Review

Pesticides, wildfire suppression chemicals, and California wildfires: A human health perspective

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ABSTRACT

In the past few decades, the frequency and severity of wildfires in California has increased. The majority of studies on wildfire-related human health effects have focused on the criteria pollutants in smoke. However, there are other minor constituents of smoke that may impact human health, particularly in specific geographic regions in California. This review summarizes what we currently know about the contribution of pesticides and wildfire suppression chemicals to wildfire-induced human health effects. In California there is heavy use of pesticides in agricultural settings and at the urban interface. When wildfires burn land treated with pesticide, these chemicals and their combustion products are volatilized and can be inhaled by humans. These constituents can be transported long distances in smoke, although those at the highest risk for exposure are near the wildfire source. Toxicity of some pesticides by inhalation has been demonstrated, although the health effects of pesticide combustion products in smoke have not been characterized. In order to effectively fight wildfires, large volumes of wildfire suppression chemicals are used. Wildfire suppression chemicals include retardants, for long-term application, and foams, for short term application. Based on the available data, foams are more likely to have an impact on human health than retardants. Moreover, foams tend to be applied at the urban interface, while the retardants are generally applied in remote areas. Understanding the health effects of the compounds we choose to introduce into our environment and how they alter and are altered by extreme events like wildfires is an important consideration for fire and land management. Our investigation has uncovered that there are significant data gaps in this area.

INTRODUCTION

When wildfires burn, people immediately look toward the protection of their homes, property, and family. The harmful effects of breathing wildfire smoke are well documented. The major focus in public health studies has been the criteria pollutants ozone, carbon monoxide, and particulate matter. However, potential adverse health effects from other chemical constituents of smoke may be under-appreciated. Little consideration has been given to how human alteration of the environment can alter the toxic properties of wildfire emissions. This poses an important question: how are wildfires changed by the presence of pesticides and wildfire suppression chemicals? Recent reviews of human health effects focus on the inhalation of biomass smoke [1-3]. Our review will address the human health threat of pesticides and wildfire suppression chemicals during wildfires, and identify further data gaps in this area.

Episodic wildfires have plagued California and the arid western states since before European settlement [4]. In the last few decades, there has been a global

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increase in the length of wildfire seasons (18.7%) and in the frequency of these extended wildfire seasons (53.4%) [5]. The wildfire season in the western United States has increased by 78 days (64%) since the 1980s [6, 7]. The greatest regional increase in wildfire frequency over the past few decades have been in Northern California (18%) and the Northern Rockies (60%) [6, 7]. Coupled with the increases in length and the frequency of these long wildfire seasons is an increase in burn severity. Fires are burning longer than in previous decades; the average time between wildfire discovery and fire control increased by 29.6 days (495%) since 1987 [6, 7]. Two key drivers for these increases include climate change [6-8] and human activity [8-11].

In 2016 there were 6,986 fires in California that burned 564,835 acres. These California fires represent 10% of the total number of national fires last year, as reported by The California Department of Forestry and Fire Protection (CalFire) and the United States Forest Service [12]. Not surprisingly, California has invested significant financial and industrial resources to combat these extreme events, spending up to 524 million dollars in a bad fire year in fire suppression costs [13]. In addition to these direct costs, there is also an indirect cost to human health. While difficult to quantify, one study estimated that the economic cost of health effects from the largest wildfire in Los Angeles County's (with a population of more than 10 million people) modern history was $9.50 per exposed person per day [14].

The majority of research on wildfires and human health has focused on the effects of wildfire smoke and its constituents. Components of wildfire smoke/biomass burning have been reported under a variety of conditions, and in multiple geographic regions and seasons. In California, air quality impacts have been characterized and/or modeled for some of the most impactful fires in the last ten years: the 2013 Rim MegaFire [15], the 2011 Lion Fire [16], the 2008 Northern California wildfires [17], and the 2007 Southern California wildfires [18]. These studies demonstrate the significant impact that wildfires have on air quality in California. Specifically, wildfire smoke has been identified as a public health concern because it contains a complex mixture of potentially harmful compounds including polyaromatic hydrocarbons (PAHs), ozone,

and respirable particulate matter (PM). What we know about the human health effects of these wildfire exposures is largely limited to studies of susceptible populations and a few studies of firefighters. Wildfire health effects have been recently reviewed [1-3]. The studies of the major California wildfires describe emissions of major components of wildfire smoke (PAHs, ozone, PM); however, these studies often do not analyze pesticides and wildfire suppression chemicals, which are minor components in wildfire smoke. These minor components may also have consequences for public health.

An underappreciated aspect of wildfires is the effect of pesticides and wildfire suppression chemicals present in the environment prior to burning or that were added to the fires in the firefighting process. For example, pesticides and their breakdown and pyrolysis products can be volatilized and distributed into the environment through wildfire burning. Genualdi *et al.* demonstrated that pesticides released into the environment through wildfires can travel long distances with the wildfire smoke [3]. In addition, firefighters have an array of chemicals at their disposal that allow them to more easily contain wildfires while protecting physical structures and homes impacted by fires encroaching on the urban interface. The urban interface is defined as the transition between urban and rural lands. While these chemicals are not believed to be acutely toxic to humans, their high-volume usage when combating wildfires raises concerns about their effect on human health. However, we don't fully understand how man-made chemicals, such as pesticides and wildfire suppression chemicals, impact fire emissions and human health.

Accompanying the rise in frequency and severity of California fires in the past few decades, the volume of pesticides and fire suppressants used in California has also increased. From 2012 to 2015, the total weight of pesticide chemicals applied in California increased from 185,807,008 million pounds to 194,046,727 million pounds [2]. The volume of aerial fire retardant used in that same time frame increased from 3,332,410 million gallons to 7,141,190 million gallons [1, 19-21]. It should be noted that changes in the total amount of pesticides or wildfire suppression chemicals does not account for temporal changes in the types of chemicals applied to land or the number of acres of land to which they were applied.

Understanding the health effects of the compounds we choose to introduce into our environment and how they alter and are altered by extreme events like wildfires is an important consideration for fire and land management. It is unclear how anthropogenic chemicals contribute to the total human and ecological risks from wildfires. This gap in the literature must be addressed.

Two questions investigated by this review:

(1) Do pesticides pose an added risk to human health from California wildfires?

(2) Do chemical methods of fire suppression contribute to adverse human health outcomes?

Our investigation has uncovered that there are significant data gaps in this area. The next sections will outline what data are available and what is known about human health effects from these chemicals.

1. Pesticides

When forests, prairies, and farmlands catch fire, the biomass, pesticides and herbicide chemicals applied to these lands burn. Intense heat, winds and aerosolized organic matter disperse pesticides, which include insecticides and herbicides and their pyrolysis products (products of incomplete combustion) through the air during combustion of wildfires [3]. These chemicals are used extensively in the agricultural sector, and for invasive species management programs in forested and residential areas [22].

1.1. Pesticide use in California

The California Department of Pesticide Regulation (CDPR) has determined that the amount of pesticides (including herbicides and insecticides) applied to lands has increased in the past 10 years [22]. CDPR quantifies pesticide use in California by the amount of active ingredient applied to land. Active ingredient refers to the weight of toxic pesticide, but does not consider other formulation components like dispersal and emulsifying agents. In 2014, a total of 189 million pounds of active ingredient were applied in California. To assess the threat of prior pesticide application during a wildfire, the area of land and quantity of active ingredient used are important parameters because together they provide an estimate of the amount of pesticide that could be volatilized during a fire.

1.2. Fire threat in regions of pesticide application

The wildfire season is lengthening (18.7% longer globally from 1979 to 2013) [5] and extending into the spring months [6, 7]. An extended fire season will overlap with peak pesticide application (spring), meaning the presence of larger quantities of pesticides. The co-incidence of these events will increase the presence of pesticides during the wildfire season and thus expand the threat to human health. This, combined with the increase in pesticide use in California, creates additional cause for human health concern.

Figure 1 shows the overlap between pesticide application and fire hazard risk. The perimeter of the Central Valley and lands adjacent to coastal cities has the greatest overlap. Although agricultural areas with the highest pesticide application are not the regions under the most significant fire threat, the overlap in pesticide use and fire threat is most striking in lands adjacent to high population densities. This means that during fires in untreated forests, pesticide exposure is of less concern despite the larger nature of these fires. Rather, smaller fires burning at the urban interface have a higher threat of exposing a large population to the combustion products of pesticides.

Importantly, pounds of active ingredient applied can be misleading. While pesticide use has been on the rise in California, CDPR noted a decrease in the use of known reproductive toxins, carcinogens, cholinesterase inhibitors, ground water contaminants, and oils [22]. Although these trends may seem beneficial, it is well known that the elimination of a known chemical toxicant may increase the use of structurally similar compounds. For example, when the EPA banned the indoor use of chlorpyrifos, a common organophosphate pesticide, pyrethroid use increased. Although considered less toxic to humans than chlorpyrifos, pyrethroids have now been shown to exhibit developmental neurotoxicity and thus still pose a significant threat to humans [23]. This variation in potency and health outcomes demonstrates the importance of not just monitoring the volume and acreage of active ingredient applied but also the threat these compounds, and structurally related compounds with unknown health effects, pose to human health.

Although cities in close proximity to wildfires may be under a higher threat for exposure to pesticide

Figure 1. There is overlap between regions at risk for wildfires (A) and regions where pesticide is applied (B). Overlapping regions are shown in yellow (**C**). Maps A and B were created in QGIS using GIS data from CalFire (2007) and CDPR (2015). Map C was created in Adobe Photoshop and regions of overlap were pseudocolored yellow.

combustion products, smoke has the potential to transport these products or the parent compound long distances. Long-range transport of pesticides *via* wildfire smoke is possible, and may impact human health. Indeed, Genualdi *et al.* [3] recorded trans-pacific transport of pesticides in wildfire smoke. The authors determined that pesticides were transported from Siberian wildfires to Oregon and Washington in smoke, demonstrating the ability of wildfire smoke to transport pesticides previously applied to land. Based on the pesticide application and fire threat, pesticides can contribute to the composition of wildfire smoke and thus threaten human health.

1.3. Exposure and health effects associated with pesticides

The toxicological impact of pesticides could be due to inhalation of the active ingredient (parent compound) or the breakdown products of combustion (derivatives/byproducts). Biomass with freshly applied pesticides pose a minor risk to firefighters, who are in close proximity to the combustion, because the active ingredient does not exceed the No-Observed-Effect-Level (NOEL) [24]. However this does not account for the fact that the parent pesticide compounds have usually gone through some thermal (and/or microbiological) transformation before inhalation. Pesticide application can alter the natural composition of wildfire smoke. For example, the application of "common pesticides" (2,4-D, niclosamide and triadimefon) resulted in

an increased concentration of PCDD/F (polychlorinated dibenzodioxins/difurans) in smoke [25, 26]. Several studies have found that these transformations can produce toxicants such as carbon tetrachloride, phosgene, hydrogen cyanide, benzene, sulfur gases, and PCDD/F [27-30]. PCDD/F is a class of compounds, of which the most toxic is the dioxin TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin). PCDD/F compounds pose a significant threat to humans as reviewed by Mukerjee [31]. These combustion products are not co-regulated with the parent compound, therefore the NOEL levels do not protect against these potentially toxic derivatives produced by wildfires.

McMahon *et al.* [32] found the release of common pesticides from wildfires depends strongly on the temperature of the wildfire. In laboratory-controlled fires the authors found that in "complete combustion" situations where the fire burns at >500 °F, pesticide residues were not found in the smoke. However, when the fire was smoldering at <500 °F, traces of pesticides were detected in the resulting smoke. In contrast, Nelson reviewed the state of pesticides after fire consumption and concluded that 1-10% of the parent compound survived the blaze [33]. Thus, the potential threat posed by these compounds depends greatly on the environmental conditions of the fire (compound burned, heat, smoke, wind and transport).

Some argue that laboratory-replicated fires do not accurately capture the complexity of natural

wildfires, and so do not accurately model the risk of these fires. In response, Wang *et al.* [34] studied the concentration of toxic pollutants released from natural wildfires during the four stages of burning: pre-event, flaming, smoldering, and post-event. As part of this study they measured "emerging pollutants" including pyrethroids and other pesticides during these four periods of burning. Between the pre-event and flaming stages, the concentration of contaminants increased or decreased depending on the compound; but during the smoldering period all contaminants increased from the pre-event, most to significantly higher levels. For example, chlorpyrifos was recorded as 130 pg/m^3 pre-event in the air, dropping to 27 pg/m^3 during flaming, yet grew to 140 pg/m^3, and 180 pg/m^3 during the smoldering and post-event stages, respectively. These measurements from naturally occurring wildfires support the laboratory findings by McMahon *et al.* (1995), and hence the conclusion can be drawn that smoldering fires produce more contaminants.

Although conventional toxicity data exist for occupational exposure to parent pesticide compounds, studies do not account for inhaled pesticide derivatives. During wildfires, firefighters are at the highest risk of pesticide exposure. The available toxicity data of these conditions include case studies of pesticide/chemical warehouse fires, which have been reviewed [33]. The firefighters who combatted these fires showed a variety of symptoms from smoke inhalation to acute toxic exposure to the burning pesticide. In some cases, this was caused by improper use of safety equipment. Nelson concluded the most immediate risk to firefighters in these direct pesticide-burning incidents is explosion or acute exposure due to the concentrated state of the pesticide.

Acute inhalation dose can also be impacted by respiration rate or other factors such as stress. This is important for both firefighters and susceptible populations in communities near the burn sites. People, especially children, who experience a wildfire event can be significantly affected by posttraumatic stress [35]. The immunosuppressive effects of pesticides have been reviewed [36]. After the 2003 southern California wildfires there was an increase in hospital admissions for acute bronchitis and pneumonia [37].

Currently there is a limited understanding about the human health risk of pesticides volatilized during wildfires. This data gap is two-fold. First, we have limited knowledge of how pesticides are volatilized and transported during actively burning wildfires. Second, very little is known about the inhalation effects of pesticide derivatives, let alone how mixtures with other wildfire constituents may modify this human health risk. More research in this area is needed to understand how volatilized pesticides might impact human health.

2. Wildfire suppression chemicals

A number of chemicals have been developed to suppress wildfires. The properties of these wildfire suppression chemicals allow firefighters to more easily contain wildfires while also protecting physical structures and homes that are impacted by fires encroaching on the urban or rural interface. There are two major types of wildfire suppression chemicals: foams and retardants [38, 39]. The main difference between foams and retardants is their composition and thus, intended use. Because of these differences in composition and use, the potential effect of these compounds on human health varies; in this section the effects of each class are reviewed.

2.1. Types and volumes of wildfire suppression chemicals

Retardants are inorganic, salt-based, and highly soluble in water [39]. The most common retardant used in suppressing wildfires is Phos-Chek. The chemical components of Phos-Chek formulations vary, although major components include: ammonium phosphates, performance additives (trade secrets), corrosion inhibitors, wetting agents, and coloring dyes [39]. Retardants are dropped from planes in the air to directly support firefighters on the ground [39]. Due to their persistence in the environment for weeks or months, they are most effectively used to pre-treat lands highly susceptible to fire threats [39]. In contrast, foams are generally detergent-based organic chemicals with hydrophobic properties. Foams are used for short-term applications when wildfires burn near the urban interface and are of immediate danger to humans. Three subtypes of foams are used. Class A foams are mostly comprised of hydrocarbon surfactants, and are used for all types of wildfires [36]. Class B foams are comprised of hydrocarbon- and fluoro- surfactants, and are used when wildfires burn flammable liquids and gases [36]. Firegels are polymer coatings that are applied to protect structures because they slow or even stop combustion [40]. Table 1 summarizes the types of

**Table 1.** Types of wildfire suppression chemicals and their characteristics.

Type	Subtype	Brand	Trade name	Application method	Estimated usefulness	Major chemical components
Retardant	N/A	Phos-Chek	MVP	Air equipment	Weeks/Months	Monoammonium phosphate, Diammonium phosphate, Performance additives
			259			Ammonium polyphosphate solution, Attapulgus clay, Iron oxide, Performance additives
			LC95			Diammonium phosphate, Guar gum, or a derivative, Performance additives
			Fire-Trol 936			Mixture of ammonium polyphosphate, corrosion inhibitor, wetting agent, and fugitive dye
			Fire-Trol 934			Mixture of ammonium polyphosphate, corrosion inhibitor, and wetting agent
			Fire-Trol 931			Mixture of ammonium polyphosphate, clay, corrosion inhibitor, and coloring agents
Foam	Class A	Phos-Chek	WD881	Ground equipment	Minutes/Hours	Surfactants (Alpha-olefin Sulfonate Solution, 2,4-pentanediol, 2-methyl-, water, lauryl alcohol, d-limonene)
			First response			Surfactants (Alpha-olefin Sulfonate Solution, 2,4-pentanediol, 2-methyl-, water, lauryl alcohol, d-limonene)
			Fire-Trol Firefoam 103			High efficiency surfactants (Alpha-olefin Sulfonate Solution, 2,4-pentanediol, 2-methyl-, n-Octanol), foaming and wetting agents, corrosion inhibitor
			SOLID			Surfactants, 2,4-pentadiol, 2-methyl-, performance additives
			Firefoam 103B			Alpha-olefin Sulfonate Solution, 2,4-pentanediol, 2-methyl-, n-Octanol
		Ansul	Silv-Ex			Specialty hydrocarbon surfactants, stabilizers, corrosion inhibitors and solvents
			Fire control concentrate			Fluorine-free hydrocarbon surfactants
			Jet-X			Synthetic based formulation comprised of hydrocarbon surfactants, solvents, and stabilizers

Table 1 continued..

Type	Subtype	Brand	Trade name	Application method	Estimated usefulness	Major chemical components
Foam	Class B	Phos-Chek	AFFF	Ground equipment	Minutes/Hours	Water, hydrocarbon surfactants, solvents, and C6 fluorosurfactants
		Phos-Chek	AR-AFF			Water, hydrocarbon surfactants, solvents, C6 fluorosurfactants and fluoropolymers
			Fluorine free			Water and hydrocarbon surfactants
			Multi-Expansion H930			Synthetic surfactants
		Ansul	Ansulite			Fluoro- and hydrocarbon surfactants
	Firegel	Phos-Chek	Insul-8	Ground equipment	Hours/Days	64742-47-8 Distillates (petroleum), hydrotreated light and other nonhazardous substances

wildfire suppression chemicals, application method, intended use and major chemical components.

Between 2012 and 2015, the US Forest Service estimated that over 23 million gallons of retardant was used in the state of California for wildfire management [1, 19-21]. California is one of the major consumers of retardants, as this volume represents over half of the total retardant applied to lands in the US between 2012 and 2015. According to the US Forest Service, the amount of retardants applied annually in the US corresponds to the number of acres burned. However, the data indicate that while the number of acres burned in California has remained unchanged since 2012, retardant use has increased (Figure 2). Indeed, the amount of land burned in California from 2012 and 2015 fluctuated between 600 to 900 thousand acres [41-44]. The increasing use of retardants could be explained by the increasing severity of wildfires in California. Although the number of acres of land burned by wildfires did not change between 2012 and 2015, the severity of the wildfires required elevated use of retardants. Over time, if the severity of wildfires continues to increase, we can expect that retardant use will increase as well.
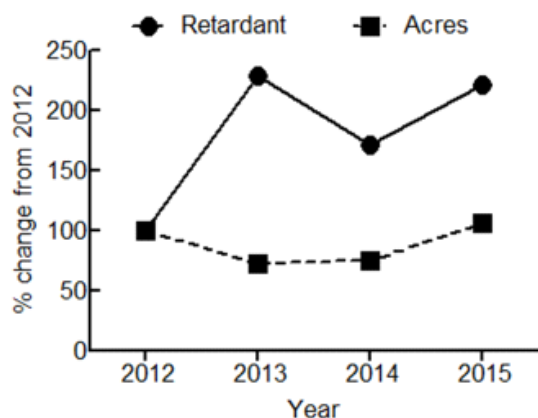
Figure 2. Relative change in annual amount of land burned by wildfires and amount of wildfire retardant used. The use of wildfire retardant has increased as the number of acres of land burned by wildfires has remained relatively unchanged. Circles indicate the relative amount of retardant used annually to suppress wildfires, while squares indicate the total number of acres burned annually by wildfires in the US. All values are represented as % change from the year 2012.

In contrast to the extensive data on retardant use, there are no data on the annual use of firefighting foams. With the currently available data, it is thus possible to generate risk assessments based on the level of exposure of humans to retardants, but not for foams.

2.2. Exposure and health effects associated with retardants

To understand the health impacts of retardants on the general population, Labat-Anderson Incorporated performed a quantitative risk assessment in 1994, which was updated in 2003 [45]. Significant data gaps were present in the assessment because no long-term toxicity data was available for any of the chemicals as a whole, and cancer risks could not be determined [45]. It was concluded that for typical retardant exposures, there were no health risks for the general population; however, in specific maximum exposure scenarios, there was significant risk for all powder retardants and several mixtures for civilians [45]. The maximum exposure scenario involved a "drench" situation, where retardants dropped from the plane landed directly on firefighters and civilians on the ground. An additional conclusion from a follow-up risk assessment in 2013 was to stop the consumption of vegetables that may have been inadvertently treated with retardant. Components of retardants can cause transient increases in soil nitrates. Nitrates can concentrate in vegetables and convert to nitrite when consumed, resulting in changes in hemoglobin that can reduce oxygen transport throughout the body, especially in infants [46].

Importantly, the group most likely to be exposed to retardants is firefighters, not the general population. An article by Kalabokidis in 2000 reviewed the health impacts from exposure to retardants in the firefighter population. It was determined that the risks from exposure to retardants would pose minimal risk to firefighters based on acceptable daily intake values, except for drench situations [47]. This finding was similar to the conclusions from the previously discussed risk assessments. Interestingly, because the purpose of the retardants is to suppress the wildfire, the study by Kalabokidis in 2000 found that retardant treatment leads to incomplete combustion and thus caused increased smoke production [47]. In large wildfires, smoke

production is already considerable and therefore the relatively minimal contribution from retardant treatment does not significantly increase the amount of smoke produced [47]. In small wildfires however, the contribution of retardant-induced smoke is in higher proportion to the total volume of smoke, and thus could heighten smoke-induced health effects in humans [47].

In this review we suggest that wildfires near the urban interface are the most likely sites for pesticide-wildfire interaction in California. While there is little risk for human health impacts after direct exposure to retardants, increased wildfire smoke production after retardant use could cause heightened human health effects from smoke inhalation. Thus, we propose that the people most at risk for health impacts from pesticide and retardant interactions with wildfires are those that live near the urban interface in high population densities. These are the regions that experience relatively smaller wildfires and have abundant pesticide use (Figure 1). Future epidemiological studies that characterize the health impacts of wildfire smoke in California should consider the interaction between retardant use and smoke generation in small, urban wildfires.

2.3. Exposure and health effects associated with foams

Some foams (primarily Class B) include the perfluoroalkyl acids (PFAAs), of which perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) have garnered the most attention in terms of toxicological impact [48]. PFFAs are essential components of firefighting foams because their low vapor pressure, high fluorine content, and high water solubility efficiently suppress fires. Due to their chemical and physical properties, most PFFAs or PFOS released are predicted to be found in surface waters and persist in the environment [49]. Consequently, PFOS have been shown to accumulate in surface waters, especially in areas where wildfires have been treated with foams [50]. Because of the persistence of PFOS, it can be readily detected in human serum and has a half-life of 8.67 years [51-53].

The use of PFOS was largely phased out in 2002 in the US. Moreover, PFOS was included in the Stockholm Convention on Persistent Organic Pollutants as a priority pollutant in 2009 [54, 55]. Due to decreased use of PFOS, Kato and colleagues reported that between 1999 and 2008, the average serum concentration of PFOS in the US has decreased. In contrast, the average serum concentrations of other PFAA compounds with structures similar to PFOS have risen [56, 57]. Rotander and colleagues recently reported that firefighters have significantly elevated serum concentrations of PFAAs and PFOS [52]. This demonstrates that although exposure to PFOS in the US has decreased over time, firefighters with close contact to foams likely experience more exposure to the compounds than the general population.

Recently, Barzen-Hanson and colleagues identified 40 new classes of PFAAs from waters historically contaminated with firefighting foams [58]. It is not understood if these new compounds have replaced traditional PFFAs in foam formulations or whether they are produced *via* biotransformation in the environment [58]. Exposure to these new compounds could occur from consuming fish from lakes affected by firefighting foams [51], although other routes of exposure are possible [59]. Thus, despite the phase out of PFOS the public may not be protected from potential direct and/or interactive toxicities [60, 61]. It is possible that new classes of PFFAs and/or biotransformation of traditional PFFAs like PFOS in the environment leads to toxicity.

The potential toxic effects of PFAAs and PFOS have been reviewed in several animal models, potential exposure scenarios, and for their potential effects on a number of tissues and organs [48, 62, 63]. These reviews provide an excellent summary of published findings regarding PFAA and PFOS toxicity. A limitation of PFAA and PFOS toxicity studies is that they have been conducted in rodents at relatively high doses compared to human exposure levels. A wider range of doses would be of great value to the field, especially with consideration for potential exposures during the firefighting process [63].

The epidemiologic evidence supporting human health effects of firefighting foam components is inconclusive. One study concluded that there was insufficient data to support if PFAAs or PFOS posed significant risk to human health [64].

However, Fei and colleagues determined that high exposure to PFOA and PFOS was associated with reduced fecundity, and the exposure levels measured were similar to those seen in many industrialized countries [65]. Washino and colleagues determined that there was a significant correlation between prenatal exposure to PFOS and reduced birth weight, specifically in females [66]. Moreover, it has been suggested in recent years that PFAAs may be endocrine disrupting compounds, causing decreased testosterone and increased estradiol levels [61]. Thus, the potential adverse effects of these compounds found in firefighting foams are broad.

CONCLUSION

For both pesticides and wildfire suppression chemicals, we have identified the urban interface as the site most likely to impact human health. This is the region where pesticides, wildfire suppression chemicals, and wildfires meet. We think it is important for future epidemiological and air quality studies to investigate: (1) Are pesticides and their derivatives present in wildfire smoke? (2) Do wildfire suppression chemicals alter smoke production and composition? (3) Are there combined effects at this important junction?

While it is unfeasible to not use any chemical agents to control agriculture or to actively suppress wildfires, usage requires more oversight and restrictions to minimize their human health impacts. Ultimately, the benefits of applying these chemicals must be weighed against their drawbacks in order to protect the public from the immediate threat of fire while minimizing exposure to compounds with unknown human health effects.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

ABBREVIATIONS

CalFire	:	The California department of forestry and fire protection
PAHs	:	Polyaromatic hydrocarbons
PM	:	Particulate matter
CDPR	:	California department of pesticide regulation
NOEL	:	No-observed-effect-level
PCDD/F	:	Polychlorinated dibenzodioxins/difurans
TCDD	:	2,3,7,8-tetrachlorodibenzo-p-dioxin
PFAAs	:	Perfluoroalkyl acids
PFOS	:	Perfluorooctane sulfonate
PFOA	:	Perfluorooctanoic acid

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