

Review

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

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Received: 30 March 2018; Accepted: 9 May 2018; Published: 12 May 2018



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 in relation to two smoke exposure scenarios—wildfire fire and prescribed fire. A systematic search was conducted to identify scientific papers to be included in this review. The 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

1. 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 to 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}–PM₁₀), acrolein, benzene, carbon dioxide, carbon monoxide, formaldehyde, crystalline silica, total particulates, and polycyclic aromatic hydrocarbons (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 through 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 [23]. Fann et al. (2018), estimated that wildfire events affected additional premature deaths and respiratory hospital admissions in Louisiana, Georgia, Florida, northern California, Oregon and Idaho. Additionally, the short and long term economic value of exposure to wildfire events were \$63 and \$450 billion (in present value), respectively [24].

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 [25]. The understanding that this practice is unsustainable has led to increased interest in using fire on the landscape to improve ecological health [26]. Human health is intrinsically coupled to

ecological health, but this relation is confounded by smoke exposure [27]. Understanding relative risk from fire management actions is essential to informed protection of public health.

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 with more information on the exposure differences of smoke exposure from wildfire compared with prescribed fire. Ultimately, this information can be used to understand and quantify the health risks associated with smoke exposure from wildfire compared with prescribed fire.

2. 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 [28].

The 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.

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. During the title review, reasons for articles to be excluded included: (1) were not conducted in the United States; (2) indicated a focus on developing models to estimate PM_{2.5} emissions, source apportionment, or plumes; (3) conducted an occupational exposure study; (4) measured other air contaminants; (5) indicated that they were conducted in a laboratory. Of the selected articles, we 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-h standard (PM_{2.5} concentration $\geq 35 \mu\text{g m}^{-3}$) [29], 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.

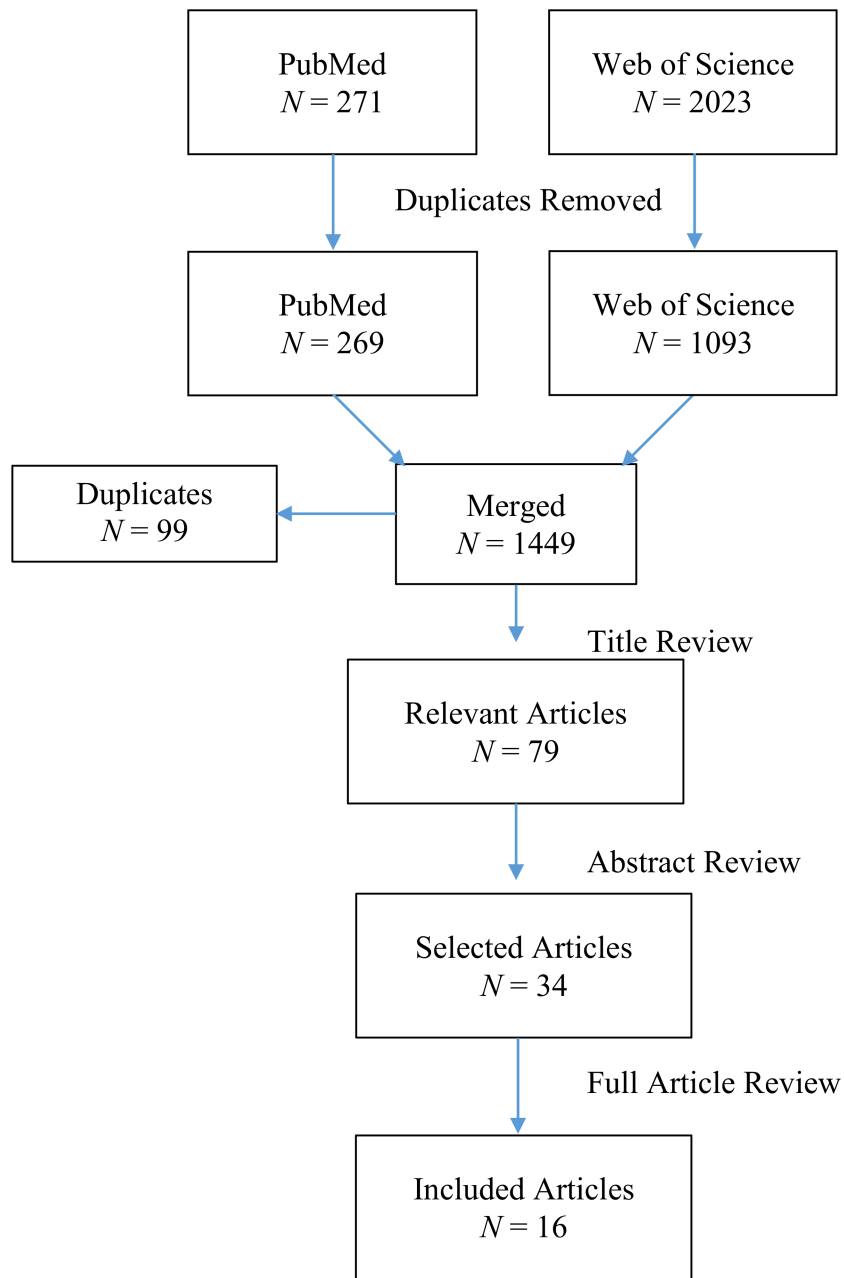


Figure 1. Flow diagram of study selection.

Table 1. Characteristics of included studies and answers to synthesis objectives.

Study	Event Location and Name, (Dates)	Fire Size (ha) ^a	PM _{2.5} Concentration ($\mu\text{g m}^{-3}$)		NAAQS Exceedance ^b	# of Days Sampled	Data Source	Sampling Time Range
			Mean	Range				
Wildfire Events								
Ward and Smith 2005 [30]	Montana Missoula Fire Season (8/13 and 8/25/2000)	-	39.9 and 42.2	Not Reported	2 days	2	Monitor	24 h Average
Ward et al. 2006 [31] ^c	Montana Missoula Wildfires (8/14–8/18/2003)	-	87.5	46–136.8	7 days	4	Monitor	24 h Average
	Montana Missoula Wildfires (8/31–9/2/2003)	-	54	37–69		3		
Viswanathan et al. 2006 [32]	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	24 h Average
Herron-Thorpe et al. 2010 [33]	Pacific Northwest Wildfires (7/3–8/22/2007)	-	16.8	Not reported	10 days	51	Model	24 h Average
	Pacific Northwest Wildfires (6/22–8/27/2007)	-	15.9	Not reported	19 days	67		
Strand et al. 2011 [34] ^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 [35]	California Lion Fire (7/8–9/7/2011)	8370	7.7–20.1	Max-166.7	0 days	62	Monitor	24 h Average
Burley et al. 2016 [36]	California Aspen Fire (7/22–8/11/2013)	9227	41.5	11.7–92.7	13 days	20	Monitor	24 h 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)	5202	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 [37]	California Rim Fire (8/17–10/24/2013)	104,131	6–121	1–450	Not Reported	49	Monitor	24 h Average
Zu et al 2016 [38]	Quebec Wildfires-Impacts in Boston (7/7–7/16/2002)	-	23	4.1–64.5	Not Reported	28	Monitor	24 h 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 [39]	Arizona (Flaming Phase Samples) Oct/Nov 2001–2002	20–80	Not reported	523–6459	Not Reported	6	Monitor	1.5–2 h Samples
	Arizona (Smoldering Phase Samples) Oct/Nov 2001–2002			155–904		6		4–51 h Samples
Lee et al. 2005 [40]	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, Achteimeier et al. 2006 [41,42]	Georgia Non-chipped plot (2/13/2003)	1	519.9	13.6–805.7	Not Reported	1	Monitor	12 h Average
	Georgia Chipped plot (2/12/2003)	1	198.1	94.3–300.3	Not Reported	1	Monitor	12 h Average
Hu et al. 2008 [43]	Prescribed Fire impacts on Atlanta (2/28/2007)	1200	37.8	NA	1 day	1	Model	24 h Average
Robinson et al. 2011 [44]	Northern Arizona Broadcast Burns (2001–2007)	10–40	2800	523–8357	Not Reported	15	Monitor	1–3 h Samples
	Northern Arizona Pile Burns (2001–2007)		3000		Not Reported	6		
Pearce et al. 2012 [45]	South Carolina Savannah River Site Burns (2003–2007)	10–1111	74.01	5.69–1415.96	Not Reported	55	Monitor	22 h 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} ($35 \mu\text{g m}^{-3}$) [29]; ^c Ward et al., (2006) [31] used PM₁₀ monitoring concentration data to estimate PM_{2.5} concentrations; ^d Strand et al. (2011) [34] reported hourly median and maximum concentration, and these values are used in place of the concentration mean and range, respectively. PM: particulate matter; NAAQS: National Ambient Air Quality Standards.

3. 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 nine 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 et al. (2006) measured PM_{2.5} concentrations in Missoula, Montana, while 298,172 ha burned throughout all of Montana [31].

In the five studies that examined the impacts of specific wildfire events, the wildfires ranged in size from 5202 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) [34] 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) [35,37] both used permanent and temporary monitors that were located 7–189 km from the Rim Fire and 16.6–242.8 km from the Lion Fire, respectively.

Eight studies that were selected used direct air monitoring methods to assess PM_{2.5} exposures, while Herron-Thorpe et al. (2010) [33] 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 focused on comparing studies that used the same averaging time (24 h 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 $\mu\text{g m}^{-3}$, with a 24 h maximum concentration of 1659 $\mu\text{g m}^{-3}$. The 2013 Rim Fire and 2003 Montana Fires reported the highest mean PM_{2.5} concentrations of 121 and 86.5 $\mu\text{g m}^{-3}$, respectively [31,37]. 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 [34].

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) [43] simulated PM_{2.5} concentrations using fire and atmospheric conditions from a specific prescribed fire event. Almost all sampled prescribed fires were performed as broadcast burns, where fire was applied directly across a predetermined area and was confined to that space. One sampled prescribed fire was conducted as a pile burn operation, where only piles of cut vegetation are ignited and burned [44]. Naeher et al. (2006) and Achtemeier et al. (2006) [41,42] 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 1200 ha, with the largest event being two adjacent prescribed fires in the Southeast United States, outside of Atlanta (Hu et al., 2008) [43].

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) [44] 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) [41,42] also placed monitors inside the prescribed fire and along the fire perimeter on the downwind side of the prescribed fire burn unit. Pearce et al. (2012) [45] 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) [43]

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 fire.

Reported mean concentration of PM_{2.5} from the selected studies ranged from 37.8 µg m⁻³, in Atlanta, Georgia, to 3000 µg m⁻³ at a prescribed fire in Arizona [43,44]. Additionally, the same prescribed fire in Arizona during the flaming phase produced the highest maximum PM_{2.5} concentration of 8357 µg m⁻³ [44]. Only Hu et al. (2008) [43] examined the impacts of a prescribed fire on NAAQS exceedances and reported that one day exceeded the NAAQS (24 h mean = 37.8 µg m⁻³) during the prescribed fire event. Unlike the wildfire studies that generally used a consistent averaging time (24 h), prescribed fire studies averaged concentration over many different time periods. Averaging times ranged from 1.5–2 h samples to a four-day total average.

4. Discussion

Due to differences in study objectives and methodology, PM_{2.5} concentrations from wildfire smoke were found to be lower than reported PM_{2.5} concentrations from prescribed fire smoke. Although the acres burned on wildfires was up to 100 times larger, monitoring location, distance and concentration averaging time was shown to have an impact on the reported PM_{2.5} concentrations. 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, prescribed fire studies used air monitoring methods that focused on characterizing PM_{2.5} exposures and emissions directly from, and next to, the burns site.

Wildfire and prescribed fire smoke exposure, similar to other emissions, is dependent on proximity to the source. Wildfire studies that were examined measured smoke at locations that ranged from 7 to 242.8 km from the wildfires, while prescribed locations ranged from next to the burn perimeter (0 km) and up to 80 km away from the burn. The dependence on proximity and smoke direction was demonstrated by Burley et al. (2016) [36], showing that megafires, such as the Rim and King fires, largely missed their monitoring site due to smoke plume direction, while the smaller and closer Aspen Fire transported more directly and had the highest exposure impacts at Devils Postpile National Monument. Hu et al. (2008) [43] was the only prescribed fire study identified that assessed the air quality impact from PM_{2.5} to a large urban area. The 24-h PM_{2.5} concentration in an urban area (Atlanta, Ga) that was estimated from this prescribed burn was 37.8 µg m⁻³ and in the range of the measured wildfire concentrations. In addition, the distance of the burn (80 km) was also similar to the monitor distance for wildfires.

The selected wildfire studies largely reported PM_{2.5} mean concentrations that were generally averaged over a 24 h time period. However, the prescribed fire studies reported mean concentrations that were sampled over time periods ranging from 1–96 h. The short duration prescribed fire sampling events resulted in mean concentrations (198.1–3000 µg m⁻³) that were higher than the prescribed fires that reported 22–24 h average PM_{2.5} concentrations (37.8–74.01 µg m⁻³). The shorter prescribed fire sampling events captured the periods of higher smoke emissions, while the longer averaging time for wildfire studies resulted in lower mean PM_{2.5} concentrations.

Wildfire exposures are often episodic and short-term, but if they happen often, over a course of a fire season over many years, they could be considered long-term exposures. 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 [46].

This review highlights the lack of consistent information about exposures to PM_{2.5} from fire smoke, especially from prescribed fires. Monitoring for prescribed fire was more focused on capturing the smoke emission directly next to the fire and not downstream from the burn, while wildfire studies either used existing urban sites and/or monitored for sensitive receptors. There were many studies identified during the initial search 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 those of wildfires. Prescribed fire exposure studies should be designed to examine emissions directly from the burn but also consider and measure the impacts on downwind communities. Additionally, one could use an area of the United States that is prone to frequent wildfires and estimate exposure through modeling from recent specific wildfires and prescribed fires to examine exposure differences. This approach was suggested by Baker et al. (2016), as it would lead to better model inputs for fire size and emissions, and could be validated against an existing monitoring network [47]. An additional approach that could be used would be a health impact assessment used by Fann et al (2018) [24] to estimate the incidence and economic value of human health impacts attributable to wildfire smoke compared to prescribed fire smoke [24]. Lastly, improved exposure estimates could be used to quantify the risk of adverse health effects from each of these different exposure scenarios [48].

5. Conclusions

Destructive wildfires have higher rates of biomass consumption and have greater potential to expose more people to 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 of 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 is often 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 impact over the landscape and related impacts is essential for properly assessing population exposure to smoke from different fire types.

Funding: This research was funded by United States Department of Agriculture Forest Service Pacific Southwest Research Station: #A17-0121-001.

Acknowledgments: We would like to thank Penny Morgan for feedback on an earlier draft of this review. This work was supported by the United States Department of Agriculture Forest Service Pacific Southwest Research Station (#A17-0121-001). The manuscript reflects solely the opinion of the authors and not of the funding source.

Conflicts of Interest: The authors declare no conflicts of interest.

References and Notes

1. Pyne, S.J. *Fire. [Electronic Resource]: A Brief History*; University of Washington Press: Seattle, WA, USA, 2001.
2. Ryan, K.C.; Knapp, E.E.; Varner, J.M. Prescribed fire in North American forests and woodlands: History, current practice, and challenges. *Front. Ecol. Environ.* **2013**, *11*, e15–e24. [[CrossRef](#)]
3. Anderson, K. *Tending the Wild: Native American knowledge and the Management of California's Natural Resources*; University of California Press: Berkeley, CA, USA, 2005; ISBN 0-520-23856-7.
4. Stephens, S.L.; Moghaddas, J.J.; Edminster, C.; Fiedler, C.E.; Haase, S.; Harrington, M.; Keeley, J.E.; Knapp, E.E.; McIver, J.D.; Metlen, K.; et al. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. *Ecol. Appl.* **2009**, *19*, 305–320. [[CrossRef](#)] [[PubMed](#)]
5. Stephens, S.L.; Martin, R.E.; Clinton, N.E. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *For. Ecol. Manag.* **2007**, *251*, 205–216. [[CrossRef](#)]

6. Quinn-Davidson, L.N.; Varner, J.M. Impediments to prescribed fire across agency, landscape and manager: An example from northern California. *Int. J. Wildland Fire* **2012**, *21*, 210–218. [[CrossRef](#)]
7. Broyles, G. *Wildland Firefighter Smoke Exposure*; US Forest Service: Washington, DC, USA, 2013.
8. Naeher, L.P.; Brauer, M.; Lipsett, M.; Zelikoff, J.T.; Simpson, C.D.; Koenig, J.Q.; Smith, K.R. Woodsmoke Health Effects: A Review. *Inhal. Toxicol.* **2007**, *19*, 67–106. [[CrossRef](#)] [[PubMed](#)]
9. Adetona, O.; Reinhardt, T.E.; Domitrovich, J.; Broyles, G.; Adetona, A.M.; Kleinman, M.T.; Ottmar, R.D.; Naeher, L.P. Review of the health effects of wildland fire smoke on wildland firefighters and the public. *Inhal. Toxicol.* **2016**, *28*, 95–139. [[CrossRef](#)] [[PubMed](#)]
10. Reid, C.E.; Brauer, M.; Johnston, F.H.; Jerrett, M.; Balmes, J.R.; Elliott, C.T. Critical Review of Health Impacts of Wildfire Smoke Exposure. *Environ. Health Perspect.* **2016**, *124*, 1334–1343. [[CrossRef](#)] [[PubMed](#)]
11. Dockery, D.W.; Pope, C. A.; Xu, X.; Spengler, J.D.; Ware, J.H.; Fay, M.E.; Ferris, B.G.; Speizer, F.E. An Association between Air Pollution and Mortality in Six U.S. Cities. *N. Engl. J. Med.* **1993**, *329*, 1753–1759. [[CrossRef](#)] [[PubMed](#)]
12. Valavanidis, A.; Fiotakis, K.; Vlachogianni, T. Airborne particulate matter and human health: Toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. *J. Environ. Sci. Health Part C Environ. Carcinog. Ecotoxicol. Rev.* **2008**, *26*, 339–362. [[CrossRef](#)] [[PubMed](#)]
13. Stuart, B.O. Deposition and clearance of inhaled particles. *Environ. Health Perspect.* **1984**, *55*, 369. [[CrossRef](#)] [[PubMed](#)]
14. Miller, F.J.; Gardner, D.E.; Graham, J.A.; Lee, R.E.; Wilson, W.E.; Bachmann, J.D. Size Considerations for Establishing a Standard for Inhalable Particles. *J. Air Pollut. Control Assoc.* **1979**, *29*, 610–615. [[CrossRef](#)]
15. Brook, R.D.; Rajagopalan, S.; Pope, C.A.; Brook, J.R.; Bhatnagar, A.; Diez-Roux, A.V.; Holguin, F.; Hong, Y.; Luepker, R.V.; Mittleman, M.A.; et al. Particulate Matter Air Pollution and Cardiovascular Disease. *Circulation* **2010**, *121*, 2331–2378. [[CrossRef](#)] [[PubMed](#)]
16. Brook, R.D.; Urch, B.; Dvonch, J.T.; Bard, R.L.; Speck, M.; Keeler, G.; Morishita, M.; Kaciroti, N.; Harkema, J.; Corey, P.; et al. Insights into the Mechanisms and Mediators of the Effects of Air Pollution Exposure on Blood Pressure and Vascular Function in Healthy Humans. *Hypertension* **2009**, *54*, 659–667. [[CrossRef](#)] [[PubMed](#)]
17. Gauderman, W.J.; Avol, E.; Gilliland, F.; Vora, H.; Thomas, D.; Berhane, K.; McConnell, R.; Kuenzli, N.; Lurmann, F.; Rappaport, E.; et al. The Effect of Air Pollution on Lung Development from 10 to 18 Years of Age. *N. Engl. J. Med.* **2004**, *351*, 1057–1067. [[CrossRef](#)] [[PubMed](#)]
18. Pope, C.A.; Bhatnagar, A.; McCracken, J.; Abplanalp, W.T.; Conklin, D.J.; O’Toole, T.E. Exposure to Fine Particulate Air Pollution Is Associated with Endothelial Injury and Systemic Inflammation. *Circ. Res.* **2016**. [[CrossRef](#)] [[PubMed](#)]
19. Delfino, R.J.; Brummel, S.; Wu, J.; Stern, H.; Ostro, B.; Lipsett, M.; Winer, A.; Street, D.H.; Zhang, L.; Tjoa, T.; et al. The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. *Occup. Environ. Med.* **2009**, *66*, 189–197. [[CrossRef](#)] [[PubMed](#)]
20. Henderson, S.B.; Johnston, F.H. Measures of forest fire smoke exposure and their associations with respiratory health outcomes. *Curr. Opin. Allergy Clin. Immunol.* **2012**, *12*, 221–227. [[CrossRef](#)] [[PubMed](#)]
21. Rappold, A.G.; Stone, S.L.; Cascio, W.E.; Neas, L.M.; Kilaru, V.J.; Carraway, M.S.; Szykman, J.J.; Ising, A.; Cleve, W.E.; Meredith, J.T.; et al. Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. *Environ. Health Perspect.* **2011**, *119*, 1415–1420. [[CrossRef](#)] [[PubMed](#)]
22. Henderson, S.B.; Brauer, M.; Macnab, Y.C.; Kennedy, S.M. Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort. *Environ. Health Perspect.* **2011**, *119*, 1266–1271. [[CrossRef](#)] [[PubMed](#)]
23. Holstius, D.M.; Reid, C.E.; Jesdale, B.M.; Morello-Frosch, R. Birth weight following pregnancy during the 2003 Southern California wildfires. *Environ. Health Perspect.* **2012**, *120*, 1340–1345. [[CrossRef](#)] [[PubMed](#)]
24. Fann, N.; Alman, B.; Broome, R.A.; Morgan, G.G.; Johnston, F.H.; Pouliot, G.; Rappold, A.G. The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Sci. Total Environ.* **2018**, *610–611*, 802–809. [[CrossRef](#)] [[PubMed](#)]
25. Schweizer, D.W.; Cisneros, R. Forest fire policy: Change conventional thinking of smoke management to prioritize long-term air quality and public health. *Air Qual. Atmos. Health.* **2017**, *10*, 33–36. [[CrossRef](#)]

26. North, M.P.; Stephens, S.L.; Collins, B.M.; Agee, J.K.; Aplet, G.; Franklin, J.F.; Fule, P.Z. Reform forest fire management. *Science* **2015**, *349*, 1280–1281. [[CrossRef](#)] [[PubMed](#)]
27. Schweizer, D.; Cisneros, R.; Traina, S.; Ghezzehei, T.A.; Shaw, G. Using National Ambient Air Quality Standards for fine particulate matter to assess regional wildland fire smoke and air quality management. *J. Environ. Manag.* **2017**, *201*, 345–356. [[CrossRef](#)] [[PubMed](#)]
28. Bernes, C.; Borgerhoff-Mulder, M.; Felton, A.; Frampton, G.K.; Gusset, M.; Haddaway, N.; Johansson, S.; Knight, T.M.; Land, M.; Livoreil, B.; et al. *Guidelines for Systematic Review and Evidence Synthesis in Environmental Management. Version 4.2*; Collaboration for Environmental Evidence: London, UK, 2013.
29. US EPA. NAAQS Table. Available online: <https://www.epa.gov/criteria-air-pollutants/naaqs-table%20> (accessed on 30 March 2017).
30. Ward, T.J.; Smith, G.C. The 2000/2001 Missoula Valley PM_{2.5} chemical mass balance study, including the 2000 wildfire season-seasonal source apportionment. *Atmos. Environ.* **2005**, *39*, 709–717. [[CrossRef](#)]
31. Ward, T.J.; Hamilton, R.F.; Dixon, R.W.; Paulsen, M.; Simpson, C.D. Characterization and evaluation of smoke tracers in PM: Results from the 2003 Montana wildfire season. *Atmos. Environ.* **2006**, *40*, 7005–7017. [[CrossRef](#)]
32. Viswanathan, S.; Eria, L.; Diunugala, N.; Johnson, J.; McClean, C. An analysis of effects of San Diego wildfire on ambient air quality. *J. Air Waste Manag. Assoc.* **2006**, *56*, 56–67. [[CrossRef](#)]
33. Herron-Thorpe, F.L.; Lamb, B.K.; Mount, G.H.; Vaughan, J.K. Evaluation of a regional air quality forecast model for tropospheric NO₂ columns using the OMI/Aura satellite tropospheric NO₂ product. *Atmos. Chem. Phys.* **2010**, *10*, 8839–8854. [[CrossRef](#)]
34. Strand, T.; Larkin, N.; Rorig, M.; Krull, C.; Moore, M. PM_{2.5} measurements in wildfire smoke plumes from fire seasons 2005–2008 in the Northwestern United States. *J. Aero. Sci.* **2011**, *42*, 143–155. [[CrossRef](#)]
35. Schweizer, D.; Cisneros, R. Wild land fire management and air quality in the southern Sierra Nevada: Using the Lion Fire as a case study with a multi-year perspective on PM_{2.5} impacts and fire policy. *J. Environ. Manag.* **2014**, *144*, 265–278. [[CrossRef](#)] [[PubMed](#)]
36. Burley, J.D.; Bytnerowicz, A.; Buhler, M.; Zielinska, B.; Schweizer, D.; Cisneros, R.; Schilling, S.; Varela, J.C.; McDaniel, M.; Horn, M.; et al. Air Quality at Devils Postpile National Monument, Sierra Nevada Mountains, California, USA. *Aerosol Air Qual. Res.* **2016**, *16*, 2315–2332. [[CrossRef](#)]
37. Navarro, K.M.; Cisneros, R.; O’Neill, S.M.; Schweizer, D.; Larkin, N.K.; Balmes, J.R. Air-Quality Impacts and Intake Fraction of PM_{2.5} during the 2013 Rim Megafire. *Environ. Sci. Technol.* **2016**, *50*, 11965–11973. [[CrossRef](#)] [[PubMed](#)]
38. Zu, K.; Tao, G.; Long, C.; Goodman, J.; Valberg, P. Long-range fine particulate matter from the 2002 Quebec forest fires and daily mortality in Greater Boston and New York City. *Air Qual. Atmos. Health* **2016**, *9*, 213–221. [[CrossRef](#)] [[PubMed](#)]
39. Robinson, M.S.; Chavez, J.; Velazquez, S.; Jayanty, R.K.M. Chemical Speciation of PM_{2.5} Collected during Prescribed Fires of the Coconino National Forest near Flagstaff, Arizona. *J. Air Waste Manag. Assoc.* **2004**, *54*, 1112–1123. [[CrossRef](#)]
40. Lee, S.; Baumann, K.; Schauer, J.J.; Sheesley, R.J.; Naeher, L.P.; Meinardi, S.; Blake, D.R.; Edgerton, E.S.; Russell, A.G.; Clements, M. Gaseous and particulate emissions from prescribed burning in Georgia. *Environ. Sci. Technol.* **2005**, *39*, 9049–9056. [[CrossRef](#)] [[PubMed](#)]
41. Naeher, L.P.; Achtemeier, G.L.; Glitzenstein, J.S.; Streng, D.R.; Macintosh, D. Real-time and time-integrated PM(2.5) and CO from prescribed burns in chipped and non-chipped plots: Firefighter and community exposure and health implications. *J. Exp. Sci. Environ. Epidemiol.* **2006**, *16*, 351–361. [[CrossRef](#)] [[PubMed](#)]
42. Achtemeier, G.L.; Glitzenstein, J.; Naeher, L.P. Measurements of smoke from chipped and unchipped plots. *South. J. Appl. Forest.* **2006**, *30*, 165–171.
43. Hu, Y.; Odman, M.T.; Chang, M.E.; Jackson, W.; Lee, S.; Edgerton, E.S.; Baumann, K.; Russell, A.G. Simulation of air quality impacts from prescribed fires on an urban area. *Environ. Sci. Technol.* **2008**, *42*, 3676–3682. [[CrossRef](#)] [[PubMed](#)]
44. Robinson, M.S.; Zhao, M.; Zack, L.; Brindley, C.; Portz, L.; Quarterman, M.; Long, X.F.; Herckes, P. Characterization of PM_{2.5} collected during broadcast and slash-pile prescribed burns of predominately ponderosa pine forests in northern Arizona. *Atmos. Environ.* **2011**, *45*, 2087–2094. [[CrossRef](#)] [[PubMed](#)]
45. Pearce, J.L.; Rathbun, S.; Achtemeier, G.; Naeher, L.P. Effect of distance, meteorology, and burn attributes on ground-level particulate matter emissions from prescribed fires. *Atmos. Environ.* **2012**, *56*, 203–211. [[CrossRef](#)]

46. ATSDR. *Public Health Assessment Guidance Manual. Appendix G: Calculating Exposure Doses*; Centers for Disease Control: Atlanta, GA, USA, 2005.
47. Baker, K.R.; Woody, M.C.; Tonnesen, G.S.; Hutzell, W.; Pye, H.O.T.; Beaver, M.R.; Pouliot, G.; Pierce, T. Contribution of regional-scale fire events to ozone and PM_{2.5} air quality estimated by photochemical modeling approaches. *Atmos. Environ.* **2016**, *140*, 539–554. [[CrossRef](#)]
48. CAL EPA. *The Air Toxics Hot Spots Program Guidance Manual for Preparation of Health Risk Assessments*; Office of Environmental Health Hazard Assessment: Sacramento, CA, USA, 2015.



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