous 60 seconds to kill wood-destroying pest insects. Factors that influence the treatment are wood moisture content, size and density of wood, and the frequency of the microwaves (FAO, 2019).

Section 2.10.2: Scale of Use

There are two microwave devices registered in California. The Xterminator 4.0 built by Hi-Tech Termite Control, Inc. was registered on November 13, 2012. The Zapper built by Biederman Design Labs was registered on September 2, 2011 (DPR, 2025d).

The use of microwaves to control termites and wood-destroying beetles is advertised in the United States and worldwide. Data regarding the use of microwave treatments to control wood-destroying organisms in California are available with the SPCB. These data have never been analyzed or reported in the scientific literature.

Section 2.10.3: Effectiveness and Duration of Pest Control

In a laboratory study with microwave ovens (500 W, 1,000 W, and 2,000 W), approximately 84% mortality of *I. minor* was consistently achieved with exposures ranging from 20 seconds to 150 seconds (Lewis et al., 2000). The high absorption efficiency of wood caused high mortality of *I. minor* under both direct and indirect irradiation (Nakai et al., 2009). The heating process varies with the frequency, power intensity, and substrate dimensions. Exposures of *C. brevis* for 10 seconds in 80 W and 100 W ovens resulted in 100% kill (Batt & Eman, 2019).

In a simulated field study, microwave treatments provided mixed results. Nearly 90% of drywood termites were killed in artificially infested boards. In naturally infested boards, mortality exceeded 90% 4 weeks after the exposures. To achieve this level of mortality in practice requires knowing of the extent of an infestation, its location, and access to the infested wood (Lewis & Haverty, 1996).

Rafters in a residential building in Valencia, Spain, infested with the furniture beetle *Anobium punctatum* (De Geer) and the drywood termite *Kalotermes flavicollis* (F.) were treated with microwaves (Martinez et al., 2013). An acoustic emissions device was used to detect insect activity prior to treatment. The individual treatment area was approximately 15 cm × 15 cm and it took 8 hours to treat 10 rafters (240 cm long). There was no acoustic activity 3 months after the treatment, and beetles did not emerge the following spring, suggesting the treatment was successful.

Museum artifacts infested with furniture beetles were treated with a Microwood 12 microwave apparatus (Patrascua et al., 2018). The treatment surface was approximately 90–100 cm^2, and the artifacts were treated in 50 cm^2 sections. In addition, aluminum foil and tape were used to help shield the device. There were no signs of beetle activity for at least 12 months after treatment.

Microwave treatments do not provide any residual protection, and treated objects are subject to reinfestation as soon as they cool.

> 69. **FINDING:** Microwave devices are being used to control wood-destroying beetles in wooden packing material, stored products, and artifacts susceptible to insect infestation.

> 70. **FINDING:** There are limited data concerning the effectiveness of using microwave treatment to control drywood termites.

Section 2.10.4: Costs Associated with Microwave Treatments

Microwave treatments cost approximately \$6–\$8 per square foot (Graham & Pomares, 2025). The total price will depend on the size of the objects to be treated and the costs of the technician travelling to the site. No cost estimate could be obtained for treating the hypothetical structure provided in ***Appendix VI***. However, several pest control firms indicated that their minimum charges to visit a structure and conduct localized treatments ranged from \$800 to \$1,200.

Section 2.10.5: Additional Requirements for Use

Knowing the location and extent of an infestation and access to the infested wood is essential for successful microwave treatment (Lewis & Haverty, 1996). Even small distances (e.g., 100 mm) between the microwave-radiating antennae and the surface of the infested wood greatly reduce their effectiveness (Krajewski, 2017). The units are mounted on tripods, and treating areas within attics and crawl spaces could be difficult. When using the Microwood 12 microwave apparatus, all nails, staples, screws, and other metal objects were removed before treating infested objects (Patrascua et al., 2018). Some visible damage and minor warping of the wood were noted after testing (Lewis & Haverty, 1996).

Section 2.10.6: Availability, Ease, and Reliability

The microwave device must be in close contact with infested materials. Preparing a site for treatment is an involved process that requires shielding around the treated objects. Only a small area can be treated, and the unit must be repeatedly moved to treat larger areas (Mwave, 2025). Areas in the attic or crawlspace of a home may be difficult to treat. One study concluded that the current microwave devices for heat-treated termite control are "cumbersome, consume significant electric supply, and are therefore dangerous to use" (Yanagawa et al., 2020, p. 2). A fire extinguisher and smoke detector should be on site (Mwave, 2025).

Section 2.10.7: Human Health Impacts

There are no health hazards or precautionary statements filed with DPR (DPR, 2025d). However, electromagnetic radiation—like that emitted by microwaves—has long been suspected as having possible human health effects. Some studies suggest possible links between excessive exposure to microwave radiation and cancer, tumors, headaches, fatigue, Alzheimer's, and Parkinson's Disease (Zamanian & Hardiman, 2005).

In a demonstration of the Proto3GE1150 microwave device, additional shielding was placed around objects and the unit producing the microwaves. From 25 feet away, a technician with a microwave detector found evidence of microwave leakage (Mwave, 2025).

> 71. **FINDING:** No research exists on the risks of microwave exposure in structural pest control settings. Microwave radiation has been suggested to have potential risks to human health in other contexts.

> 72. **CONCLUSION:** Uncontrolled exposure to high-frequency energy like microwave radiation has the potential to harm human health.

> 73. **RECOMMENDATION:** The safety of microwave devices in occupational exposure settings should be reviewed.

Section 2.10.8: Environmental and Ecological Concerns

There are no environmental hazards associated with microwave treatment for drywood termite infestations (DPR, 2025d). The energy consumption of microwave units is significant. A study at the University of Manchester reported that in the European Union, some 130 million microwaves emit as many carbon equivalents as nearly 7 million cars (Manchester, 2018; Gallewgo-Schmid et al, 2018).

Section 2.11: Biological Treatments

Section 2.11.1: Background

Termites have natural defenses against many pathogens, and the few successful examples of biological control are limited to subterranean termites (Chouvenc & Su, 2010; Chouvenc et al., 2011). Research conducted with biological agents to control termites has also focused on subterranean termites (Qasim, 2015; Hassan et al. 2024).

In the drywood termite, *Kalotermes flavicollis*, cannibalism and necrophagy of dead infected termites prevented the spread of *M. anisopliae* in the colony (Chouvenc et al., 2010). Deposits of the fungus *Metarhizium anisopliae* (Metschnikoff) on filter paper and wood killed nymphs of the drywood termite *C. brevis* (Nasr & Moein, 1997). Bio-Blast biological termiticide containing *M. anisopliae* was approved in California in 1995 to control subterranean and drywood termites, but it was no longer approved as of 2001.

> 74. **FINDING:** There are no known biological control agents for the control of drywood termites.

Section 2.12: Wood Removal

Section 2.12.1: Background

Removing structural wood infested with drywood termites is an effective treatment method that has been recommended for more than a century (Brown et al., 1934). Wood removal and replacement can be conducted in conjunction with whole-structure treatments and localized treatments.

Section 2.12.2: Scale of Use

In a review of completion notices of structures treated in Southern California from 1992 to 1993, nonchemical treatments were conducted on 6% of treated structures. Wood removal ranked third behind Electro-Gun and microwave (T. Atkinson, pers. commun., 2/5/2025). There are no published reports examining how often wood removal is used to control drywood termites.

Section 2.12.3: Effectiveness and Duration of Pest Control

In natural settings, drywood termites feed and nest within single pieces of wood, and removing boards could remove the entirety of the existing colony. Wood removal could be an effective method for controlling small and localized colonies.

Section 2.12.4: Costs Associated with Wood Removal

The labor and cost of replacement materials will depend on the extent of the wood removal.

Section 2.12.5: Additional Requirements for Use

Not all PMPs provide wood replacement, and treatment may require carpentry services.

Section 2.12.6: Availability, Ease, and Reliability

The suitability and reliability of wood removal to control drywood termites will depend on the extent and accessibility of the infested wood.

Section 2.12.7: Human Health Impacts

There are no human health impacts associated with wood removal.

Section 2.12.8: Environmental and Ecological Impacts

There are no environmental or ecological impacts associated with wood removal.

Section 2.13: No Treatment

Section 2.13.1: Background

Colonies of drywood termites are considerably smaller than subterranean termites. Mature colonies of *I. minor* consist of the primary reproductives, one or more supplementary reproductives, five to 120 soldiers, and 1,200 to 2,600 nymphs (Harvey, 1934), whereas subterranean termite belonging to the genera *Reticulitermes* or *Coptotermes* may consist of hundreds of thousands to millions of workers. Damage to structures by drywood termites proceeds slowly. Based on laboratory feeding studies, the amount of wood consumed by an *I. minor* colony of 1,000 nymphs in 1 year is approximately 70 g (about 0.15 lb) of wood (Grace & Yamamoto, 2009). Consequently, it may be years before drywood termite damage is detected.

Multiple colonies within a structure commonly—or even a single piece of wood—exist, especially in older structures (Harvey, 1934; Grace et al., 2009). A 7.6 m (25 feet) long redwood telephone and telegraph pole that was in service for 37 years had 19 active colonies, 24 reproductives, 319 soldiers, and 10,935 nymphs (Harvey, 1934). It is unknown how long *I. minor* colonies persist.

> 75. **FINDING:** The presence of an active drywood termite infestation in a structure poses a threat to the structure.

Section 2.13.2: Costs Associated with No Treatment

Drywood termites will continue to damage a structure until all their preferred wood sources have been depleted. The time until materials or the structure are severely damaged varies depending on factors such as species, design of the structure, environmental conditions, wood used in construction, and location of the structure in California. If the infestations remain untreated, the materials or wood members will no longer be structurally sound and must be replaced.

Consumers in California could lose between $4.5 billion and $16.5 billion if none of the structures with drywood termites were treated over 15 years (Zilberman & Lewis, 2024). Given a median cost of $869,500 for homes in California (as of 2025) and an estimated loss of 7% of value (Zilberman & Lewis, 2024), this would equal approximately $60,000 worth of damage per structure after 15 years (CAR, 2025).

Section 2.13.3: Human Health Impacts

The decision to not treat would eliminate potential exposure to SF.

Section 2.13.4: Environmental and Ecological Concerns

With increased urbanization, *I. minor* is spreading eastward into the desert areas of California and along the Colorado River into Colorado (Jones, 2004; Rust, 2006). Structures provide a temperature-regulated setting that allows termite development even in hot and arid environments. Not treating existing infestations provides a source of **alates** to infest nearby structures. In addition to structures in urban areas, landscape trees and ornamental shrubs can be infested by *I. minor* (Light, 1934).

Section 2.14: Use and Support of Alternatives in Other Countries

SF fumigation to control drywood termites is not regularly conducted in most countries besides the United States. The cost of the equipment and the cost to the homeowner make it prohibitive. In addition, drywood termites are important pests of structures in only a few countries. There are no other countries actively supporting or providing subsidies for SF fumigation alternatives.

Section 2.15: Negative Consequences of Fumigant Alternatives

The estimated cost of damage and loss in equity of structures caused by *I. minor* in California annually is between $4.5 billion and $16.8 billion if nothing is done to control them (Zilberman & Lewis, 2024; Zilberman et al. 2024). If SF fumigation is severely restricted, the costs would increase to $1.4 billion to $4.3 billion. If only local treatments are performed to control drywood termites, then the costs would be $3.2 billion to $4.9 billion. Based on these estimates, this study concluded the benefit of SF fumigation is greater than the GHG costs to the environment ($1 billion to $2 billion annually, assuming only 20% of structures with drywood termites are fumigated; Zilberman et al., 2024). However, this study used a lower cost of carbon than many standard models—with a per ton cost of carbon dioxide (CO_2) set between $30 and $150, while the U.S. EPA (2023) estimates that the current social costs per ton of CO_2 range from $120 to $340—and they did not include in their cost-benefit analysis any estimates of the health impacts of SF fumigation.

Of the currently available alternative treatments, only whole-structure heat treatments can guarantee that all the drywood termites have been eliminated in the structure. If only alternative treatments for SF fumigation were available, then it may not be possible to certify that structures are free of drywood termites. This would have a severe impact on homeowners selling properties, buyers, and lending agencies.

> 76. **FINDING:** Strict reliance on less effective alternative treatments for drywood termites may negatively affect real estate values and increase spending on localized treatments and repairs.

Section 2.16: Potential Benefits of Wide-Scale Use of Alternatives

Approximately 80% of the structures being treated in California are already treated with alternative methods (T. Atkinson, pers. commun. 2/15/2025). Even broader adoption of SF alternatives would reduce the handling of a highly toxic substance and associated exposures for workers, occupants, and bystanders. In 2023, approximately 3.4 million pounds of SF were used in California (DPR, 2024). Every pound of SF eliminated is equivalent to reducing CO_2 emissions by 3,046 pounds (Chapter 1, ***Section 1.8***).

Section 2.17: Fumigant Alternatives With the Best Tradeoffs

As explored in the preceding sections, localized treatments for drywood termites vary widely in their mechanisms, effectiveness, and practical considerations. Broadly, they can be grouped into physical treatments (heat, cold, electrocution, and microwaves) and chemical treatments (surface sprays and drill-in-treat methods). Each approach has specific advantages and limitations depending on the infestation's size, location, and accessibility. ***Table 2.1*** summarizes the advantages and disadvantages of alternative treatments.

Heat treatments offer a key advantage: They do not require precise knowledge of termite locations. Localized heat applications can treat entire rooms or areas (e.g., attics, porches) by containing the heat with polyethylene or vinyl sheeting. This makes heat an attractive option for larger, more diffuse infestations where the exact extent of termite activity is uncertain. Furthermore, when used to treat an entire structure, heat is notable for being the only nonfumigant, whole-structure treatment accepted under the SPCA (SPCB, 1998). However, treatment success hinges on achieving lethal temperatures throughout the structure, which can be difficult and requires careful monitoring. Heat treatments are also logistically demanding because heat-sensitive items must be removed or protected.

Conversely, cold, electrocution, and microwave treatments, as well as wood removal, demand exact knowledge of infestation sites. These methods primarily treat individual boards or small areas, and their effectiveness depends heavily on the PMP's ability to access the affected wood. For instance, although Electro-Gun and microwave devices can effectively target termites in exposed areas, their use may be impractical where infestations are located behind walls or in restricted spaces.

Chemical treatments, including surface sprays of borates and drill-in-treat methods, offer a different tradeoff. Surface borate applications do not require precise targeting of termite galleries because borates can penetrate wood to some extent. However, the degree of penetration varies with wood type, and their effectiveness will depend on the depth of termite galleries. Drill-in-treat techniques attempt to overcome this by injecting insecticides directly into galleries after drilling small access holes. While offering long-lasting residual protection, the success of drill-in-inject methods depends on accurately locating galleries and drilling a sufficient number of holes to deliver the chemical where it is needed. Chemical treatments vary in toxicity, with some being extremely toxic Category II chemicals.

Overall, localized treatments are most appropriate for small, accessible infestations. No single localized method guarantees the complete elimination of drywood termites throughout a structure. Even well-executed localized efforts carry a risk of missing hidden colonies. Consequently, treatment selection requires balancing infestation extent, structural accessibility, feasibility, cost, and the property owner's risk perception related to chemicals, with full-structure heat treatment standing out as the only nonfumigation option for comprehensive eradication.

> 77. **FINDING:** Of the alternatives, only heat treatment does not require precise knowledge about the location of termite galleries. The effectiveness of localized treatments depends upon precise location information.

> 78. **FINDING:** Tradeoffs among the localized chemical treatments include effectiveness, degree of wood penetration, residual protection, and toxicity.

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Chapter 3: Research on Alternatives to Sulfuryl Fluoride

Section 3.1: Overview

This chapter focuses on research into alternatives for sulfuryl fluoride (SF) fumigation to control wood-destroying insects, especially drywood termites. Section 3.2 discusses the chronological development of research programs and the funding sources for drywood termite and wood-destroying beetle control in California. Section 3.3 highlights the specific research projects conducted in California, with an emphasis on the past 30 years. Section 3.4 considers the scale of research and control programs conducted worldwide. Section 3.5 deals with the impact of environmental conditions on research and possible alternatives. Section 3.6 considers the suitability of research to identify alternative treatments for fumigation in California. Section 3.7 provides some promising areas for research including better detection tools, new active ingredients for localized treatments, drywood termite baits, and molecular investigations with drywood termites. Finally, Section 3.8 offers perspective on why research progress in this area has been slow.

Chapter 3 contains 27 FCRs: 13 Findings, 10 Conclusions, and 4 Recommendations.[6]

Section 3.2: Background

Research on the control of wood-destroying insects that attack seasoned lumber, especially drywood termites, has been sporadic and limited. These pests are not widely encountered in the United States, and research funding to control them has never been a priority of state or federal funding agencies or industry. Localized chemical applications of insecticides originally **registered** to control other structural pests are a cheaper and more popular treatment option than fumigation to control drywood termites.

Additionally, urban pest control, especially for drywood termites, is not a large enough market for the chemical industry to justify research into alternatives to fumigation. For example, in 2023, California home and property owners spent approximately $291 million to $882 million controlling drywood termites (Zilberman et al., 2024). Insecticides account for less than 10% of these costs. In 2023, 78,324 structures were fumigated with 2.3 million pounds of SF in California (DPR, 2024). The cost of SF to the pest management professionals was approximately $31 million. The total costs to the California consumer for SF fumigations ranged

[6] 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.

from $172 million to $287 million. It is impossible to estimate the costs of the chemicals and materials used in localized treatments, but they are considerably less than the cost of SF fumigation. The costs of insecticides and materials used to control drywood termites are a small proportion of the total expenditure to control drywood termites.

Meanwhile, in 2024, the estimated cost to bring a new insecticide to market in the United States and the European Union was $301 million and took between 8 and 12 years (Sparks, 2013; AgbioInvestor, 2024). The estimated cost of registering a new insecticide with the U.S. Environmental Protection Agency (EPA) could be as high as $64 million dollars depending on the tests required (EPA, 2025b).

State and federal agency funding and support for research and extension activities for the control of wood-destroying pests of structures has declined in recent years as funding priorities have shifted away from applied urban pest research. At one time, there were nearly two full-time positions in the University of California (UC) system devoted exclusively to research and extension of wood-destroying insects in urban settings. Currently, there is only one half-time appointment across the 10 UC campuses devoted to the control of drywood termites.

The problems and economic impacts associated with drywood termites are primarily confined to California, Florida, and Hawaii. The major economic impact of *Incisitermes minor* is primarily restricted to urban areas of California, whereas *Cryptotermes brevis* is the main drywood termite pest in Florida and Hawaii (Rust & Su, 2012).

In many ways, specialty agricultural crops face challenges similar to pest management: They constitute a fairly small market share of the pest control industry, and there is little monetary incentive for chemical manufacturers to invest in alternatives. In California, the IR-4 Project supports research and funding for pest management for California's specialty crops, which otherwise would not receive significant investment. It is a partnership between the National IR-4 Project (established in 1963 by the U.S. Department of Agriculture [USDA] and the land-grant universities) and the California Department of Food and Agriculture (IR-4, 2025). Its goals include developing safe and effective pest management strategies, supporting the registration of new pesticides and nonconventional pest management technologies, and promoting public health and well-being. The program works with growers, registrants, and other stakeholders to develop data for the EPA, support the registration of specialty uses on minor crops, and conduct research trials at land-grant universities and USDA Agriculture Research Service facilities. Given the paucity of research funding for identifying alternatives to drywood termite control, the structural pest control industry could benefit from a program similar to IR-4.

79. **FINDING:** Funding for research and extension activities related to wood-destroying insects of seasoned structural lumber has declined over time. No central agency exists to coordinate the research and extension needs of the structural pest control industry and the public in California.

80. **CONCLUSION:** The lack of dedicated funding and the limited economic markets for pest control of drywood termites hinders the research and development of new alternative strategies.

81. **CONCLUSION:** The structural pest control industry would benefit from a program similar to California's IR-4 Project, which would develop alternative pest control methods and share this information with the public.

82. **RECOMMENDATION:** The California Department of Pesticide Regulation and other relevant agencies, industry groups, and stakeholders should consider establishing a program within the IR-4 Project or develop a similar program devoted to urban structural pest management.

Section 3.3: Research Investigations in California

Some of the earliest discussions of the biology, distribution, and control of drywood termites in California appeared in the seminal *Termite and Termite Control* (Kofoid, 1934). Chapters included descriptions of its life cycle, development of secondary reproductives, swarming, and the dispersal of drywood termites. The effectiveness of hydrogen cyanide and chloropicrin fumigation and localized treatments with arsenical dust and other compounds were reviewed. In addition, nonchemical approaches to prevent drywood termites from infesting structures were discussed, including paint and wood coatings; repairing holes, cracks, and checks in lumber; using wood preservatives; and covering attic and crawl space vents with screens.

Research and extension activities concerning wood-destroying insects in California have primarily been conducted by individual faculty at UC Berkeley, UCLA, and UC Riverside. However, UC faculty and extension specialists with expertise on the biology and control of drywood termites were not replaced as they retired. This has had a negative impact on research and the sharing of information with the public. It has also delayed the development of alternative treatment strategies to SF fumigation.

Testing of liquid fumigants, various formulations of insecticides, and desiccant dusts began in the mid-1950s at the University of California, Los Angeles (UCLA; Ebeling & Pence, 1956; Ebeling & Wagner, 1959). Using desiccant dust such as silica gel to prevent termite swarmers from reinfesting structures emerged from this early work (Ebeling & Wagner, 1959, 1964; Ebeling et al., 1968). Ebeling and colleagues conducted field studies with fumigants and localized treatments to determine their long-term effectiveness. They were the first to investigate how quickly drywood termites reinfested structures. Between 1986 and 1997, Ebeling and industry collaborators investigated the use of electricity, cold, and heat to control drywood termites (Ebeling, 1983, 1985, 1994, 1997; Forbes & Ebeling, 1987). As a result, several devices were registered with the California Department of Pesticide Regulation (DPR) to control drywood termites.

In 1986, the California Structural Pest Control Board (SPCB) established the Structural Pest Control Research Fund to stimulate basic and applied research on urban integrated pest management (Section 8674 (t) (1); SPCB, 2021; ***Table 3.1***). The fund is supported by a $2 monthly fee paid by the pest control companies for a pesticide use stamp or stamp number that is filed with each county. This $2 fee generates approximately $160,000 annually (SPCB, 2025). The fund has supported research on basic biology of drywood termites, the use of chloropicrin as a warning agent, termite detection devices, the chemical nature of drywood termite pellets, localized chemical treatments, the use of heat and cold to control drywood termites, and the detection of wood-destroying beetles (***Table 3.1***).

The detection of drywood termites in structures is difficult because the termites tunnel and feed within the wood. The presence of drywood termites' characteristic six-sided wood fecal pellets is probably the single most important piece of evidence for detecting termite infestations. Inspectors and researchers alike have wondered whether there is any way to determine the age of the pellets and the colonies that produced them. This would be a significant advancement given that there is currently no way to determine whether fecal pellets are from active or previous infestations. Studies at UC Berkeley found that drywood termite fecal pellets contained the cuticular hydrocarbons (chemical compounds found on the outer surface, or cuticle, of an insect's body) of the species that produced them (Haverty et al., 2005; Lewis, 2009a). The hydrocarbons from the pellets were qualitatively and quantitatively like those collected directly from the termites' bodies, making it possible to identify the termite species that produced them. This was verified for five species of drywood termites in Hawaii (Grace, 2009).

Researchers have also sought to determine the age of fecal pellets. One study compared the cuticular hydrocarbons of fecal pellets that were aged up to 1 year (Lewis et al., 2010). Of the 73 hydrocarbons identified, 19 changed over time. However, determining pellet age required 1,000 drywood pellets and expensive laboratory equipment such as gas chromatography–mass spectroscopy. The research has not been pursued.

Table 3.1. Research funded by the Structural Pest Control Research Fund that relates to wood-destroying organisms and their control.

Title	Reference
Evaluation of Efficacy of Chloropicrin as a Warning Agent to Prevent Unauthorized Entry During Structural Fumigation	Lee & Liscombe, 1993
The Effects of Temperature and Humidity on the Movement of the Western Drywood Termite	Rust & Cabrera, 1994
Seasonal Changes in Composition of Colonies of the Western Drywood Termite, *Incisitermes minor* (Hagen) (lsoptera: Kalotermitidae)	Atkinson, 1994
Simulated Field Evaluation of Six Techniques for Controlling the Drywood Termite *Incisitermes minor* (Isoptera: Kalotermitidae) in Residences	Lewis & Haverty, 1996
Determination of Trophic Interactions Among Western Drywood Termites, with the Intention to Develop an Effective Bait for Control	Rust & Cabrera, 1999
Evaluation of In-place Wooden Roof Treatments	Wilcox et al., 2000
Final Report, Development of a Monitoring and Mass Trapping Tool for Wood-destroying Beetles in Structures	Lewis et al., 2001
Development of Acoustic Emission Detection Equipment for Wood-Destroying Insects	Beall, 2001
Evaluation of Chemical Localized Treatment for Drywood Termite Control	Rust & Venturina, 2009
Field Evaluations of Localized Treatments for Control of Drywood Termite Infestations in California	Lewis et al., 2009
Assessment of Devices and Techniques for Improving Inspection and Evaluation of Treatments for Inaccessible Drywood Termite Infestations	Lewis, 2009a
Evaluation of Bait Station System Efficacy for Reduced-Risk Subterranean Termite Management in CA	Sutherland, 2023

Grants from the SPCB sponsored research at UC Berkeley and UC Riverside to determine the effectiveness of localized chemical treatments in the laboratory (Rust & Venturina, 2009; Lewis, 2009b,) and the field (Lewis & Haverty, 1996; Lewis et al., 2009). The active ingredients tested included DOT, d-limonene, fipronil, imidacloprid, and thiamethoxam. Injections of fipronil consistently provided the best results in those studies. The comparative field study was the first attempt at determining the effectiveness of various localized treatments in residential housing in California (Lewis & Haverty, 1996). In recent years, DPR has supported research at UC Riverside to develop an in-wood baiting system for drywood termites using chitin synthesis inhibitors (Poulos et al., 2025).

83. **FINDING:** Research and extension activities concerning wood-destroying insects in California have been primarily conducted by a handful of University of California faculty.

84. **FINDING:** Since 1991, about 80% of funding for research and extension activities on wood-destroying insects of structures in California was provided by pest control fees collected by the Structural Pest Control Board.

Section 3.4: Scale of Research

Research on wood-destroying organisms has been primarily focused on pests other than drywood termites. The U.S. Department of Agriculture (USDA) Forest Service established a research program in the mid-1930s that focused on the control of subterranean termites in Madison, Wisconsin, and Gulfport, Mississippi (Beal, 1984: Mulrooney et al., 2007). This program provided the EPA with data regarding the use of soil insecticides to control subterranean termites. Some studies regarding wood-destroying beetles, primarily anobiids, were conducted at the Gulfport laboratories, but drywood termites were never included. Research on the biology and control of the drywood termite species *C. brevis* has been conducted in Florida and Hawaii. Research topics include the systematics of the genus *Cryptotermes*, its biology, localized chemical treatments, preventive applications to prevent establishment of colonies, and heat treatments (see ***Section 1.3***, ***Section 2.3.1***, and ***Section 2.6***).

Worldwide, the two most significant drywood termite structural pests are *I. minor* and *C. brevis*. In the past 20 years, their importance as invasive species has accelerated new research. *C. brevis* is native to Peru and Chile and is believed to have spread to Central America and the Caribbean in the 1500s via commerce (Scheffrahn et al., 2009). Outside its native range, *C. brevis* is only found in structural lumber, wooden objects, and furnishings. This species is restricted to climates that are stable and humid even with very little or no rainfall (Scheffrahn et al., 2009). Their distribution is limited to coastal regions in the Americas, Africa, Australia, and oceanic islands.

C. brevis was first detected in Australia in the 1940s. The Queensland Government established a program to inspect, survey, and control the termite in 1997. It supported research and interest into alternative treatments such as localized chemical treatments and spot or whole-of-room treatments with heat. The program initiated an extensive but unsuccessful effort to eradicate *C. brevis*, and was discontinued in 2021 (Fitzgerald & Hassan, 2023).

The discovery of *C. brevis* in the Azores, Portugal, in 2004 stimulated research into its distribution and control in the islands (Borges et al., 2014; Guerreiro et al., 2014). It included research on the use of heat, solid fumigants (naphthalene, para-dichlorobenzene, and dichlorvos strips), and inert gases to control drywood termites in furniture (Borges et al., 2007). There has been no termite research published from the Azores since 2015.

Western drywood termites were first reported as established in Japan in 1976. By 2004, they had spread to numerous structures in the Kansai and Hokuriku areas (Indrayani et al., 2004). This stimulated research into drywood termite biology and control in Japan (Indrayani, 2007). The use of microwaves (Indrayani et al., 2006) and x-ray computed-tomography (Himmi et al. 2016 a,b) helped provide insights into the nest structure of *I. minor*. A novel use of toxicants formulated as baits was tested (Indrayani et al., 2008). However, in recent years the research activity in Japan has declined.

> 85. **FINDING:** Research on the biology and control of drywood termites is limited, with studies on *I. minor* primarily limited to California and, to an extent, Japan.

> 86. **CONCLUSION:** Interest and support for research on the control of drywood termites have mostly been reactive, driven by recent introductions of drywood termites to various parts of the world.

Section 3.5: Research on Environmental Conditions

In nature, drywood termite colonies infestations are confined to a single piece of wood. Therefore, they are exposed to the surrounding environmental conditions such as extreme cold, heat, moisture, and drought. These factors greatly affect their natural distribution and their potential to establish colonies in natural environments. In Southern California, drywood termites are rarely encountered at elevations greater than 1,500 meters (4,921 feet). However, heating and cooling of structures can dramatically alter the temperature and moisture content of structural lumber and impact drywood termite survival. Climate change and urbanization will accelerate the expansion of the range of drywood termites in California (Buczkowski & Bertelsmeier, 2017).

It is unclear whether environmental conditions will affect the use of alternative treatments. At the extremes of their distribution range, drywood termite infestations are more likely to be hidden in inaccessible areas that provide warmth in the winter and cooling in the summer. These areas may be difficult to locate and treat with localized methods.

Section 3.6: Suitability of Research to Identify an Alternative for California

With increased urbanization and the spread of residential areas into previously agricultural and natural areas in California, the problems associated with the western drywood termite will increase. Drywood termite colonies are cryptic and difficult to locate. Determining the effectiveness of alternative treatments in the field often requires destructive sampling that is not always feasible.

Drywood termite colonies can be only maintained in the laboratory for 4–6 months, and access to field populations is necessary to conduct research. Obtaining enough drywood termites for laboratory studies requires a lot of infested wood because drywood termite colonies are small, and the physical act of removing them from wood can result in considerable mortality. California is the logical location to conduct research on drywood termites, as opposed to the southeastern United States, where infestations are limited.

> 87. **FINDING:** Large numbers of drywood termite colonies will be required for laboratory and field studies.

> 88. **CONCLUSION:** California is the ideal location to conduct laboratory and field research into alternative control measures to SF fumigation to control drywood termites.

Section 3.7: Alternatives Undergoing Research

Finding alternatives to fumigation for controlling drywood termites has been an ongoing research goal for nearly a century. No single strategy has provided total success. Some promising areas for future research include better methods or devices to detect infestations and their gallery structure, improved localized treatments, and better baits. Additional studies on the role of food sharing (**trophallaxis**) in drywood termite colonies could be conducted in conjunction with the bait studies and could lead to more effective localized treatments.

Some of these avenues for research perpetuate society's over-reliance on chemicals to resolve pest challenges. As pests develop resistance, the regulatory landscape changes, or economic pressures increase, users become increasingly locked in to chemical solutions, and the adoption of nonchemical alternatives becomes ever more challenging.

Inspection Devices

Inspecting and detecting evidence of drywood termites and wood-destroying beetles are prerequisites for controlling these pests. Many existing detection tools (***Section 2.3***) generate excessive false positives and negatives and often fail to detect insects in inaccessible voids and hidden areas in structures. None of the existing tools can reliably quantify insect activity or the number of insects, which would be useful for assessing effectiveness of alternative termite and beetle treatments.

> 89. **FINDING:** Localized treatments rely on successful detection of termite galleries within structures, yet existing methods for detection and localization are inadequate.

> 90. **CONCLUSION:** Better detection of termite galleries would improve the effectiveness of registered localized chemical treatments as well as any new active ingredients. It would also minimize damage to wood, sheetrock, paneling, and other wall coverings.

> 91. **RECOMMENDATION:** DPR should consider supporting research into devices and other methods for termite detection.

Age-Dating Pellets

The presence of drywood termite fecal pellets is a clear indicator that structural lumber has previously had or currently has an infestation. Pellets are produced when termites clear their galleries in preparation for swarming or when they are otherwise dislodged from infested wood. The pellets can remain in the structure for years if not removed and cleaned up after treatments. Determining the age of the pellets would be valuable for assessing whether the infestation is active and the age of the colony. For example, pellets less than 1 year old would suggest that colonies may still be active, while pellets more than 5 years old might suggest otherwise. If rapid age determination techniques could be developed, analyzing drywood pellets could become an important tool in managing drywood termites. Unnecessary fumigations and localized treatments would also be avoided.

The size and color of pellets are two metrics that could prove useful. An analysis of fecal pellets from various drywood termite species revealed that *C. brevis* pellets were significantly larger, less elongated, and had a smaller concavity on the faces of the prism compared to those of *Kalotermes flavicollis* (Bobadilla et al., 2020). The success rate exceeded 75% for identifying these two species through pellet size and shape. Factors such as colony condition and termite diet influenced the dimensions of fecal pellets in *Cryptotermes dudleyi* (Zega et al., 2020). Mature colonies produced larger pellets than newly established colonies. Fecal pellets of *C. brevis* also change color over time; however, color analyses to determine colony age have limited value due to the high variability in color when pellets are first deposited (Haigh et al., 2024). Further research would be needed to determine if this approach is feasible and practical.

The gut microbiome of termites is responsible for the digestion of wood in drywood and subterranean termites. The gut microbiome of two subterranean termites—*Reticulitermes* *flavipes* (Kollar) and *Microcerotermes biroi* (Desneux)—differed significantly (Chakraborty et al., 2023). The core microbiome was affected by termite feeding activities, but not significantly affected by wood age. These studies are in the preliminary stages, and additional research with drywood termites is warranted.

An ongoing project at UC Riverside is examining if molecular biomarkers from gut bacteria can be used to determine the age of fecal pellets. Freshly produced, 3-, 6-, and 12-month-old fecal pellets have been compared using genetic sequencing and data processing technologies. The data suggest significant differences exist between the fresh and aged fecal pellets (D. Choe, pers. commun., 3/6/2025). Eight chemicals including heptacosone, pentacosone, and hexacosone accounted for approximately 70% of the chemical differences between aged samples.

92. **FINDING:** Termite pellets are telltale signs of termite infestations, but current termite detection practices cannot differentiate between active and inactive termite infestations.

93. **CONCLUSION:** Rapid analyses of pellet age could provide important information that affects treatment recommendation and eliminates unnecessary termite treatments.

94. **FINDING:** Chemical and molecular investigations of drywood termite pellets may provide species-specific markers and identify molecular changes as pellets age.

Localized Chemical Treatments

Many of the active ingredients used for decades to treat termite galleries—such as arsenical dusts, chlorpyrifos, and pentachlorophenol—are now banned for urban use because of environmental and human health concerns. Most available products contain pyrethroids, borates, and pyrethrins (Chapter 2, ***Table 2.2***) and are typically less effective than their predecessors (***Section 2.9***). For localized chemical treatments to be effective, the toxicants must exhibit delayed toxicity, be nonrepellent, be bioavailable, kill termites over a broad range of concentrations, and be shared or spread among the termites. Toxicants with these properties exploit the social behavior of drywood termites (Rust & Su, 2020). Injections of spinosad into termite galleries were effective in controlling drywood termites in laboratory and field studies (***Section 2.3.6***). Although still perpetuating a reliance on chemicals to solve pest challenges, spinosad is far less toxic than SF. Despite the promise it showed in treating drywood termites, spinosad was never registered for drywood termite control.

95. **FINDING:** A less toxic chemical treatment, spinosad, demonstrated effective control but was never brought to market.

Active ingredients belonging to a new insecticide class, isoxazolines, have not been studied as localized treatments, even though their mode of action and toxicity to insects are similar to fipronil. These compounds inhibit certain nerve receptors and are extremely toxic to insects when ingested. Several compounds such as fluralaner and afoxolaner are currently approved as oral treatments to control fleas and ticks on cats and dogs. They are being considered for human use to control human diseases transmitted by insects (Miglianico et al., 2018). Laboratory tests would reveal their effectiveness with drywood termites and wood-destroying beetles.

The use of attractants, pheromones, and adjuvants (additive that helps the pesticide spread, stick, or penetrate better) combined with spot treatments could increase the treatment range of drill-in-treat methods (***Section 2.6***) and significantly improve their effectiveness within a drywood termite colony. Laboratory data suggests that chemicals such as β-pinene can attract workers and can increase the activity of spot treatments of fipronil (Poulos et al., 2024). Another promising compound, (Z)-3-dodedecenol, is a major component of the **trail pheromone** (a chemical path left by insects to communicate directions) of *K. flavicollis* and six other drywood termite species (Sillam-Dussès et al., 2009). *I. minor* termites also respond to this trail pheromone (Chrysanti, 2012).

The architecture and design of termite galleries prevent liquids and foams from easily penetrating the gallery system. Another potential area for further research is improving the dispersion of the active ingredient into the termite colony. Formulations that increase the uptake of active ingredients and enhance termite grooming would increase the activity of localized treatments. Formulations that increase spread and transfer of active ingredients would increase the likelihood of eliminating colonies.

96. **FINDING:** Adding attractants and pheromones to insecticides shows potential for enhancing the effectiveness of localized treatments for drywood termites. Although it would sustain our reliance on chemicals for resolving pest challenges, this approach would ultimately reduce the total volume of pesticides used against drywood termites.

97. **CONCLUSION:** To fully realize the potential of attractants and pheromones, a broader range of effective and less toxic chemical and behavioral agents must be identified and tested.

98. **RECOMMENDATION:** Additional research should be conducted to identify new active ingredients, attractants, and pheromones for localized treatments. This research must also consider any possible environmental and human health effects and whether continued chemical treatments should be pursued.

Drywood Termite Baits

Bait containing chitin synthesis inhibitors (CSIs) has revolutionized subterranean termite control (Rust & Su, 2012). CSIs inhibit the formation of chitin, a crucial component of the insect's exoskeleton, or cuticle. When the termites molt, they die due to the compromised cuticle. The delayed action allows CSIs to spread throughout the colony by transferring among termites. In choice feeding studies with *I. minor* nymphs and **pseudergates** (immature termites functioning as workers), bistrifluron concentrations of 0.5% and 1% resulted in greater than 99% mortality by day 60 (Poulos et al., 2025). Lethal doses of bistrifluron were retained by *I. minor* and transferred to nestmates. Additionally, baits containing CSIs may prevent the development of supplementary reproductives and winged reproductives, which are responsible for future infestations and reinfestations in the treated colony.

> 99. **FINDING:** Chitin synthesis inhibitors show potential as active ingredients for baits to control drywood termites.

> 100. **CONCLUSION:** Additional research with chitin synthesis inhibitors and other potential active ingredients in baits is warranted.

Molecular Studies

Using molecular biomarkers to study the genetic diversity and colony structure of drywood termites could provide a means of determining the colony size and age, colony range, and treatment effectiveness (Lewis, 2009a; Booth et al., 2010). Research has identified genetic biomarkers (polymorphic microsatellite loci) in drywood termites that can help determine patterns of dispersal, gene flow, and colony breeding structure (Indrayani et al., 2006; Booth et al., 2008). When 20 colonies were analyzed, 45% were simple families (original king and queen present), 30% were extended families (more than one reproductive), and 25% were mixed families (more than one colony has fused together) (Lewis, 2009a; Booth et al., 2010). The study concluded that the single-family colonies were less than 5 years old, and the extended families were more than 10 years old. The ability to determine the age of a termite colony in a home is significant because research suggests that younger, single-family colonies are likely to be amenable to localized treatments, while older, multifamily colonies are likely to be more dispersed throughout the structure (thus requiring a whole-structure treatment or a more concerted effort to locate termite galleries throughout the home).

Austin et al. (2012) reported that 10 and 12 different haplotypes existed for *I. synderi* and *I. minor*, respectively. Enough genetic variation existed within these two species to permit studies into their dispersal and possible introductions. Lee et al. (2024) confirmed using genetic markers that drywood termites introduced in Korea were *I. minor* from Japan and the United States. This has practical implications for detecting invasive colonies worldwide.

101. **FINDING:** Molecular biomarkers are useful in determining genetic diversity and colony structure of drywood termites, which in turn could help assess treatment needs and outcomes. However, these tools have only been applied in a limited number of studies and colonies.

102. **CONCLUSION:** Broader research is needed to validate and expand the practical use of molecular studies for drywood termites.

103. **RECOMMENDATION:** Studies with molecular biomarkers should be expanded.

Essential Oils

Using essential oils (EOs) to control various insects in urban settings— including termites— has been widely promoted in recent years. Many EOs are minimum-risk pesticides and exempted from the Federal Insecticide Rodenticide and Fungicide Act, making them an attractive alternative to conventional insecticides (EPA, 2025a). Most of the research with EOs has been conducted against subterranean termites, and there are few studies with drywood termites.

Deposits of the EOs from basil, citronella, hosho, and rosemary greater than 56µg/cm^2 killed more than 50% of *C. brevis* pseudergates. All deposits except hosho oil prevented termite feeding (Sbeghen et al., 2002). Fresh deposits of d-limonene, an essential oil, were effective against *I. minor* through both direct contact and vapor for 24–48 hours (Rust & Venturina, 2009). When injected into boards infested with drywood termites, only 51% of the termites were killed 19 days after the treatment (Rust & Venturia, 2009). After 48 hours, deposits of d-limonene were not toxic but prevented feeding. Clove oil was also toxic against drywood termites, and several EOs repelled the drywood termite *Cryptotermes cynocephalus* Light (Meisyara et al., 2021). Thymol provided both contact and vapor toxicity to pseudergates against *C. brevis* (Santos et al., 2017). Thymol deposits repelled termites, and sublethal exposures resulted in nestmates not recognizing one another.

Certain vegetable oils combined with iodine prevented feeding by *C. brevis* (Sousa et al., 2019). When applied to wood, citrus waxes (combination of citrus fruit wax and EOs) prevented feeding by *C. brevis* (Sbeghen-Loss et al., 2011).

Spot treatment of the EO methyl salicylate on a drywood termite gallery in wooden blocks, which were then subjected to a heat treatment, resulted in increased termite mortality when compared with a temperature-alone treatment (Perry & Choe, 2020a, b). The main purpose of the EO in these experiments was to eliminate any spots within the gallery that could be used by termites to escape high temperatures during the heat treatment. Only two field trials were conducted.

104. **FINDING:** Many essential oils exhibit contact toxicity and brief residual activity against drywood termites. Some essential oils exhibit vapor toxicity to drywood termites. Many essential oils and other vegetable oils deter termite feeding. However, most essential oils are volatile and rapidly lose their effectiveness.

105. **CONCLUSION:** Essential oils may not be effective as a standalone treatment.

Alternative Fumigants

Fumigants such as ethyl formate and ethanedinitrile (EDN) have been considered as potential replacements for SF. Ethyl formate was first identified as a fumigant in 1927 (Bharathari & Jayas, 2024). It is mostly used to fumigate stored products to control pests such as merchant grain beetles and lesser grain borers. Both the liquid and vapor are flammable and explosive and not safe to use for structural fumigation. Another disadvantage is that high concentrations are often required to kill stored product pests. Its effectiveness on termites and wood-destroying beetles has not been evaluated.

EDN was first discovered in 1815, but its potential as a fumigant was not realized until 1996 (Gidiglo, 2021). EDN may have some limited uses as a structural fumigant. Research has focused on controlling pests in stored products and timber. The active ingredient generated by EDN is hydrogen cyanide, an extremely lethal gas. EDN has been registered in New Zealand and Australia to control beetles in timber. EDN has a low boiling point (-21.2°C, -6.2°F) and high vapor pressure (3,868 mmHG at 21.1°C), which are both qualities needed for structure fumigation. However, EDN is also extremely flammable. Australia requires that exhaust gases must be scrubbed and a 50-meter buffer zone established around the fumigation site (AUS, 2013).

Section 3.8: Reasons for the Lack of Research Progress

Research into developing alternatives to SF fumigation for the control of drywood termites has lagged for many reasons. These include the lack of interest or long-term commitment to research from state and federal agencies, the small size of the pest control market to control drywood termites, the cost of registering new products and devices, the biology and ecology of the drywood termites, and the confidence the pest control industry has in SF fumigation and several existing alternatives.

The SPCB has been the only state agency consistently providing research funding for structural pest control over the past 30 years, generated by fees paid by the pest control industry. The missions of major entomological funding agencies such as the USDA and the

California Department of Food and Agriculture do not include the control of urban insect pests such as drywood termites, and there are no commodity boards or other agencies to provide research support for structural pest control. Research funding from UC Agriculture and Natural Resources for urban pest issues, including drywood termites, is nonexistent. In recent years, DPR has provided some funding to mitigate pesticide runoff into urban waterways and develop alternative treatments for drywood termites.

Drywood termite control is a very small share of the pest control industry, which disincentivizes investment into this area, particularly given the high costs of bringing new insecticides to market. In the past 60 years, only three insecticides were registered strictly for urban structural pest control and not for agricultural use: SF (drywood termites), propetamphos (cockroaches and fleas), and fipronil (general urban insect pests). From a chemical manufacturer perspective, the urban pest control market for drywood termites is not large enough to justify those investments. The costs of developing pest control devices are unknown.

The total pest control market for chemicals to control drywood termites is small compared with agriculture. Competition within this small market may have also impeded progress in the past. In the 1990s, research showed that spinosad was an effective localized treatment for drywood termites in the laboratory and field studies. At that time, Dow Chemical, the company developing spinosad, also provided two other products for drywood termite control: SF and chlorpyrifos. According to a Dow Chemical representative, spinosad was not pursued because of the limitations inherent to localized treatments (i.e., they are not effective unless precise termite locations are known) (E. Thoms, pers. commun., 8/5/2025). Paradoxically, Dow Chemical continued to produce and market chlorpyrifos (another localized treatment with the same limitations) for drywood termites until the EPA ended its use on termites in 2005 (EPA, 2006). This suggests that the decision not to pursue spinosad likely reflected a combination of factors beyond just its treatment method, including the small market size and redundancy of spinosad with the existing product.

Biological and ecological factors present further barriers. The cryptic nature of drywood termites create challenges in detecting infestations and determining the effectiveness of whole-structure and localized treatments. Failure to kill the entire population results in the development of **neotenic** reproductives and new colonies within the structure. Colonies develop slowly, and it may take years to determine the effectiveness of alternative treatments in the field. Colonies cannot be maintained in the laboratory for extended periods of time, and it is difficult to simulate field conditions in the laboratory. All these factors make it difficult to conduct laboratory and field research.

The pest control industry has relied on SF fumigation because of the certainty in its effectiveness. Localized treatments, especially drill-in-treat, have been conducted for a century as an alternative treatment, and the industry is comfortable in applying these treatments. This long-standing reliance on familiar methods has limited the search for newer or less-proven alternatives.

From the consumer perspective, drywood termite infestations are relatively rare. The home and property owner may be confronted with the problem of drywood termites only once or twice in the lifetime of their structure. Many homes within California are not within the active geographical range of drywood termites. The demand for services and information about fumigation and potential alternative treatments is limited primarily to homeowners and property owners experiencing active drywood termite infestation. This limited market further constrains public interest and sustained investment in research and innovation.

Despite these barriers, interest in alternative treatment methods has grown modestly since SF was identified as a potent greenhouse gas in 2009. However, the primary constraint remains the same: a lack of sustained funding for research into drywood termite control.

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Chapter 4: Addressing Barriers and Increasing Adoption of Fumigant Alternatives

Section 4.1: Chapter Overview

This chapter explores the barriers that inhibit the adoption of fumigant alternatives and discusses strategies to overcome these barriers and encourage broader adoption of these alternatives, including ways to share information about alternatives with potential users.

Section 4.2 provides important context regarding the relative rates at which SF fumigation is chosen compared to alternative treatments. Section 4.3 explores factors that may influence the choice of SF over other options, including regulations, homeowner and property owner decision-making, the limited selection of alternative whole-structure treatments, and patterns of urban and suburban development. Section 4.4 examines the promotion of alternative treatments and strategies to incentivize their use. Finally, Section 4.5 discusses how information is disseminated to potential users.

Chapter 4 contains 32 FCRs: 18 Findings, 11 Conclusions, and 3 Recommendations.[7]

Section 4.2: Background

In California, there are 4,353 companies that provide a wide variety of pest control services including fumigation and localized alternative treatments (IBIS, 2025). Each company employs inspectors that recommend and provide its specific services to control drywood termites and wood-destroying beetles.

Records show localized treatments are much more common than SF fumigation when drywood termites are discovered. Completion notices filed with the California Structural Pest Control Board (SPCB) in 1993–1994 for Riverside, San Bernardino, and Orange counties indicated 22% were fumigated with SF or methyl bromide and 78% were treated with one of the alternative treatments listed in Chapter 2 (T. Atkinson, pers. commun., 2/2/2025). Of the alternative treatments, 72% were treated with localized injections of chlorpyrifos. The number of structures fumigated with SF in California in 2023 was 78,834 (DPR, 2024). Assuming selection rates were similar to those in 1993–1994, then approximately 358,336 alternative localized treatments were performed in 2023. An analysis of inspection reports and completion notices from pest control companies could definitively confirm the current extent of this preference for localized treatments. Social science research could provide insights into this

[7] 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.

preference, which is likely due to the reduced costs and hassle of localized treatments, as well as concern regarding toxicity of SF.

> 106. **FINDING:** Historically, localized treatments for drywood termites have been significantly more common than fumigations with sulfuryl fluoride (78% versus 22% of treatments provided, respectively), although several decades have passed since these trends were evaluated.

Section 4.3: Barriers to Adoption of Alternative Treatments

Motivations, preferences, and socioeconomic reasons for the use, curtailment, or avoidance of fumigants in agriculture have been widely studied by social scientists, and many of these are discussed in a separate report on pre-plant fumigants (CCST, 2025). However, there is little analogous research on the use of fumigants in structural applications. Additionally, fumigant use in structural applications involves not only different pests and ecological conditions but different regulatory concerns, different decision-makers, different market transactions, and thus different barriers to adoption. That said, some research on pesticide use may apply across sectors and could provide insight into barriers to adoption to structural fumigation alternatives. Each of the barriers described in this section present potential levers for regulatory action or investment, which, if addressed, could lead to an even broader adoption of fumigant alternatives and merit consideration within the larger context of policy development processes. However, the discussion of these barriers and how they might be addressed or ameliorated should not be taken to mean that these are recommendations of the report's Steering Committee unless indicated as such.

Regulatory Barriers

One clear barrier to adoption specific to structural fumigation are regulations that require pest management professionals (PMPs) to recommend whole-structure treatments. Section 1991.8 of the Structural Pest Control Act (SPCB, 2021) stipulates that structures must be recommended for whole-structure treatment if there is evidence of the wood-destroying pests extending into an inaccessible area. Fumigation and a whole-structure heat treatment are the only two all-encompassing treatments recognized by California law (SPCB, 1998). However, whole-structure heat treatments cannot be conducted on all structures because of heat-sensitive items, heat sinks, and size of the structure (Chapter 2, ***Section 2.4***). Consequently, there are circumstances in which SF fumigation may be the only available option because the drywood termites are in inaccessible areas and the structure is not amenable to heat treatment.

Following the Structural Pest Control Act, the only alternative to whole-structure treatment when termites are within inaccessible areas is to find and expose all infested wood for localized treatment. If exposing the infested area(s) for local treatment, Section 1991.8

requires removing the infested wood or using another method of treatment that exterminates the infestation. However, none of the alternative localized treatments are as effective in killing termites throughout a structure as SF fumigation. There is no guarantee that infestations in inaccessible areas are controlled with any of the alternative localized treatment strategies because there is simply no way to be certain that every individual termite has been located and eliminated. In contrast, SF fumigations are considered 99.995% effective in eliminating drywood termite infestations throughout a structure (T. Iniechen, pers. commun., 4/21/2025), providing PMPs the certainty needed to certify that the structure is pest free. This is critically important to PMPs because their failure to eliminate termites can be appealed to the SPCB and is subject to legal action by a homeowner or property owner.

There is near-zero tolerance for some urban insect pests because of public health laws, regulatory statutes, and accepted industry practices. For example, the presence of cockroaches in food-handling establishments is a violation of many local public health laws. Establishments in violation are closed and potentially fined until the problem is corrected. Similarly, the presence of live termites in a structure is deemed unacceptable by the Structural Pest Control Act (Section 1991.8 calls for the extermination of all wood-destroying organisms). The problem is not considered resolved until all termites have been eliminated from the structure.

> 107. **FINDING:** When termites extend into inaccessible areas and the structure is not amenable to heat treatment, the Structural Pest Control Act requires that pest management professionals recommend fumigation with sulfuryl fluoride.

> 108. **FINDING:** Pest management professionals can be held liable if treatments fail to completely eliminate termite infestations.

> 109. **FINDING:** Only fumigations with sulfuryl fluoride and whole-structure heat treatments provide pest management professionals with enough certainty to certify that structures are "pest free."

> 110. **CONCLUSION:** Further adoption of fumigant alternatives will likely remain limited until California regulations or liability frameworks evolve to limit the legal risks associated with using them to treat structurally complex or inaccessible infestations, or until alternative treatments can provide comparable levels of certainty of eradication as fumigation with sulfuryl fluoride.

Pesticide Suppliers and Service Providers

The interests and concerns of PMPs may pose barriers to adoption and could benefit from research. In agriculture, numerous studies have shown how pesticide companies, pesticide control advisors, and agricultural extension agents influence farmers' pesticide use. However, there are no studies examining how PMPs select and recommend pest control services to home and property owners. It can be inferred that the certainty afforded by SF fumigation plays a role in recommendations by PMPs when termite infestations are not easily resolved by localized treatments (particularly given PMPs liability for failed exterminations). Additionally, research on pesticide use indicates that pesticide suppliers and service providers encourage the use of fumigants and localized chemical treatments to maintain their markets. This body of research also suggests that pesticide suppliers and service providers become more aggressive in selling pesticides and pesticide services when their markets decline (Harrison, 2011; Robbins & Sharp, 2003). Consequently, unless service providers are also providing alternative treatments, they have little economic incentive to promote them.

> 111. **FINDING:** Pesticide companies and pest control services have an interest in maintaining markets for their services and may encourage fumigation with sulfuryl fluoride.

> 112. **CONCLUSION:** To encourage adoption of alternative treatments, pesticide companies could be actively discouraged from promoting or marketing fumigation with sulfuryl fluoride and encouraged to add alternative treatments to their service portfolios.

Difficulty in Confirming Termite Presence

As discussed in Chapter 2, determining the presence of active termite infestations is difficult due to the limitations of available inspection equipment and the amount of destructive sampling that would be required to find live termites. Instead, inspectors consider various factors and indicators to evaluate the likelihood of an active infestation. These include the geographic location of the structure; the age of the structure; the presence of fecal pellets, termite wings, dead **alates**, and damaged wood; and the time since the last inspection, fumigation, or treatment. Inspection devices can help an inspector pinpoint areas of possible termite activity, but these devices cannot definitively confirm the presence of drywood termites.

Following treatment, inspectors are required to recommend to customers that evidence of drywood termites (e.g., pellets, damaged wood) be removed or covered (SPCB, 2021). However, inspectors or PMPs are not required remove this evidence themselves. Drywood termite pellets, termite wings, and even dead **alates** can remain in structures for years. Subsequent inspectors may encounter this evidence and possibly recommend additional treatments. Many inspectors visibly mark the locations where there is evidence of termites. Additionally, inspection and completion tags must be posted in a structure by PMPs (Section 1996.1, SPCB 2021). The inspection tag provides information about the firm that inspected the structure. The completion tag provides the firm's name, date of completion, trade name of the chemical, and active ingredients or method used to treat the wood-destroying organisms. This provides future inspectors with valuable information when conducting new inspections.

> 113. **FINDING:** Evidence of termites can persist for years if not removed following treatment. This can lead to new inspectors mistaking remnants of previous infestations for a current one that requires treatment.

> 114. **CONCLUSION:** Removing or covering of evidence of drywood termite activity is essential following either whole-structure or localized treatments. The emergence of new evidence after treatment will assist future inspectors in determining whether previous treatments were effective and if new treatments are necessary.

> 115. **CONCLUSION:** The Structural Pest Control Act would be improved by requiring that pest management professionals remove or cover evidence of drywood termites after treatment.

Property Owner Decision-Making

While recommendations or even pressure from PMPs are influential, ultimately the decision to use alternative treatments or SF fumigation resides with the home or property owner. The socioeconomic and cultural factors that influence an owner's choice among the various pest management options for drywood termites have never been directly evaluated. Consequently, there is no research to help understand why an owner chooses fumigation as the treatment strategy and the barriers for adopting alternative treatments.

The threat and fear of damage to what is often a person's most valuable asset—their home—likely influence the decision to choose SF fumigation over alternative control methods. In a survey of Dutch homeowners, respondents who were particularly concerned about insect pests that damage structures were more likely to purchase pest control services (Schoelitsz et al., 2018). Multiple surveys indicate that as the perceived threat to human health or property increases, so does the likelihood of homeowners seeking pest control services (Bhandiar, 2003; Schoelitsz et al., 2018). Furthermore, the likelihood of purchasing a pest control contract increases with higher home values (Bhandari, 2003).

The ability to act on this perceived threat may be influenced by a property owner's financial resources and interest in building maintenance. For example, a study of Louisiana homeowners found that their willingness to purchase a contract for subterranean termite control increased significantly with higher pre-tax annual income (Bhandari, 2003). Only 26% of respondents with annual incomes less than $20,000 purchased contracts, compared to 77% of respondents with annual incomes greater than $20,000. While there are no data available about the rates at which heat treatments are chosen over SF fumigation in California, the higher costs of heat treatments may pose an additional barrier to the adoption of this alternative, even in circumstances where the structures are amenable to heat treatments (heat treatments cost an average of $5,000, while SF fumigation costs approximately $2,500). Similarly, some property owners may not have the desire or means to conduct adequate building maintenance that might stave off infestations and reduce the need for fumigations.

Only with whole-structure treatments can a structure be certified as pest-free, and studies show that such guarantees are important to homeowners. In the survey of Louisiana homeowners, respondents indicated that treatment success, guarantee, and quality of service were the most important criteria for contracting subterranean termite control services (Bhandari, 2003). One important limitation to this research on homeowner preferences is that it assumes the homeowner is the primary occupant. These preferences could be significantly different if the property owner leases out the property, and preferences of occupants and the property owner may differ. Legally, this decision resides with the property owner. Research on indoor pests in low-income and public housing suggests that renters dislike the pests but see the problem as a one shaped by disinvestment and poor maintenance which could be redressed through public policy (e.g., requirements for regular maintenance) rather than pesticides (Biehler et al., 2019). Other drivers for the continued use of SF fumigation could include a general aversion and dislike for insect pests (cf. Schoelitsz et al., 2018). However, there are relatively few surveys focused specifically on the public's perceptions of wood-destroying organisms.

Although this has not been carefully studied, some individuals may have a stronger aversion to visible insect infestations than to the use of chemical fumigants, particularly when the immediate discomfort or perceived threat posed by pests outweighs concerns about potential chemical exposure. Indeed, while some are quite concerned with the potential of chemical exposure and may shun SF fumigation, an abiding idea that chemicals are perfectly safe—"better living through chemicals"—may also pose a barrier to adoption (Harrison, 2011).

A homeowner or property owner may select SF fumigation because it is more straightforward, less destructive, and provides a certainty that localized treatments cannot guarantee. When the drywood termite infestations extend into inaccessible areas, the PMP is legally required to expose the infested wood if localized treatments are used (SPCB, 2021). This may require the removal of sheetrock, stucco, flooring, facia, and other surfaces obscuring the infested wood. Extrapolating from agricultural research, pest treatments that are more certain and less complex to implement tend to prevail (Uekotter, 2014; Guthman, 2019).

116. **FINDING:** No studies have been conducted to determine which factors influence homeowners and property owners when deciding from among alternatives to control drywood termite infestations. Research on other indoor pests suggests that socioeconomic factors affect the ability to conduct adequate building maintenance (such as wood replacement) to hinder infestation.

117. **CONCLUSION:** Efforts to encourage broader adoption of alternatives to sulfuryl fluoride fumigation would greatly benefit from sociological research that examines the impact of various factors shaping the ability to prevent infestation as well as decisions to fumigate, including the role of socioeconomic status and policies and practices that might encourage preventive measures.

Real Estate Transactions

Another significant barrier to adoption of alternative treatments are the stipulations set by buyers, financial institutions, or other intermediaries involved in real estate transactions, as well as concerns with potential liability issues during these transactions. Approximately 70% to 75% of all fumigations in California result from inspections conducted during the purchase of property (T. Ineichen, pers. commun., 4/21/2025). This observation is supported by the correlation between housing sales data and the number of structures fumigated in California (***Section 1.6***). Such patterns have been identified elsewhere: A survey of Louisiana homeowners found that owners selling their property were more likely to contact PMPs than those not selling (Bhandari, 2003). Loan agencies such as the Veterans Administration and the Federal Housing Administration require that the structure be certified pest free as a condition of the loan (Reyes, 2019). Most lending agencies require a termite inspection (SPCB, 2025). Most real estate agents in California recommend a wood-destroying organism inspection, and advice to do so appears in numerous guides for first-time home buyers (Reyes, 2019; Marsh, 2025; Real Estate, 2025; US Realty Training, 2025). Although the actual number of homes fumigated with SF because of real estate transactions is unknown, the data could be derived from inspection reports and notices of work completed filed with the SPCB. Nor is there research on how property owners and homeowners process information from structural inspection reports, PMPs, and external sources. Without understanding these dynamics, it will be difficult to propose new approaches to increase the current level of acceptance of alternative treatments.

118. **FINDING:** Loan agencies and other financial institutions typically require that structures be certified pest free as part of real estate transactions. Such stipulations present barriers to the adoption of fumigant alternatives as long as sulfuryl fluoride fumigation and heat treatment are the only treatments capable of meeting that standard.

Limited Whole-Structure Treatment Options

As discussed in ***Section 4.2***, localized treatments are the most popular choice for targeting drywood termite infestations in California. Therefore, there is reason to believe that when fumigations do occur, it is usually in situations where termite infestations cannot be effectively managed by localized treatment. Heat treatment is the only other whole-structure option available, but it is significantly more expensive and not suitable for all structures. Consequently, a barrier to the adoption of fumigation alternatives is the lack of other effective, cost-efficient, and widely available whole-structure treatments.

By the same token, the continued regulatory approval of SF fumigation may be the most significant barrier to the adoption of heat treatment or development of other treatments. As studies of agricultural fumigants have shown, growers are less inclined to experiment with non-chemical alternatives when familiar and effective chemicals remain available (Harrison, 2011; Guthman, 2019). The strategy referred to as "technology-forcing environmental regulation" has proven to be an effective regulatory tactic in the development of alternative treatments. Technology-forcing involves setting regulatory standards beyond current or usual technological capabilities to enforce innovation (McGarity, 1994). The federal Clean Air Act of 1970 is an example of this strategy, leading to the innovation of the catalytic converter and a dramatic reduction in vehicle emissions. The mere possibility that SF fumigation might be banned or severely restricted in Europe and the United States following the discovery of its potency as a greenhouse gas has spurred innovative research. For example, in 2018, Douglas Products and the USDA Agricultural Research Service began conducting research to develop technology that could "scrub" (or filter out) SF from the exhaust of large, fumigated cargo containers (***Section 1.5***). (H. Kern, pers. commun., 5/5/2025).

The existing state and federal regulations on SF fumigation have not yet been sufficient to drive industry to invest in developing other viable alternatives to treat whole structures. As discussed in Chapter 3, research into alternatives for wood-destroying insects generally, and drywood termites specifically, has been sporadic and limited. The reasons for this are numerous. Most importantly, developing and marketing new pesticides is a costly endeavor, and the market for products specifically targeting drywood termites is small.

> 119. **FINDING:** Regulatory standards that exceed the capabilities of currently available technologies can drive investment in research and development.

> 120. **CONCLUSION:** The mere potential for regulation can drive innovation, but thus far existing regulations have been insufficient to incentivize the investment required to develop other viable alternatives to whole-structure SF fumigation.

Section 4.4: Promoting Acceptance and Incentivizing Adoption of Fumigant Alternatives by Property Owners

Consumers must navigate through unfamiliar information to select a pest control option following a wood-destroying pests and organisms inspection report completed in California. The inspection provides information concerning structural deficiencies, insect and fungal pests, and conducive conditions for pest problems. In addition, the report provides primary and secondary recommendations, as well as costs to control and rectify the problems. The socio-logical and economic factors that affect treatment decisions for wood-destroying organisms have not been studied and are unknown.

Several surveys of homeowners indicate that information provided by PMPs is important in a consumer's selection of pest services (Bhandari, 2003; Schoelitsz, et al., 2018). The greater the threat to human health or property, the more likely consumers are to request pest control services (Schoelitsz et al., 2018). In general, consumers expect quality service and resolution of a pest problem at a reasonable cost (Bhandari, 2003).

The PMP's acceptance and promotion of alternative strategies to SF fumigation depend on the effectiveness, concerns about toxicity, and economic viability of these treatments. Limited information exists regarding the effectiveness of heat, Electro-Gun, microwave, and some localized chemical treatments (***Section 2.7*** – ***Section 2.10***). Better data on the long-term results of these treatments could encourage PMPs to incorporate them into their existing pest management programs. Little data exist on the actual costs of alternative treatments and fumigations to the consumer and the profitability of those treatments for the PMPs.

> 121. **FINDING:** The selection of alternative treatment methods by home and property owners depends, in part, upon the knowledge and information provided by the inspectors and field representatives.

> 122. **FINDING:** Pest management professionals lack information regarding the effectiveness and viability of many of the alternative treatment methods.

> 123. **CONCLUSION:** The lack of information available to pest management professionals regarding alternative treatments may limit the adoption of these methods, underscoring the importance of improving industry access to up-to-date research and guidance on these alternatives.

Patterns of Urban and Suburban Development

To the extent that consumers are more likely to use alternative treatments when the risks of structural damage are low, the broader ecological and economic conditions that lead to more structural pests are an important barrier to the adoption of alternatives. California has the largest urban population in the United States with nearly 37.2 million residents, of which 94% now live in urban centers. To accommodate this large urban population, there are 14.7 million housing units. The occupied housing units can be further broken down into 7.66 million owner-occupied homes and 5.98 million rentals. Many of these housing units used wood products in their construction. Southern California has one of highest densities of wooden homes in the United States. These wooden structures also have the highest infestation rates of western drywood termites (*I. minor*).

Wood-destroying insects, both native and invasive, are increasingly being detected in California. Because of its position between two vast industrial centers, the East Coast and Asia, California is vulnerable to invasive pest introductions. Additionally, as stated in Chapter 1, development into the state's more arid environments is increasing the prevalence of wood-destroying insects, which is likely to worsen with global warming. Global warming also adds to the complexity of solving pest problems that include the need to protect people, homes, and home contents, as well as having minimal environmental impact.

> 124. **FINDING:** California has high urban density and many homes constructed of wood, making them more susceptible to western drywood termites and other wood-destroying insects.

> 125. **FINDING:** Climate change and new residential construction in arid areas is likely to increase drywood termite infestations.

> 126. **CONCLUSION:** To reduce the need for SF fumigation, regulatory agencies could incentivize or mandate the use of building materials less subject to infestation in new construction while also encouraging maintenance of existing wood structures.

Section 4.5: Disseminating Information to Potential Users

Surveys of urban residents provide insight concerning their attitudes and perceptions of pests inside and outside the home. The surveys rarely identified specific insect pests or control measures, especially the control of wood-destroying organisms. Most of the surveys were conducted prior to widespread use of the internet and social media platforms.

Frankie & Levenson (1978) surveyed residents of Dallas and College Station, Texas, regarding their attitudes and practices toward insect problems and insecticide use. Approximately 50% of the respondents obtained information regarding the pest problem from PMPs. Only 20% of the respondents relied on printed materials. Byrne & Carpenter (1983) conducted a telephone survey of 1,117 Arizona residents regarding the use of pesticides and other control strategies to control urban pests. Respondents relied on friends (54%), PMPs (37%), pesticide retailers (21%), and university personnel (7%) for information regarding their pest problems. A telephone survey of 447 homeowners in Minneapolis-St. Paul, Minnesota, was conducted to assess their attitudes about arthropods (Hahn & Ascerno, 1991). Their sources of pest information included the University of Minnesota (22.5%), lawn and garden stores (15.0%), and PMPs (12.5%). An online survey with 263 Dutch respondents indicated that their perceived tolerance or threshold levels of pests was a driver for making decisions about pest control services (Schoelitsz et al., 2018). Respondents rated 12 sources of information about pest management. The most trusted source was PMP websites, followed by PMPs themselves. Label information and salespeople were rated slightly lower but similarly. Family members ranked next, with science institution websites, local government websites, online forums, and books all receiving similar ratings. Local government officials, neighbors, newspapers and television, and scientific institutions were rated as the least-trusted sources. Providing a different perspective than surveys, a multilocal study of pest perceptions in the Northeast United States found that community members saw their pest problems as ecological (i.e., contextual) and could not be addressed on a structure-by-structure basis, effectively shunning the method of individual education as a way of managing infestations (Biehler et al., 2019).

127. **FINDING:** Property owners rely heavily on pest management professionals, their websites, and inspectors for information regarding structural pests and their control.

128. **FINDING:** Written materials are not widely used by the public.

Continual training and education for PMPs is an important component of the Structural Pest Control Act. The Act requires field representatives complete 16, 20, or 24 hours of continuing education over a three-year period, depending on the number of branches in which they are licensed (SPCB, 2021). Of the required hours, 2 hours of integrated pest management training are required for representatives engaged in treatment methods beyond SF fumigations. A minimum of 8 hours must be completed through approved courses covering the rules and regulations of the Structural Pest Control Act or those of structural pest control agencies. Education credits can be earned from a variety of sources, including educational courses, professional meetings, technical seminars, and association meetings provided they are approved by the SPCB.

The California Department of Pesticide Regulation (DPR) has supported demonstration projects focused on implementing and promoting a low-impact integrated pest management approach for PMPs to control Argentine ants (DPR, 2022). Workshops were conducted in

Northern and Southern California. These types of programs result in positive interaction between PMPs, university research and extension specialists, and state agencies.

> 129. **FINDING:** In California, field representatives of pest control companies are required to earn continuing education credits.

> 130. **CONCLUSION:** Workshops and training events could be avenues to promote the use of alternative treatments to control drywood termites.

Information regarding wood-destroying organisms in California and their control is scattered among different websites and agencies. While it is common to find publications addressing pests of specific crops, nurseries, and turf, similar publications or online information are rare for wood-destroying insects. Home and property owners need a comprehensive online source of information that covers the biology and recognition of wood-destroying organisms in California, inspection reports, treatment recommendations, options for controlling wood-destroying pests, and resources available. Short videos that detail each of the steps of whole-structure and localized alternative treatments possibly could be produced.

> 131. **FINDING:** Information regarding wood-destroying insects is limited, especially drywood termites.

> 132. **CONCLUSION:** A comprehensive online website that covers all aspects of the biology and control of drywood termites and wood-destroying beetles in California could help address this information gap.

> 133. **RECOMMENDATION:** The University of California Integrated Pest Management Program, California Department of Pesticide Regulation, California Structural Pest Control Board, and structural pest control industry should consider expanding their outreach program for the control of wood-destroying insects in California. This could include a clearing house for information for the public and industry, serving as a decision-support tool.

The University of California was established as a public land-grant university in 1868, with a mission to serve the public good through research, teaching, and extension. However, within the UC system there are only two research faculty and two integrated pest management advisors to cover the vast and varied indoor insect pest problems that include ants, bed bugs, cockroaches, and termites. These academic roles provide objective and research-based pest management decision-making tools for the public. Each of these pest systems on their own warrant additional research and extension resources. More UC research and extension capacity are needed, especially for drywood termites.

134. **FINDING:** California has only four academic appointments in the University of California system dedicated toward urban pest management research and extension.

135. **CONCLUSION:** The scale of urban pest management challenges in the state warrants additional appointments.

136. **RECOMMENDATION:** Resources should be directed toward creating and maintaining additional pest management research and extension personnel at the University of California to explore alternative control measures to fumigation, particularly for drywood termites, and to help educate the public about these alternatives.

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Glossary

Acute exposures: Contact with a chemical that occurs only once or for a limited period of time. Exposure to a chemical for a duration of less than 14 days.

Acute health outcomes: Short-term health effects that appear soon after exposure to a harmful substance or environmental factor, ranging from mild symptoms to severe, potentially life-threatening conditions.

Acute toxicity: Any poisonous effect that occurs within a short period of time following an exposure, usually 24–96 hours.

Alates: Winged, sexually mature individuals in a social insect colony that participate in dispersal and colony formation.

Ames test: A widely used genotoxicity screening test that uses specially engineered strains of *Salmonella* bacteria that cannot grow without a specific amino acid—typically histidine—unless a mutation restores that ability. When exposed to a potentially genotoxic chemical, an increase in the number of mutated *Salmonella* bacterial colonies indicates that the substance may cause genetic mutations.

Background levels: The typical amount of a chemical or substance present in the environment. These ambient concentrations can either be naturally occurring or due to human-made, non-site sources.

Biosolvent: A solvent derived from renewable biological sources that are biodegradable, less toxic, and environmentally friendly alternatives to traditional petroleum-based solvents.

Capsule suspension (CS): An insecticide formulation in which the active ingredient is suspended in a liquid within small capsules, enabling controlled release after application.

Chronic exposure: Contact with a substance or chemical over a long period of time. Repeated exposure to a chemical for more than 365 days (humans) and more than 90 days to 2 years (laboratory animals).

Chronic health outcomes: A long-term or persistent health effect that develops over time, often due to prolonged exposure to a harmful agent or an underlying condition.

Critical endpoints: Specific health effects or biological changes identified in human and animal studies that are most relevant for assessing risk and establishing safety standards. They typically represent the first adverse health effect, or an initial change that leads to the adverse effect, observed at the lowest administered dose or exposure level. Regulators use these endpoints to determine health-protective exposure limits.

Degradants: A substance formed from the chemical breakdown of a compound.

Dental fluorosis: A condition caused by excessive fluoride intake during tooth development, leading to changes in the appearance of tooth enamel.

Edema: Swelling caused by the accumulation of excess fluid in body tissues. Edema can occur in localized areas (such as the feet, ankles, or hands) or throughout the body.

Emulsifiable concentrate (EC): An insecticide formulation containing an active ingredient dissolved in oil, designed to create an emulsion with water for even distribution during application.

Environmental epidemiology: The study of how environmental exposures affect the health of populations. Environmental epidemiology looks for patterns, causes, and effects of health outcomes related to pollutants, chemicals, or other environmental factors. It helps identify associations between exposures (such as pesticides or air pollution) and diseases in real-world settings.

Environmental exposure: Any natural or synthetic chemical, biological, or physical substance that can potentially harm human health.

Frass: Insect excrement and debris produced by insects, particularly wood-destroying insects like termites and beetles. It often consists of fecal matter, chewed wood, plant fibers, or other organic materials.

Genotoxic: A substance that damages genetic material within a cell, potentially leading to mutations, cancer, or other genetic defects. Genotoxic substances can cause changes to DNA, which may result in chromosomal fragmentation, mutations, or inhibition of DNA repair mechanisms. Not all genotoxic substances are carcinogens (i.e., cancer-causing).

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). GWP is used to assess the relative impact of different greenhouse gases on climate change. Carbon dioxide has a GWP of 1, serving as the baseline, while other gases are rated based on their ability to trap heat. For example, methane has a GWP of 25, meaning it is 25 times more effective at trapping heat than CO_2 over 100 years.

Half-loss time: The time required for the concentration of a fumigant or pesticide in the environment to decrease by half, typically due to factors like degradation, dilution, or absorption by materials. This term is often used to describe the persistence of a fumigant in a treated area, helping to determine how long the substance remains effective or poses a risk.

Hydrolyzed: A chemical process in which a compound is broken down by water.

Intermediate exposures: Exposure to a chemical for 15–90 days in animals, unless specified elsewhere.

Lacrimator: An agent (or chemical) that irritates the eyes, causing excessive secretion of tears.

Lethal accumulated dose (LAD): A measurement of the total amount of a fumigant that accumulates over time in the air within a fumigated structure that is sufficient to cause lethal effects in a target organism. LAD takes into account both the concentration of the substance and the duration of exposure. When expressed as LAD99, it refers to the accumulated dosage required to cause death in 99% of the target population.

Modified atmosphere: An environment where the natural composition of gases (such as oxygen, carbon dioxide, and nitrogen) has been altered. In pest management, modified atmospheres may reduce oxygen levels or increase carbon dioxide to control infestations without chemicals.

Mouse lymphoma assay: A laboratory test used to detect whether a substance can cause genetic mutations. The assay exposes cultured mouse lymphoma cells to a chemical and then measures changes in their DNA that affect cell survival or growth. It is commonly used in regulatory toxicology as part of a standard battery of genotoxicity tests.

Neotenic: Sexually mature individuals in a social insect colony that retain juvenile characteristics and develop reproductive capabilities without undergoing complete metamorphosis, helping to sustain or expand colonies when primary kings or queens are absent or insufficient.

Ozone: A highly reactive gas made up of three oxygen atoms (O_3), occurring both naturally and as a result of human activities. In Earth's upper atmosphere, or stratosphere, ozone helps to absorb and protect organisms against ultraviolet (UV) rays from the sun. Ground-level ozone is a harmful air pollutant created when volatile organic compounds interact with nitrogen oxides in the presence of sunlight. Ground-level ozone is a major component of smog.

Pseudergate: Drywood termites lack true workers (sterile individuals). Drywood termite workers are called pseudergates ("false workers"), which lack wing buds. They develop from earlier instars that are often referred to as larvae (even though termites go through simple metamorphosis). Pseudergates are not sterile nor a terminal caste. Therefore, they maintain the capability of molting into a soldier, a supplementary reproductive (neotenic), or an alate.

Radiative forcing: A measure of the influence a factor (like a greenhouse gas or aerosol) has on the balance of incoming and outgoing energy in the Earth's atmosphere. The radiative forcing value of a gas depends on its concentration in the atmosphere, the wavelengths at which the gas absorbs and emits radiation, and how effectively the gas absorbs radiation at those wavelengths.

Register (a pesticide): The formal process by which a regulatory agency reviews scientific data on a pesticide's composition, efficacy, and potential risks to human health and the environment, and authorizes its sale, distribution, and use under specified circumstances.

Restricted-use pesticide (RUP): A pesticide classified by the U.S. Environmental Protection Agency as posing a higher risk to human health or the environment. Due to this risk, RUPs can only be purchased and applied by certified PMPs or individuals under their direct supervision. They are not available for purchase by the general public.

Risk assessment: A process intended to calculate or estimate the risk to a given target organism, system, or population, including the identification of uncertainties, following exposure to a particular agent. A risk assessment considers the inherent characteristics of the agent of concern as well as the characteristics of the specific target system. The risk assessment process includes four steps: hazard identification, hazard characterization, exposure assessment, and risk characterization. It is the first component in a risk analysis process.

Risk factor: Characteristics, conditions, or exposures that increase the likelihood of developing a disease or experiencing a harmful health effect. Risk factors can be environmental (e.g., chemical exposure), biological (e.g., age, genetics), or behavioral (e.g., smoking) and are important for evaluating vulnerability in public health and toxicology studies.

Suspended concentrate: An insecticide formulation in which the active ingredient is suspended in water to prevent settling and ensure uniform application.

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.

Toxicology: The study of the harmful effects of chemicals on humans or animals.

Trail pheromone: A chemical path left by an insect, typically a social species like ants or termites, to guide others toward a specific location such as a food source or nest. These trails are created using pheromones—chemical signals that influence the behavior of other members of the species.

Trophallaxis: A process that involves the direct ingestion by one individual of material excreted, secreted, or regurgitated by another. Trophallaxis is common in social insects like termites, ants, and bees. In pest control research, trophallaxis is significant because it can influence how insecticides or other treatments spread within a colony.

Unscheduled DNA synthesis assay: A laboratory test used to detect DNA repair activity following damage, serving as an indicator of a substance's genotoxic potential. This assay measures DNA synthesis that occurs outside the normal process of cell replication—hence, "unscheduled." When a cell's DNA is damaged by a chemical or radiation, repair mechanisms are activated, and new DNA is synthesized at the damage site. Researchers track this process to determine whether a substance causes DNA damage that triggers repair.

Appendix I. Wood-destroying Insect Inspection Report

The wood-destroying insect inspection report retained by a pest control firm for 3 years in accordance with the California Structural Pest Control Board regulations (SPCB, 2024a).

WOOD DESTROYING PESTS AND ORGANISMS INSPECTION REPORT

Building No.	Street	City	Zip	Date of Inspection	Number of Pages

Ordered by:	Property Owner and Party of Interest:	Report sent to:

COMPLETE REPORT ☐ LIMITED REPORT ☐ SUPPLEMENTAL REPORT ☐ REINSPECTION REPORT ☐

General Description:	Inspection Tag Posted:
	Other Tags Posted:

An inspection has been made of the structure(s) shown on the diagram in accordance with the Structural Pest Control Act. Detached porches, detached steps, detached decks and any other structures not on the diagram were not inspected.

Subterranean Termites ☐ Drywood Termites ☐ Fungus / Dryrot ☐ Other Findings ☐ Further Inspection ☐

If any of the above boxes are checked, it indicates that there were visible problems in accessible areas. Read the report for details on checked items.

Inspected by: ______________________ **State License No.** __________ **Signature** ______________________

You are entitled to obtain copies of all reports and completion notices on this property reported to the Structural Pest Control Board during the preceding two years. To obtain copies contact: Structural Pest Control Board, 2005 Evergreen Street, Suite 1500, Sacramento, CA 95815.

NOTE: Questions or problems concerning the above report should be directed to the manager of the company. Unresolved questions or problems with services performed may be directed to the Structural Pest Control Board at (916) 561-8708, (800) 737-8188 or www.pestboard.ca.gov. 43M-41 (REV. 04/2015)

Appendix II. Work Completed Notice

The work completed notice retained by a pest control firm for 3 years in accordance with California Structural Pest Control Board regulations (SPCB, 2024b).

STANDARD NOTICE OF WORK COMPLETED AND NOT COMPLETED

NOTICE - All recommendations may not have been completed - See below - Recommendations not completed.
This form is prescribed by the Structural Pest Control Board.

Building No. Street City Zip	Date of Completion

Ordered By:	Property Owner and/or Party of Interest:	Completion Sent To:

The following recommendations on the above designated property, as outlined in Wood Destroying Pests and Organisms Inspection Report dated ____________________ have been and/or have not been completed.

Recommendations completed by this firm that are in accordance with the Structural Pest Control Board's Rules and Regulations:

Recommendations completed by this firm that are considered secondary and substandard measures under Section 1992 of the Structural Pest Control Board's Rules and Regulations including person requesting secondary measure:

Cost of work completed:

Cost: $ ________________
Inspection Fee: $ ________________
Other: $ ________________
Total: $ ________________

Recommendations not completed by this firm:

Estimated Cost $ ________________

Remarks:

Signature ________________________

You are entitled to obtain copies of all reports and completion notices on this property reported to the Board during the preceding two years upon payment of a search fee to: Structural Pest Control Board, 2005 Evergreen Street, Suite 1500, Sacramento, California, 95815.
NOTE: Questions or problems concerning the above report should be directed to the manager of this company. Unresolved questions or problems with services performed may be directed to the Structural Pest Control Board at (916) 561-8708, (800) 737-8188 or www.pestboard.ca.gov. 43M-44 (Rev.10/01)

Appendix III. Standard Structural Fumigation Log

STANDARD STRUCTURAL FUMIGATION LOG

ADDRESS OF PROPERTY	CITY	DATE OF FUMIGATION
PRIME CONTRACTOR NAME AND ADDRESS PR# / BR#	SUBCONTRACTOR NAME AND ADDRESS (if applicable) PR# / BR#	
OWNER/AGENT NAME AND ADDRESS		FIRE DEPT. NOTIFIED (DATE) (HOUR)
PROPERTY DESCRIPTION		C.A.C. NOTIFIED (METHOD)(DATE)(HOUR)
NOTES / COMMENTS		

SECTION 1 – FUMIGANT RELEASED

TARGET PEST	WARNING AGENT	CUBIC FEET	OUNCES USED
FUMIGANT / E.P.A. REGISTRATION NO.	SEALING METHOD	DATE/TIME GAS INTRODUCED	
	CYLINDER SERIAL NO.	WT. BEFORE INTRO.	POUNDS APPLIED
WIND M.P.H. AIR TEMP	CYLINDER SERIAL NO.	WT. BEFORE INTRO.	POUNDS APPLIED
	CYLINDER SERIAL NO.	WT. BEFORE INTRO.	POUNDS APPLIED
EXTRAORDINARY PRECAUTIONS		TOTAL POUNDS	

☐ FUMIGUIDE B ☐ FUMIGUIDE Y ☐ VIKANE CALCULATOR ☐ FUMICALC CALCULATOR ☐ OTHER ____________

DOSAGE FACTOR	____________	UNDER SEAL	____________
TARP CONDITION	____________	TEMPERATURE	____________
SEAL CONDITION	____________	HOURS EXPOSURE	____________
WIND (MPH)	____________	MONITOR JOB (YES / NO)	____________
VOLUME			

CREW MEMBER(S) FULL NAME(S):

WAS REQUIRED SAFETY EQUIP. PROVIDED? YES ☐ NO ☐	LICENSEE RELEASING FUMIGANT LICENSE NO. SIGNATURE

SECTION 2 – VENTILATION COMMENCED

AERATION COMMENCED: DATE TIME	TARP / SEAL CONDITION

CREW MEMBER(S) FULL NAME(S):

WAS REQUIRED SAFETY EQUIP. PROVIDED? YES ☐ NO ☐	LICENSEE COMMENCING VENTILATION LICENSE NO. SIGNATURE

SECTION 3 – RELEASED FOR OCCUPANCY

TESTING DEVICE USED:	PROPERTY CERTIFIED SAFE FOR RE-ENTRY: DATE TIME

CREW MEMBER(S) FULL NAME(S):

Appendix IV. Personal Communications

- Thomas Atkinson, PhD (Assistant Entomologist, Assistant C.E. Specialist, UC Riverside, *Emeritus*)
- Doug Belle (Director of Sales, Cardinal Professional Products)
- John Berggren (Operations Manager, Omega Termite & Pest Control)
- Dong Hwan Choe, PhD (Professor, Cooperative Extension Specialist, UC Riverside)
- Tom Ineichen (Lead Special Investigator, Field Operations and Enforcement, Structural Pest Control Board, California Department of Consumer Affairs)
- Heather Kern (Vice President of Global Marketing, Douglas Products)
- Jeff Lloyd (Senior Vice President, Innovation and Sustainability, Nisus Corporation)
- Ellen Thoms (scientist, Dow AgroSciences, *Retired*)
- David Wadleigh (President, Mega Fume Inc.)
- Lee Whitmore (President, Quality Pest Services, Inc.)

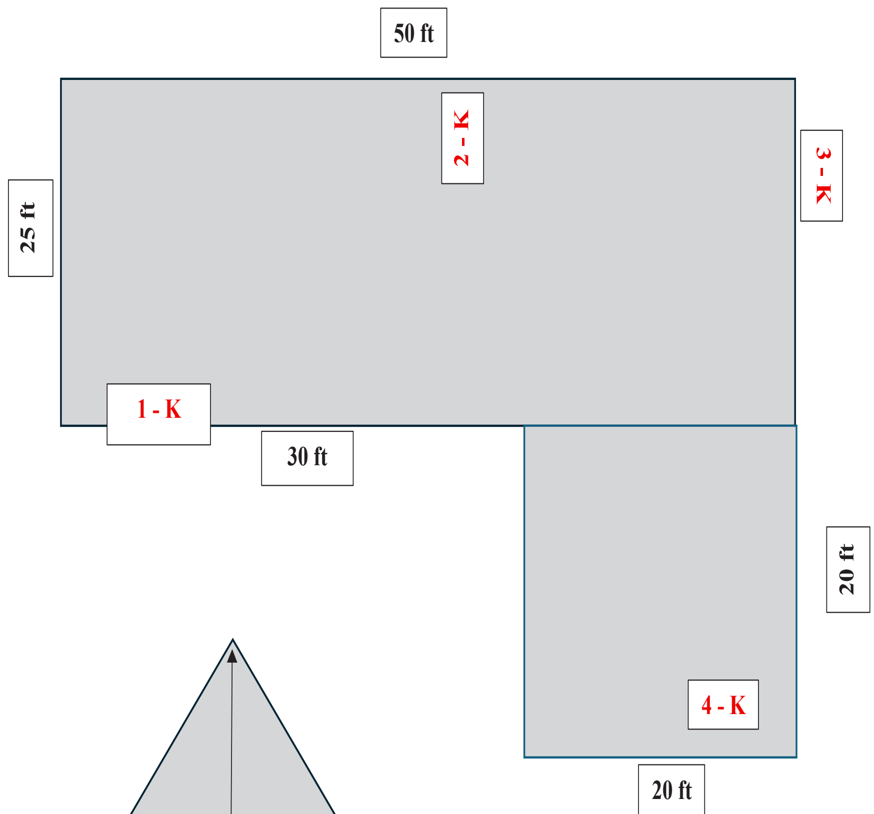
Appendix V. Effects of Temperature and Underseal SF Amount of Sulfuryl Fluoride Required to Fumigate a Hypothetical Structure

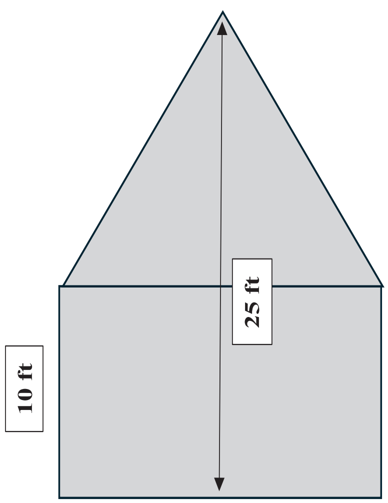
Appendix Table 1. Effects of temperature and underseal on the amount of sulfuryl fluoride required to fumigate a hypothetical structure.

Dosage Factor	1	1	1	1	1	1	1	1
Tarp Condition:	Good	Good	Good	Good	Good	Good	Good	Good
Seal Condition:	Good	Good	Good	Good	Good	Good	Good	Good
Underseal:	Slab	Slab	Slab	Slab	Slab	Slab	**Sandy Loam**	**Slab**
Wind Speed:	5 mph	5 mph	5 mph	5 mph	5 mph	5 mph	5 mph	5 mph
Structure Volume:	29,000	29,000	29,000	29,000	29,000	29,000	29,000	29,000
Fumigation Time:	20 hours	20 hours	20 hours	20 hours	20 hours	20 hours	20 hours	20 hours
Temperature:	**50° F**	**55° F**	**60° F**	**65° F**	**70° F**	**75° F**	75° F	75° F
Monitor Job:	No	No	No	No	No	No	No	No
Calculated Outputs								
Estimated Half-Loss Time:	27.6 hours	27.6 hours	27.6 hours	27.6 hours	27.6 hours	27.6 hours	4.6 hours	27.6 hours
Target Dosage:	255.5 oz/mcf	186.1 oz/mcf	144.7 oz/mcf	117.4 oz/mcf	97.8 oz/mcf	83.1 oz/mcf	83.1 oz/mcf	83.1 oz/mcf
Target Initial Concentration:	21.66 oz/mcf	15.78 oz/mcf	12.27 oz/mcf	9.95 oz/mcf	8.29 oz/mcf	7.05 oz/mcf	**17.55 oz/mcf**	**7.05 oz/mcf**
Total Gas	**39.22 lb**	**28.57 lb**	**22.21 lb**	**18.02 lb**	**15.01 lb**	**12.76 lb**	**31.77 lb**	**12.76 lb**
lb/1,000 cubic feet	1.35	0.99	0.77	0.62	0.52	0.44	1.1	0.44

Notes: Data provided courtesy of L. Whitmore and produced using a Fumiguide electronic calculator.
°F = degree(s) Fahrenheit
lb = pound(s)
mph = mile(s) per hour
oz/mcf = ounce(s) per 1,000 cubic feet

Appendix VI. Sample Structure with Drywood Termites





Dimensions
Linear feet – 190
Square feet - 1650
Cubic feet – 29,437
Single story on slab construction
Evidence of drywood termites at

1 – facia board about 4-5 ft of damage
2 – two trusses with damage (3-4 ft each)
3 – Outdoor window framing about 6 ft
4 – 1 stud on garage wall- pellets and damage 8 ft

All the damage and boards are readily accessible

Appendix VII. CCST Study Process

For 37 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, Managing Director, Director of Science, and others, 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 (SC) 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 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.

Appendix VIII. 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 (retired)
- **Ganesh Raman, PhD,** California State University

Report Monitor

- **Tony Marks-Block, PhD,** CSU East Bay

Expert Reviewers

- **Dong-Hwan Choe, PhD,** UC Riverside
- **Caroline Cox,** Center for Environmental Health (retired)
- **Rashmi Joglekar, PhD,** UCSF
- **Becky Mansfield, PhD,** The Ohio State University
- **Siavash Taravati, PhD,** UC ANR UC Cooperative Extension, Riverside County
- **Changlu Wang, PhD,** Rutgers University
- **Lee Whitmore,** Quality Pest Services, Inc.
- **David Zilberman, PhD,** UC Berkeley

Appendix IX. List of FCRs

Chapter 1: Sulfuryl Fluoride as Structural Fumigant

Chapter 3: Research on Alternatives to Sulfuryl Fluoride

Chapter 4: Addressing Barriers and Increasing Adoption of Fumigant Alternatives

Appendix X. Steering Committee Members

The Steering Committee (SC) oversees the report authors, reaches conclusions based on the findings of the authors, drafts recommendations, and writes and 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 Polytechnica State University-San Luis Obispo
- **Alan S. Kolok, PhD (Co-Chair)**, University of Idaho (emeritus)
- **Christine L. Carroll, PhD**, California State University, Chico
- **Julie Guthman, PhD,** University of California, Santa Cruz (emerita)
- **Vernard Lewis, PhD,** University of California, Berkeley (emeritus)

Gerald J. Holmes, PhD
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 NC 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, PhD
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, PhD
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 in part because of the interdisciplinary structure of the college, which she sees as an opportunity to build cross-disciplinary collaborations.

Vernard Lewis, PhD
Professor Emeritus, Cooperative Extension Specialist
UC Berkeley

Dr. Vernard Lewis earned his B.S., M.S., and Ph. D. degrees at the University of California, Berkeley in Entomology. He is an Emeritus Professor of Cooperative Extension in the Rausser College of Natural Resources. He is professionally known for his research on termites and other structural and household insect pests. Dr. Lewis was also a member of the United Nations Global Termite Expert Group and is a recent inductee into the Pest Management Hall of Fame. Dr. Lewis has travelled to over thirty-five countries as a researcher, consultant, and insect pest troubleshooter. He continues to stay involved in activities that promote the recruitment and retention of underrepresented minorities and women in science.

Julie Guthman, PhD
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 XI. Author Biosketches

Report Authors:

- **Michael Rust, PhD,** University of California, Riverside
- **Kimberly Parra, MPH, PhD,** Harvard T.H. Chan School of Public Health

Michael K. Rust
Distinguished Professor of Entomology and Graduate Division
University of California, Riverside
Michael.rust@ucr.edu

EDUCATION

1975	**Ph.D., Entomology** University of Kansas, Lawrence KS
1973	**M.A., Entomology** University of Kansas, Lawrence KS
1970	**BA Biology** Hiram College, Hiran OH

CURRENT AND PAST POSITIONS

2012-present	Distinguished Professor and Entomologist, Department of Entomology and the Graduate Division, UC Riverside
2003-2012	Professor and Entomologist, Department of Entomology, UC Riverside
2000-2003	Professor and Entomologist, Department of Entomology, UC Riverside Director for Center for Exotic Pest Research; Associate Director, University of California Integrated Pest Management Program
1997-1999	Professor and Entomologist, Department of Entomology, UC Riverside
1983-1986	Associate Professor and Associate Entomologist and Head, Division of Economic Entomology, UC Riverside
1975-1982	Assistant Professor and Assistant Entomologist, Department of Entomology, UC Riverside

HONORS AND AWARDS

2025	Entomological Society of America Pacific Branch Entomology Teamwork Award
2010	IPM Team Award 2010, National Entomological Society of America
2010	IPM Team Award 2010, Pacific Branch of the Entomological Society of America
2009	Lifetime Achievement Award – Association of Applied IPM Ecologists
2007	Pest Control Hall of Fame 2007
2008	Entomological Society of America Recognition Award in Urban Entomology
2002	PCT/Zeneca Leadership Award Fellow of American Association for the Advancement of Science
2001	Fellow of the Entomological Society of America
2000	*Pest Control Technology's* 25 Most Influential People in the Industry Mallis Recognition Award, National Conference on Urban Entomology
1999	UC Presidential Scholar in Entomology
1994	Excellence in Entomology Award - California Association, American Registry of Professional Entomologists W.W. Woodworth Award; Pacific Branch, Entomology Society of America
1993	Distinguished Achievement Award in Urban Entomology, Entomology Society of America
1991	Outstanding Urban Entomologist Award Recipient; Pacific Branch Entomology Society of America

KIMBERLY L. PARRA (she/her)

klparra@hsph.harvard.edu
Phone 831-710-1781

EDUCATION
Ph.D., Epidemiology & Biostatistics, University of Arizona, Zuckerman College of Public Health, Tucson AZ.
M.P.H., University of Arizona, Zuckerman College of Public Health, Tucson AZ
B.A., University of California, Berkeley, College of American Studies, emphasis in Public Health, Berkeley, CA.

POSTDOCTORAL FELLOWSHIP
NIH-NIEHS T32 Postdoctoral Fellow, Environmental Epidemiology, 2023 – Present.
Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA.

RESEARCH EXPERIENCE

University of Arizona - Graduate Research Associate **2016 – 2023**

Environmental Health Sciences **2018 – 2023**
PI: Melissa Furlong, PhD. Arizona Prenatal Environment And Reproductive Outcomes Study (AZPEARS Study)
PI: Paloma Beamer, PhD. "*El Trabajo no te Debe Dañar: Reduction of Hazardous Exposures in Small Businesses through a Community Health Worker (CHW) Intervention*".
Obstetrics & Gynecology Dept., College of Medicine, **2020 – 2022**
PI: Debra Guinn, MD. Arizona Prenatal Infection with SARS-COV-2 and Childhood Health and Immune Outcomes Study (AZ PISTACHIO Study)
Epidemiology & Biostatistics Dept., **2018 – 2020**
PI: Heidi Brown, PhD. Comparative study of Chagas disease seroprevalence in pregnant women from endemic regions attended at Hospital General de Mexico and Johns Hopkins Bayview, Baltimore, MD and Mexico City, MX.
Health Promotion Science Dept. **2016 – 2018**
PI: Velia Leybas Nuño, PhD *Growing Girls*, after-school empowerment program.
PI: Samantha Sabo, DrPH. *Healthy Start Program*, CHW interventions.

University of California, Berkeley - Researcher **2010 – 2020**

Farmworker COVID-19 Study — **Field Manager** — **Summer 2020**
Center for Environmental Research and Children's Health (CERCH), PI: Brenda Eskenazi, PhD
COSECHA Study — **Co-Investigator** — **2015 – 2017**
Chamacos of Salinas Evaluating Chemicals in Homes & Agriculture Study, PI: Kim Harley, PhD
HERMOSA Study — **Community PI** — **2013 – 2015**
Health & Environmental Research on Makeup Of Salinas Adolescents, co-PI: Kim Harley, PhD
CHAMACOS Study — **Field Office Coordinator** — **2010 – 2016**
Center for the Health Assessment of Mothers and Children of Salinas, PI: Brenda Eskenazi, PhD

TEACHING EXPERIENCE

Certificate in College Teaching (2023), University of Arizona, Office of Instruction and Assessment.

Curriculum Fellow **2024 to Present**
- Harvard University, Department of Epidemiology, MPH Online Program.

Graduate Teaching Assistant **2018 – 2022**
- Basic Principles of Epidemiology, Graduate, Synchronous Online, Instructor: Sydney Pettygrove.
- Epidemiological Methods, Graduate, In-person, Instructor: Leslie Dennis.
- Introduction to Epidemiology Undergraduate, Instructors: Robin Harris (in-person) and Heidi Brown (online)

Select Guest Lecturer **2020 – 2023**
- Chronic Disease Epidemiology, Graduate: *"Environmental Epidemiology & Chronic Disease Risk."*
- Epidemiology Methods, Undergraduate: *"Study Design", "Bias & Confounding."*
- Health Promotion, Undergraduate "*Community-Based Participatory Research: Results from the Hermosa Study"*
- Graduate Seminars
  - Epidemiology: *"Ambient Pesticide Exposure and Gestational Diabetes."* Nov 2020
  - Environmental Health: *"Results from the Farmworker COVID-19 Study in the Salinas Valley."*

PEER-REVIEWED PUBLICATIONS

Parra KL, Farland LV, Harris RB, Beamer P, Fournier A, Ellsworth P, Furlong MA. 2024. Prenatal exposure to agricultural pesticide applications and gestational diabetes mellitus in the AzPEARS population-based study (2014-2020). *Environmental Health Perspectives*. December 2024. *Under review.*

Parra KL, Farland LV, Harris RB, Toro M, Furlong MA. 2024. Neighborhood Deprivation and Gestational Diabetes Mellitus in AZ. *Paediatric and Perinatal Epidemiology*. December 2024. *In-press.*

Furlong MA, Paul KC, **Parra KL**, Fournier AJ, Ellsworth PC, Cockburn MG, Arellano AF, Bedrick E, Beamer PI, Ritz B. 2024. Pre-Conception And First Trimester Exposure To Pesticides And Associations With Stillbirth. *American Journal of Epidemiology*. July 2024. PMID: 39013781. DOI:10.1093/aje/kwae198.

Lothrop N, Sandoval F, Cortez I, Wagoner R, Lopez-Galvez N, **Parra K**, Wolf AM, Wertheim BC, Quijada C, Lee A, Griffin S, Bell M, Carvajal S, Ingram M, Beamer P. Studying full-shift inhalation exposures to volatile organic compounds (VOCs) among Latino workers in very small-sized beauty salons and auto repair shops. *Frontiers Public Health*. 2023 Dec 1;11:1300677. PMC10722412. DOI: 10.3389/fpubh.2023.1300677.

Parra KL, Harris RB, Farland LV, Beamer P, Furlong MA. Associations of prenatal agricultural farm work with fetal overgrowth and pregnancy complications in State of Arizona birth records. *Journal of Occupational and Environmental Medicine.* 2023 May 9. PMID: 37167931. DOI: 10.1097/JOM.0000000000002877.

Parra KL, Alexander GE, Raichlen DA, Klimentidis YC, Furlong MA. Exposure to air pollution and risk of incident dementia in the UK Biobank. *Environmental Research*. 2022 Feb 8. 112895. PMCID: PMC8976829. DOI:10.1016/j.envres.2022.112895.

Raichlen DA, Furlong MA, Klimentidis YC, Sayre K, **Parra KL**, Bharadwaj PK, Wilcox RR, Alexander GE. Association of physical activity with incidence of dementia is attenuated by air pollution. *Medicine & Science in Sports and Exercise*. 2022 Feb 7. PMCID: PMC9204780. DOI:10.1249/MSS.0000000000002888.

Guinn D, Wang DD, Furlong M, **Parra K**, Hashim SA, Ahmed M, Sprissler R, Oatmen K, Limesand S, Harris D. Hispanic ethnicity and low-income housing are associated with SARS-COV-2 infection in an Arizona birth cohort. *American Journal of Obstetrics and Gynecology.* 2022 Jan;226(1):S416–7 Epub 2021 Dec 23. PMCID: PMC8696793. DOI:10.1016/j.ajog.2021.11.692.

Parra KL, Alaofe HS, Ehiri JE, Nuño VL, Mazariegos M, Garcia B, Martinez E, Junkins A, Jolly P. Prevalence and Determinants of Underweight, Overweight, and Obesity: A Cross-Sectional Study of Sociodemographic, Dietary, and Lifestyle Factors Among Adolescent Girls in Jutiapa, Guatemala. *Food and Nutrition Bulletin*. 2021 June 22. 42(4), 502–519. PMCID: PMC8622352. DOI:10.1177/03795721211019638.

Lewnard JA, Mora AM, Nkwocha O, Kogut K, Rauch SA, Morga N, Hernandez S, Wong MP, Huen K, Andrejko K, Jewell NP, **Parra KL**, Holland N, Harris E, Cuevas M, Eskenazi B; CHAMACOS-Project-19 Study Team2. Prevalence and Clinical Profile of Severe Acute Respiratory Syndrome Coronavirus 2 Infection among Farmworkers, California, June-November 2020. *Emerg Infect Dis*. 2021 Mar 3:27(5). PMCID: PMC8084509. DOI:10.3201/eid2705.204949.

Smith AR, Kogut KR, **Parra K**, Bradman A, Holland N, Harley KG. Dietary intake and household exposures as predictors of urinary concentrations of high molecular weight phthalates and bisphenol A in a cohort of adolescents *Journal of Exposure Science & Environmental Epidemiology*. 2021 Feb 22. PMCID: PMC8380263. DOI:10.1038/s41370-021-00305-9.

Harley KG, **Parra K**, Camacho J, Bradman A, Nolan JES, Lessard C, Anderson KA, Poutasse CM, Scott RP, Lazaro G, Cardoso E, Gallardo D, Gunier RB. Determinants of pesticide concentrations in silicone wristbands worn by Latina adolescent girls in a California farmworker community: The COSECHA youth participatory action study. *Science ot the Total Environment.* 2019 Feb; 652:1022-1029. PMCID: PMC6309742. DOI:10.1016/j.scitotenv.2018.10.276.

Harley KG, Berger KP, Kogut K, **Parra K**, Lustig RH, Greenspan LC, Calafat AM, Ye X, Eskenazi B. Association of phthalates, parabens and phenols found in personal care products with pubertal timing in girls and boys. *Human Reproduction.* 2019 Jan 1;34(1):109-117. PMCID: PMC6295961. DOI:10.1093/humrep/dey337.

Berger K, Eskenazi B, Kogut K, **Parra K**, Lustig RH, Greenspan LC, Holland N, Calafat AM, Ye X, Harley KG. Association of Prenatal Urinary Concentrations of Phthalates and Bisphenol A and Pubertal Timing in Boys and Girls. *Environmental Health Perspectives*. 2018 Sep 11; 126(9):097004. PMCID: PMC6375461. DOI:10.1289/EHP3424.

Berger KP, Kogut KR, Bradman A, She J, Gavin Q, Zahedi R, **Parra K,** Harley KG. Personal care product use as a predictor of urinary concentrations of certain phthalates, parabens, and phenols in the HERMOSA study. *Journal of Exposure Science & Environmental Epidemiology*. 2018 Jan. PMCID: PMC6037613. DOI:10.1038/s41370-017-0003-z.

Gunier R, **Parra K**, Camacho J, Bradman A, Nolan J, Lessard C, Anderson K, Poutasse C, Scott R, Lazaro G, Cardoso E, Gallardo D, Harley K. Determinants of pesticide concentrations in silicone wristbands among adolescent Latina girls in the CHAMACOS study. *Environmental Science & Technology.* 2017 Nov. PMCID: PMC6309742. DOI:10.1016/j.scitotenv.2018.10.276.

Harley KG, Rauch SA, Chevrier J, Kogut K, **Parra K**, Trujillo C, Lustig RH, Greenspan LH, Sjödin A, Bradman A, Eskenazi B. Association of prenatal and childhood PBDE exposure with timing of puberty in boys and girls. *Environment International*, 2017 Jan. PMCID: PMC5308219. DOI:10.1016/j.envint.2017.01.003.

Tran V, Tindula G, Huen K, Bradman A, Harley KG, Kogut K, Calafat AM, Nguyen B, **Parra K**, Xiaoyun Y, Eskenazi E, Holland N. Prenatal Phthalate Exposure and 8-Isoprostane among Mexican-American Children with High Prevalence of Obesity. *Journal of Developmental Origins of Health and Disease*. 2017 Jan:1-10. PMCID: PMC5332297. DOI:10.1017/S2040174416000763.

Johnson MM, Deardorff J, **Parra K**, Alknon A, Eskenazi B, Shirtcliff E. Modified Trier Social Stress Test for Vulnerable Mexican American Adolescents. *Journal of Visualized Experiments*. 2016 Nov. PMCID: PMC561205. DOI:10.3791/55393.

Rowe C, Gunier R, Bradman A, Harley KG, Kogut K, **Parra K**, Eskenazi B. Residential proximity to organophosphate and carbamate pesticide use during pregnancy, poverty during childhood, and cognitive functioning in 10-year-old children. *Environmental Research*. 2016 Oct; 50:128-137. PMCID: PMC5207345. DOI:10.1016/j.envres.2016.05.048.

Madrigal, DS, Minkler, M, **Parra, K**, Mundo C, Gonzalez J, Jimenez, R, Harley, KG. Improving Latino Youths' Environmental Health Literacy and Leadership Skills Through Participatory Research on Chemical Exposures in Cosmetics: The HERMOSA Study. *International Quarterly of Community Health Education*, *36*(4), 231-240. 2016 Jul. DOI:10.1177/0272684X16657734.

Harley KG, Kogut K, Madrigal DS, Cardenas M, Vera IA, Meza-Alfaro G, She J, Gavin Q, Zahedi R, Bradman A, Eskenazi B, **Parra KL**. Reducing Phthalate, Paraben, and Phenol Exposure from Personal Care Products in Adolescent Girls: Findings from the HERMOSA Intervention Study. *Environmental Health Perspectives*. 2016 Mar. PMCID: PMC6404751. DOI:10.1289/ehp.1510514.

Mora AM, Arora M, Harley KG, Kogut K, **Parra K**, Hernández-Bonilla D, Gunier RB, Bradman A, Smith DR, Eskenazi B. Prenatal and postnatal manganese teeth levels and neurodevelopment at 7, 9, and 10.5 years in the CHAMACOS cohort. *Environment International*. 2015 Nov; 84:39-54. PMCID: PMC4570875. DOI:10.1016/j.envint.2015.07.009.

Sagiv SK, Kogut K, Gaspar FW, Gunier RB, Harley KG, **Parra K**, Villaseñor D, Bradman A, Holland N, Eskenazi B. Prenatal and childhood polybrominated diphenyl ether (PBDE) exposure and attention and executive function at 9-12years of age. *Neurotoxicol Teratol*. 2015 Nov-Dec;52(Pt B):151-61. PMCID: PMC5072748. DOI:10.1016/j.ntt.2015.08.001.

SELECT PRESENTATIONS & POSTERS

Society for Pediatric and Perinatal Epidemiologic Research (SPER) Virtual Meeting, Apr 2024. *Neighborhood Deprivation Index and GDM, and effect modification by Race in AZ*.

Arizona Reimagine Health Research Symposium (UA-ASU-NAU), Phoenix, AZ. Feb 2022. *Exposure to air pollution and risk of incident dementia in the UK Biobank*.

Society for Epidemiologic Research (SER) Virtual Meeting. Dec 2020. *Test re-test reliability of a self-reported reproductive history questionnaire among women of childbearing age*.

Carson Scholars Webinar: Impacts of Environmental Injustices on Health & Society, Oct 2020. *Tracing Pesticides from Womb to Birth in Arizona*. University of Arizona, https://youtu.be/RjKqqRedZdk

Binational Migration and Global Health Institute. *Comparative study of Chagas disease seroprevalence in pregnant women from endemic regions attended at Hospital General de Mexico and Johns Hopkins Bayview in Baltimore.* Oakland & Berkeley, CA, Jul 2019

American Public Health Association (APHA) Annual Meeting. *Reducing Latina girls' exposure to hormone disrupting chemicals in cosmetics: The HERMOSA Study*, New Orleans, LA, Nov 2014.

NIH-NIEHS, PEPH Webinar. *The HERMOSA Study: A Project to Investigate and Reduce Exposure to Endocrine Disrupting Chemicals from Beauty Products Used by Adolescent Girls, Empowering Our Youth to Address Environmental Public Health*. Sep 2013. www.niehs.nih.gov/research/supported/assets/docs/t_z/webinar_announcement_september_23_2013_508.pdf

PROFESSIONAL MEMBERSHIP & SERVICE

Society for Epidemiological Research (SER), Scientific Dissemination Committee Member
Society for Pediatric and Perinatal Epidemiologic Research (SPER)
International Society for Environmental Epidemiology (ISEE)
International Association for Population Health Science (IAPHS)
Carson Scholars, Advisory Board Member
Reclaiming STEM Institute

RELEVANT COMMUNITY EXPERIENCE

California State Assembly, 28th District	Fundraising & Volunteer Coordinator	2010 – 2012
MAOF-Salinas Migrant Program	Health Services Coordinator	2006 – 2008
Doctors on Duty Medical Clinics	Executive Analyst	2005 – 2006

SKILLS

Data Analysis: R, STATA, SEER, EpiInfo
Data Management: RedCap, Qualtrics, Open Science Framework
Community-Based Participatory Research
Science Communication
Bilingual: English/Spanish

Fumigant Use in California and an Assessment of Available Alternatives

Phase II Report on Structural Fumigation with Sulfuryl Fluoride

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