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A Review of Community Smoke Exposure from Wildfire Compared to Prescribed Fire in the United States

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Abstract

Prescribed fire, intentionally ignited low-intensity fires, and managed wildfires, wildfires that are allowed to burn for land management benefit, could be used as a land management tool to create forests that are resilient to wildland fire. This could lead to fewer large catastrophic wildfires in the future. However, we must consider the public health impacts of the smoke that is emitted from wildland and prescribed fire. The objective of this synthesis is to examine the differences in ambient community-level exposures to particulate matter ($PM_{2.5}$) from smoke in the United States from two smoke exposure scenarios – wildfire fire and prescribed fire. A systematic search was conducted to identify scientific papers to be included in this review. Web of Science Core Collection and PubMed for scientific papers, and Google Scholar were used to identify any grey literature or reports to be included in this review. Sixteen studies that examined particulate matter exposure from smoke were identified for this synthesis – nine wildland fire studies and seven prescribed fire studies. $PM_{2.5}$ concentrations from wildfire smoke were found to be significantly lower than reported $PM_{2.5}$ concentrations from prescribed fire smoke. Wildfire studies focused on assessing air quality impacts to communities that were nearby fires and urban centers that were far from wildfires. However, the prescribed fire studies used air monitoring methods that focused on characterizing exposures and emissions directly from and next to the burns. This review highlights a need for a better understanding of wildfire smoke impact over the landscape. It is essential for properly assessing population exposure to smoke from different fire types.

Keywords

Wildfire, Prescribed Fire, Smoke, Particulate Matter, Public Health, Exposure

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Introduction

Wildfire has long been an important ecological process of our natural world, only requiring three ingredients – fuel, oxygen, and heat [1]. Prior to European settlement, many forests in the United States were historically shaped by wildfires [2]. Native Americans historically used wildfire as a vegetation management tool to increase density of edible plants, provide material for basketry, and control insects and plant diseases [3]. Historically in the western US, frequent fires of low severity burned on the forest floor and resulted in coniferous forests that are more vulnerable to the effects of fire [4]. In California, Stephens et al. (2007) estimated that during the prehistoric period wildland fires emitted 47 billion kilograms of fine particulate matter ($PM_{2.5}$) annually [5].

Prescribed fire; planned and intentionally ignited low-intensity fires, and managed wildfires; wildfires that are allowed to burn for land management benefit, could be used to treat the abundance of fuel in forests and restore fire-adapted landscapes across a larger area [2]. However, smoke-caused air quality impacts and compliance to air quality regulations can be an impediment for the use of prescribed fire and the public health impacts of the smoke that is emitted from wildfire and prescribed fire must be considered [2,6]. Wildfire smoke can contain fine to inhalable particulate matter ($PM_{2.5}$–PM_{10}), acrolein, benzene, carbon dioxide, carbon monoxide, formaldehyde, crystalline silica, total particulates, and PAHs [7],[8]. Individuals can be exposed occupationally if they work as wildland firefighters or from ambient air that is contaminated with smoke from a nearby or distant wildfire [9].

Past health studies of wildfire exposure have generally examined the relationship between exposure to $PM_{2.5}$ from wildfire smoke and associated adverse health outcomes [9,10]. Fine particulate matter is derived primarily from combustion and can absorb and retain toxic substances such as volatile and semi-volatile organics (PAHs and quinones), transition metals, reactive gases (ozone and aldehydes), and sulfate and nitrate particles [11,12]. Particulate matter can be deposited in the human respiratory tract through three main mechanisms - impaction, sedimentation, and diffusion [13]. Inhalable particles with diameters of 0.5 to 2 μm are deposited in the respiratory tract through sedimentation. Larger particles, usually up to 10 μm in diameter, are deposited in the respiratory tract through inertial impaction, whereas smaller particles, <0.5 μm are deposited though diffusional deposition [14]. Fine particulate matter can be deposited in respiratory bronchioles and alveolar regions where gas exchange occurs in the human lung [13],[14]. There is evidence that $PM_{2.5}$ can cause adverse health outcomes through multiple biological mechanisms, such as increased local lung oxidative stress and inflammation leading to acute and chronic respiratory effects; the lung inflammatory responses can spill over into systemic circulation contributing to acute and cardiovascular effects [15–18].

Although there are many epidemiological studies that have provided evidence of adverse health outcomes associated with long and short-term exposure to $PM_{2.5}$ in urban environments, there are fewer studies examining health outcomes and exposures to $PM_{2.5}$ from wildfire smoke. It is important to study exposures to $PM_{2.5}$ from wildfire smoke, as the chemical composition of $PM_{2.5}$ in wildfire smoke can differ from that of urban sources of $PM_{2.5}$ [8,9]. Previous studies have suggested that $PM_{2.5}$ from wildfire smoke causes adverse respiratory health effects and possibly increased mortality and cardiovascular health effects [19–22]. A recent systematic review of health impacts from wildfire smoke by Reid et al. (2016) found evidence that wildfire smoke was associated with respiratory morbidity including exacerbations of symptoms of asthma and chronic obstructive pulmonary disease. There was some evidence, not conclusive, that wildfire smoke exposure is associated with respiratory infections and all-cause mortality [10]. Additionally, there are a few studies that found associations between wildfire smoke exposure and adverse birth outcomes such as low-birth weight; however, these studies were limited and do not provide conclusive evidence. Holstius et al. (2012) demonstrated that average birth weight was slightly reduced among infants that were in utero during the 2003 Southern California wildfires.

Smoke from wildfire is inevitable, particularly in fire prone ecosystems. Exposure to smoke can to some extent be controlled by suppression and other anthropogenic actions. Historically, in the United States, full suppression has been utilized in an attempt to eliminate smoke and fire from the landscape [23]. The understanding that this practice is unsustainable has led to increased interest in using fire on the landscape to improve ecological health [24]. Human health is intrinsically coupled to ecological health but this relation is confounded by smoke exposure [25]. Understanding relative risk from fire management actions is essential to informed protection of public health.

1.1 Synthesis Objectives

The objective of this synthesis is to examine the differences in ambient community-level exposures from smoke in the United States from two smoke exposure scenarios - wildfire and prescribed fire. Several key questions will be addressed – (1) What are the $PM_{2.5}$ concentration differences between prescribed fire and wildfire smoke exposures? (2) How do $PM_{2.5}$ concentrations from each exposure scenario compare to the National Ambient Air Quality Standards (NAAQS)? (3) How long are communities exposed to $PM_{2.5}$ during each exposure scenario? This synthesis will provide public health practitioners, air quality regulators, and natural resource managers more information on the exposure differences of smoke exposure from wildfire compared to prescribed fire. Ultimately, this information can be used to understand and quantify the health risks associated with smoke exposure from wildfire compared to prescribed fire.

Materials and Methods

A systematic search was conducted to identify scientific papers from peer-reviewed journals to be included in this review. The systematic search followed the Guidelines for Systematic Review and Evidence Synthesis in Environmental Management [26].

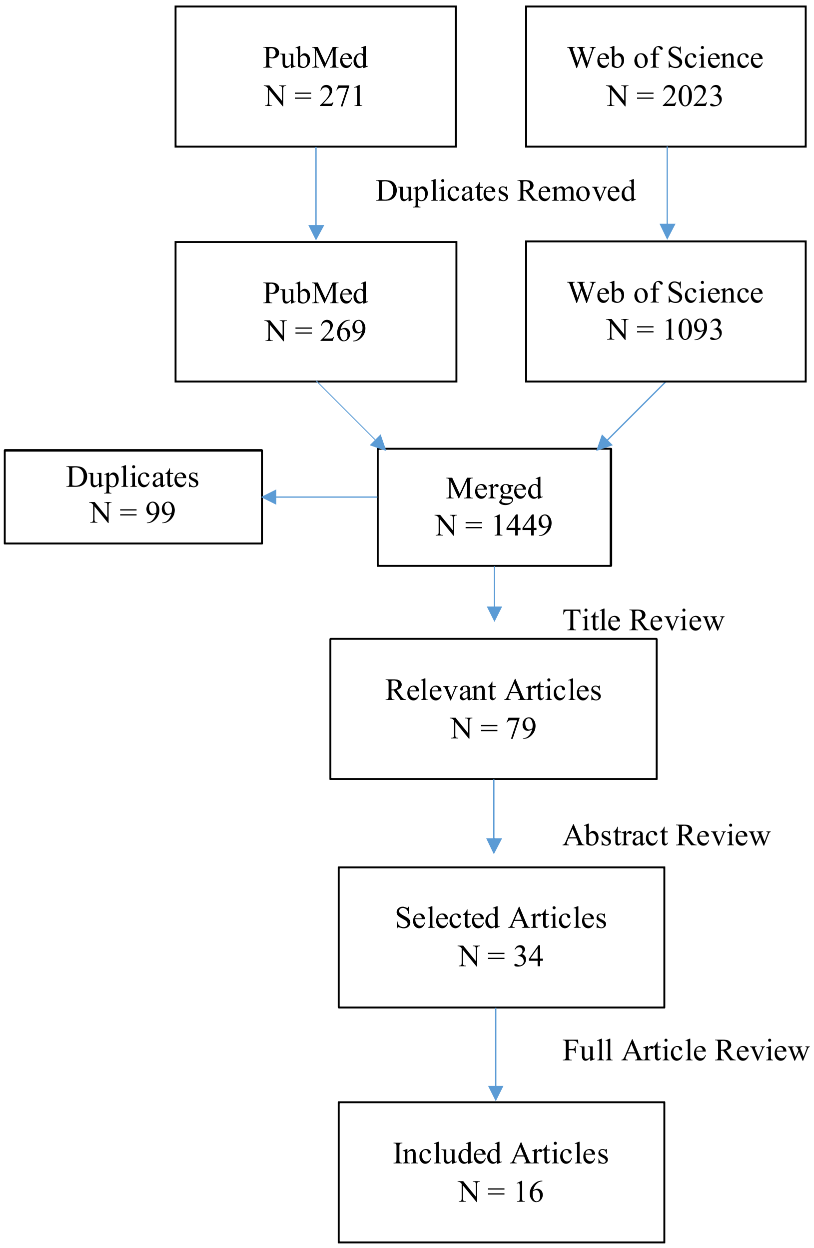
Web of Science Core Collection and PubMed for scientific papers, and Google Scholar were used to identify any grey literature or reports to be included in this review. The search strategy used the following search terms – (wildfire, wildland fire, prescribed fire, grass fire, peat fire, prescribed managed fire, prescribed natural fire) AND (smoke, exposure assessment, air quality). For each search that was performed, we recorded the search date, search terms that were used, database that was searched, and titles that were returned from the search were recorded.

The synthesis was restricted to scientific papers that met the following inclusion criteria: (1) studies that were conducted in the United States and (2) reported $PM_{2.5}$ concentrations during specific wildfire or prescribed fire events. Studies were appraised for the quality of the methods used for air monitoring or modeling used for concentration estimation. Studies that reported only $PM_{2.5}$ occupational exposures during a wildfire or prescribed fire event were not included.

The systematic search resulted in 271 journal articles from PubMed with 229 unique titles and 2023 journal articles from Web of Science with 1093 unique titles (Figure 1). Once merged, there were 1449 unique scientific journal articles. Next, we reviewed the journal titles and selected 79 relevant articles and reviewed their abstracts for extractable information that was relevant to the synthesis objectives. Based on the information provided in the abstracts, such as study methods and results, we selected the article to be further reviewed by reading the full article (N = 34). Sixteen peer-reviewed scientific journal articles met the study criteria and were included in this synthesis.

From each selected journal article, information was extracted and inputted into a table for comparison and analysis (Table 1). Extracted data from each article included information on the wildfire or prescribed fire event name and date range, reported concentration mean and range, number of reported days that exceeded the NAAQS 24-hour standard (PM2.5 concentration ≥ 35 $\mu g\ m^{-3}$), number of days sampled, the data source of the reported concentrations, and what type of average concentration average or sampling time was used for each study.

Figure 1 – Flow Diagram of Study Selection



Study	Event Location and Name, (Dates)	Fire Size (ha)[a]	PM$_{2.5}$ Concentration (µg m^{-3})		NAAQS Exceedance[b]	# of Days Sampled	Data Source	Sampling Time Range
			Mean	Range				
Wildfire Events								
Ward and Smith 2005 [27]	Montana Missoula Fire Season (8/13 and 8/25/2000)	-	39.9 and 42.2	Not Reported	2 days	2	Monitor	24hr Average
Ward and Lincoln 2006 [28][c]	Montana Missoula Wildfires (8/14 - 8/18/2003)	-	87.5	46 -136.8	7 days	4	Monitor	24hr Average
	Montana Missoula Wildfires (8/31 - 9/2/2003)	-	54	37 - 69		3		
Viswanathan et al. 2006 [29]	California Cedar, Paradise and Otay Fires (10/26 - 11/4/2003)	113,424, 22,945, 18,988	Not reported	Max - 104.6, 170	2 days	10	Monitor	24hr Average
Herron-Thorpe et al. 2010 [30]	Pacific Northwest Wildfires (7/3 - 8/22/2007)	-	16.8	Not reported	10 days	51	Model	24hr Average
	Pacific Northwest Wildfires (6/22 - 8/27/2007)	-	15.9	Not reported	19 days	67		
Strand et al. 2011[31][d]	Idaho Frank Church Fire (8/11-9/14/2005)	22,194	2 – 22	8 - 244	3 days	13-77	Monitor	Hourly Average
	Washington Tripod Fire (7/24/2006-Mid Oct/2006)	70,820	3 – 69	49 - 1659	47 days			
	Region-fire wide event Western MT (8/2007-Mid Oct/2007)	-	3 – 57	21 -575	11 days			
	Region-fire wide event Northern CA(6/21/2008-9/2007)	-	4 – 95	28 - 472	40 days			
Schweizer and Cisneros 2014 [32]	California Lion Fire (7/8-9/7/2011)	8,370	7.7 - 20.1	Max - 166.7	0 days	62	Monitor	24hr Average
Burley et al. 2016 [33]	California Aspen Fire (7/22 - 8/11/2013)	9,227	41.5	11.7 - 92.7	13 days	20	Monitor	24hr Average
	California Rim Fire (8/17 - 10/24/2013)	104,131	8.7	1.3 - 69.9	2 days	49		
	California French Fire (7/28 - 8/17/2014)	5,202	14.4	7.9 - 21.9	0 days	20		
	California King Fire (9/13 - 10/9/2014)	39,546	6.6	1.6 - 27.8	0 days	26		
Navarro et al. 2016 [34]	California Rim Fire (8/17 - 10/24/2013)	104,131	6 - 121	1 - 450	Not Reported	49	Monitor	24hr Average
Zu et al. 2016 [35]	Quebec Wildfires - Impacts in Boston (7/7-7/16/2002)	-	23	4.1 - 64.5	Not Reported	28	Monitor	24hr Average
	Quebec Wildfires - Impacts in New York City (7/7-7/16/2002)	-	25.2 - 27.3	4.8 - 84.2	Not Reported	28		
Prescribed Fire Events								
Robinson et al. 2004 [36]	Arizona (Flaming Phase Samples) Oct/Nov 2001-2002	20-80	Not reported	523 - 6459	Not Reported	6	Monitor	1.5-2 hr Samples
	Arizona (Smoldering Phase Samples) Oct/Nov 2001-2002			155 - 904		6		4 -51 hr Samples
Lee et al. 2005 [37]	Georgia Prescribed Burn (4/15 and 16, 4/28 and 29/2004)	82-154	1810	Not Reported	Not Reported	4	Monitor	Total Average
Naeher et al. 2006, Achtemeier et al. 2006 [38,39]	Georgia Non-chipped plot (2/13/2003)	1	519.9	13.6 - 805.7	Not Reported	1	Monitor	12hr Average
	Georgia Chipped plot (2/12/2003)	1	198.1	94.3 - 300.3	Not Reported	1	Monitor	12hr Average
Hu et al. 2008 [40]	Prescribed Fire impacts on Atlanta (2/28/2007)	1,200	37.8	NA	1 day	1	Model	24hr Average
Robinson et al. 2011 [41]	Northern Arizona Broadcast Burns (2001-2007)	10-40	2800	523 - 8357	Not Reported	15	Monitor	1 -3 hr Samples
	Northern Arizona Pile Burns (2001 – 2007)		3000		Not Reported	6		
Pearce et al. 2012 [42]	South Carolina Savannah River Site Burns (2003 – 2007)	10-1,111	74.01	5.69 – 1415.96	Not Reported	55	Monitor	22hr Average

a. Fire size is reported for studies that examined specific fire events
b. Days that were reported to be above the US EPA NAAQS for PM$_{2.5}$ (35 µg m^{-3})[43]
c. Ward et al., 2006 used PM$_{10}$ monitoring concentration data to estimate PM$_{2.5}$ concentrations
d. Strand et al. 2011 reported hourly median and maximum concentration, these values are used in place of the concentration mean and range, respectively

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Results

The systematic review identified 16 studies that characterized exposures to $PM_{2.5}$ from wildfire and prescribed fire events (Table 1). Generally, studies directly measured $PM_{2.5}$ concentrations with existing air monitoring networks or temporary monitoring stations placed in communities that were deployed specifically for fire events. Although there were studies that attempted to model concentrations of $PM_{2.5}$ from wildfire or prescribed fire smoke, they did not report $PM_{2.5}$ concentrations associated with a specific fire event and did not meet the inclusion criteria.

The systematic search identified 9 scientific studies that examined exposure to $PM_{2.5}$ from wildfire smoke. The studies covered a wide geographic area and were focused on wildfires that occurred in California, Montana, the Pacific Northwest, and Canada that impacted major cities in the United States. The selected papers reported $PM_{2.5}$ concentrations from several large wildfires (region-wide events) occurring at one period or during specific wildfire events. For example, Ward and Lincoln (2006), measured $PM_{2.5}$ concentrations in Missoula, Montana while 298,172 ha burned throughout all of Montana.

Of the five studies that examined the impacts of specific wildfire events, the wildfires ranged in size from 5,202 to 113,424 ha for the French and Cedar fires in California, respectively. Only three studies reported where the $PM_{2.5}$ monitors were located in relation to the fire events. Strand et al. (2011) deployed monitors in local communities and small towns at a minimum of 12 to 36 km from the fire locations in Idaho, Washington, Western Montana, and Northern California. Navarro et al. 2016 and Schweizer et al. 2014, both used permanent and temporary monitors that were located 7-189 km from the Rim Fire and 16.6-242.8 km for the Lion Fire, respectively.

Eight studies that were selected used direct air monitoring methods to assess $PM_{2.5}$ exposures, while [30] used a modeling approach to estimate $PM_{2.5}$ concentrations from specific wildfire events during 2007 in the Pacific Northwest. From the data extracted from the studies, we focus on comparing studies that used the same averaging time (24-hr average) to calculate a mean and range of $PM_{2.5}$ concentrations. Mean $PM_{2.5}$ concentrations from wildfires ranged from 8.7 to 121 $\mu g\ m^{-3}$, with a 24-hr maximum concentration of 1659 $\mu g\ m^{-3}$. The 2013 Rim Fire and 2003 Montana Fires reported the highest mean $PM_{2.5}$ concentrations of 121 and 86.5 $\mu g\ m^{-3}$, respectively [28,34]. On average $PM_{2.5}$ concentrations from wildfires were sampled and reported for 30 days; events ranged from 2 to 77 days. During wildfire events, the number of days that exceeded the NAAQS ranged from 2 to 47 days and averaged 11 days. The $PM_{2.5}$ concentrations from the Tripod Fire smoke in Eastern Washington resulted in 47 days that were above the NAAQS [31].

Seven scientific studies were identified that measured exposure to $PM_{2.5}$ at prescribed fires in Arizona, Georgia and South Carolina. Six studies used air monitoring equipment to measure $PM_{2.5}$ concentrations, while one study Hu et al. (2008), simulated $PM_{2.5}$ concentrations using fire and atmospheric conditions from a specific prescribed fire event. Almost all prescribed fires sampled were performed as broadcast burns, where fire was applied directly across a predetermined area and was confined to that space. One prescribed sampled was conducted as a pile burn operation, where only piles of cut vegetation are ignited and burned [41]. Naeher et al. (2006) and Achtemeier et al. (2006), reported $PM_{2.5}$ concentrations from the same prescribed fire event where researchers examined the effects of mechanical chipping on smoke measurements. The size of the prescribed fires ranged from 1 to 1,200 ha with the largest event being two adjacent prescribed fires in the Southeast United States outside of Atlanta (Hu et al., 2008).

Generally, the prescribed fire air sampling occurred during the burn operation and monitors were placed inside or next to the fire perimeter. For example, Robinson et al. (2011) placed monitors next to the fire perimeter on Day 1 of sampling and inside the fire perimeter on Day 2 to capture emissions during the smolder phase of the fire. Naeher et al. (2006) and Achtemeier et al. (2006) also placed monitors inside the prescribed fire and along the fire perimeter on the downwind side of the prescribed fire burn unit. Pearce at el. (2012) measured concentrations using a grid of 18 monitors that were placed 10-12 km on the downwind side of the prescribed fire burn unit. Hu et al. (2008), was the only study to report $PM_{2.5}$ concentrations from a prescribed fire in an urban center, Atlanta, Georgia, which was 80 km from the prescribed fires.

Reported mean concentration of $PM_{2.5}$ from the selected studies ranged from 37.8 $\mu g\ m^{-3}$ in Atlanta, Georgia to 3000 $\mu g\ m^{-3}$ at a prescribed fire in Arizona respectively [40,41]. Additionally, the same prescribed fire in Arizona during the flaming phase produced the highest maximum $PM_{2.5}$ concentration of 8357 $\mu g\ m^{-3}$ [41]. Only Hu et al. (2008), examined the impacts of a prescribed fire on NAAQS exceedances and reported that one day exceeded the NAAQS (24-hour mean = 37.8 $\mu g\ m^{-3}$) during the prescribed fire event. Unlike the wildfire studies that generally used a consistent averaging time (24-hour), prescribed fire studies averaged concentration over many different time periods. Averaging times ranged from 1.5-2 hour samples to a four day total average.

Discussion

$PM_{2.5}$ concentrations from wildfire smoke were found to be lower than reported $PM_{2.5}$ concentrations from prescribed fire smoke. Wildfire studies focused on assessing air quality impacts to communities that were close to the fire (for example 12-36 km) and urban centers that were far from the wildfire. However, the prescribed fire studies used air monitoring methods that focused on characterizing $PM_{2.5}$ exposures and emissions directly from and next to the burns. Wildfire and prescribed fire smoke exposure, similar to other emissions, is dependent on proximity to the source. This was demonstrated by Burley et al. (2016) showing that megafires such as the Rim and King fires largely missed their monitoring site due to smoke plume direction while the smaller Aspen Fire transported more directly and had the highest exposure impacts at Devils Postpile National Monument. Hu et al. (2008) was the only prescribed fire study identified that assessed the air quality impact from $PM_{2.5}$ from a prescribed burn to a large urban area. However, when the 24-hr $PM_{2.5}$ concentrations at an urban area (Atlanta, Ga) were studied from this prescribed burn, the mean concentration measured was 37.8 $\mu g\ m^{-3}$ and in the range of the measured wildfire concentrations.

Additionally, the wildfire studies selected generally reported $PM_{2.5}$ mean concentrations that were averaged over a 24-hr time period. However, the prescribed fire studies reported mean concentrations that were sampled over time periods ranging from 1-96 hrs. The short duration sampling events resulted in mean concentrations that were higher than the prescribed fires that reported 24-hr average $PM_{2.5}$ concentrations. The shorter sampling events captured the periods of higher smoke emissions.

Wildfire exposures are often episodic and short-term exposures, but if they happen often over a course of a fire season over many years, they could be considered a long-term exposure. From the studies that were reviewed, the wildfire events that were included occurred over multiple weeks and months, while the prescribed fire events occurred over a few days. The duration of an event is important to consider because the longer exposure durations can lead to higher cumulative exposures to air contaminants [44].

This review highlights the lack of consistent information about exposures to $PM_{2.5}$ from wildfire smoke, especially from prescribed fires. Monitoring for prescribed fire was more focused on capturing the smoke emission directly next to the fire while wildfire studies either used existing urban sites and/or monitored for sensitive receptors. There were many studies identified during the initial search of studies that have assessed smoke from wildfires or prescribed fires, but there were few studies that directly reported concentrations of $PM_{2.5}$ to meet the inclusion criteria. Characterization of $PM_{2.5}$ air quality impacts to communities from prescribed fire smoke is needed to better understand how $PM_{2.5}$ exposures are different compared to wildfires. Improved exposure estimates could be used to quantify the risk of adverse health effects from each of these different exposure scenarios [45].

Conclusions

Destructive wildfires have higher rates of biomass consumption and have greater potential to expose more people smoke than prescribed fires. Naturally ignited fires that are allowed to self-regulate can provide the best scenario for ecosystem health and long-term air quality. Generally prescribed fire smoke is much more localized, and the smoke plumes tend to stay within the canopy which absorbs some of the pollutants reducing smoke exposure. Land managers want to utilize prescribed fire as a land management tool to restore fire-adapted landscapes. Thus, additional work is needed to understand the differences in exposures and public health impacts of smoke from prescribed fire compared to wildfire. One way to do this would be for managers to collaborate with air quality departments (internal to agency or external) to monitor $PM_{2.5}$ concentrations in communities near a prescribed fire.

Consistent monitoring strategies for all wildland fires whether prescribed or naturally occurring are needed to allow the most robust comparative analysis. Currently, prescribed fire monitoring often is focused on capturing the area of highest impact or characterizing fire emissions while wildfire monitoring often relies on urban monitors supplemented by temporary monitoring of communities of concern. A better understanding of smoke extent over the landscape and relative impacts is essential for properly assessing population exposure to smoke from different fire types.

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