Journal of Environmental Management 144 (2014) 265–278

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Wildland 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

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ARTICLE INFO

Article history:
Received 11 March 2014
Received in revised form
3 June 2014
Accepted 9 June 2014
Available online

Keywords:
Smoke impacts
Wildland fire
Policy
Public health
Air quality

ABSTRACT

Management of fire is an important and controversial policy issue. Active fire suppression has led to a backlog of fuels, limited the ecological benefits of fire, and reduced short-term smoke impacts likely delaying these emissions to future generations over a larger spatial extent. Smoke impacts can be expected to increase as fire size and intensity increase and the fuel backlog is consumed; whether through reintroduction of fire under desirable conditions or through stand replacing fire. Land Management Agencies would like to increase the use of naturally ignited fires to burn during favorable conditions as a way to reduce catastrophic fires. This study provides information about the levels of air quality impacts expected from these types of fires and discusses some of the policy controversies of managed fire that propagate inconsistencies between agencies and enter the public discourse. The Lion Fire, a primarily low intensity 8,370 ha fire that was extensively monitored for Particulate Matter less than 2.5 microns ($PM_{2.5}$), is used to quantify impacts to air quality. $PM_{2.5}$ monitoring sites are used to assess exposure, public health impacts, and subsequently quantify annual air quality during a year with a fire that is within the historic normal fire size and intensity for this area. Ground level $PM_{2.5}$ impacts were found to be localized with 99% of the hourly Air Quality Index readings in the moderate or good category for the sites impacted by the fire. $PM_{2.5}$ concentrations at sites nearest the fire were below annual federal air quality standards for $PM_{2.5}$ with annual 98th percentile at the most impacted sites (Johnsondale, Kernville, and Camp Nelson) of 35.0, 34.0, and 28.0 $\mu g\ m^{-3}$ respectively. Smoke impacts to $PM_{2.5}$ concentrations were not found to reach the populated Central Valley. The findings suggest that this type of fire can be implemented with minimal public health impacts thus allowing an opportunity for air and fire managers to alter policy to allow additional burning in an area with severe anthropogenic air pollution and where frequent widespread fire is both beneficial and inevitable. The more extensive air quality impacts documented with large high intensity fire may be averted by embracing the use of fire to prevent unwanted high intensity burns. A widespread increase in the use of fire for ecological benefit may provide the resiliency needed in Sierra Nevada forests as well as be the most beneficial to public health through the reduction of single dose exposure to smoke and limiting impacts spatially.

1. Introduction

Wildland fire management is an important subject for policy makers to address. It is necessary for some ecosystems to thrive but, depending on environmental and weather conditions, may cause detrimental impacts to air quality and to human health. However, some wildland fires and the subsequent smoke impacts to human health may be necessary to best mitigate the extreme air quality events from large high intensity fires. By proactively managing fire under desirable conditions, improved ecological health can provide a resilient and robust forest system in the Sierra Nevada that can help lessen public health impacts from anthropogenic emissions while minimizing air quality impacts from wildfire emissions.

Fire has a significant role in the formation and health of forests in the California Sierra Nevada (Kilgore, 1981). Before active suppression of wildfires, slow moving low intensity ground fires dominated this ecosystem providing an ecological pressure that

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http://dx.doi.org/10.1016/j.jenvman.2014.06.007
0301-4797/

shaped the fire-adapted and tolerant species native to this area. The natural process of frequent, low intensity burns is essential to maintaining healthy landscape level populations and overall forest health (e.g. Swetnam et al., 2009; Moreira et al., 2010; Ferrenberg et al., 2006; Keeley et al., 2005; Zimmerman and Laven, 1987; Parmeter and Uhrenholdt, 1975). Fire adaptation and tolerance are necessary for the continued health of this ecosystem particularly in the face of climate change (Stephens et al., 2010).

Wildfire activity has increased with longer wildfire seasons coupled with larger size and longer duration wildfires (Westerling et al., 2006) since the radical suppression tactics utilized over the last century and a half. High severity stand-replacing fire has been increasing in the Sierra Nevada since the mid-1980s, with mean and maximum fire size and annual area burned at or above those before the national policy of suppression was instituted (Miller et al., 2009). Total burned areas in recent years, which currently are considered "extreme fire years," are typical of historically normal burn years (Stephens et al., 2007). Although burned area is similar, emissions of current fires can be greater because of excessive fuel loading from past fire suppression and increased fire intensity caused by warmer and dryer conditions.

Fire policy by Land Management Agencies (LMAs) has being changing over the last two decades. Past suppression policies are now recognized as one important factor leading to the catastrophic and unnatural forest fires presently occurring. Prescribed Burning (PB) started to be implemented in federally protected lands in California in an attempt to re-introduce fire as a natural process in the forest. In California, the National Park Service started implementing PBs in 1960s and the U.S. Forest Service started in the 1990s. After years of PB, it is apparent that the small scale burning typical of PB (<200 ha) will not lead to the landscape level restoration of fire sought by LMAs. Thus LMAs are proposing wider implementation of managed fire (MF). A MF is typically started with a natural ignition (lightning) and of larger size than PB. MFs utilize smoke dispersal, meteorological, and fuel conditions which allow for the safest implementation. MF is different from fires that use full suppression tactics in that larger areas are allowed to burn, when there is no threat to life or property, to maximize the beneficial effects of fire while reducing fire cost and increasing firefighter safety.

The Lion Fire was a naturally ignited fire in California that was allowed to burn as a MF. LMAs suggested that this type of fire (MF) could be implemented successfully allowing for fire to return to the landscape without causing ecological damage and at the same time impacts to air quality can be minimized to the extent that air pollutants in the most smoke impacted areas are below federal thresholds.

The Lion Fire is representative of a fire the size and intensity which historically occurred and is needed to restore and sustain the natural role of fire in the Sierra Nevada (Beaty and Taylor, 2008). Historically fire in this forest type burned on average between 11 and 40 years (Van de Water and Safford, 2011), but this area had not burned in approximately 90 years, therefore fuel loads were greater producing larger emissions that would not have occurred with the historically lower fuel loads from more frequent fire.

1.1. Wildland fire, smoke, and ambient air quality

Burned area alone is not indicative of emissions from wildland fire. In addition to fire size, fuel loading, fire intensity, and fuel consumption at a minimum need to be understood to accurately assess emissions. Emissions from a wildland fire are not indicative of ground level concentrations of Particulate Matter less than 2.5 microns ($PM_{2.5}$) and are difficult to predict (Yao and Henderson, 2014) even during large fires. Ground level concentrations and the subsequent impacts to air quality and human health are a product of emissions, plume height, transport distance, dispersal, and a suite of meteorological parameters. Background levels of pollutants in a fire-adapted ecosystem must also account for the reduction of smoke during an era of suppression where background levels are artificially reduced or in essence delayed until fuels are consumed. Lack of fire as has been typical during the era of fire suppression can be taken as artificially reducing smoke impacts to local air quality while providing a backlog of future emissions. Fire suppression in the Sierra Nevada which predates the beginnings of air quality monitoring for public health has likely led to an unsustainable expectation that background air quality in the Sierra Nevada is primarily smoke free. Burned areas during times now considered extreme fire years are potentially more indicative of the areas burned before fire suppression was implemented in California, although the overall impacts to ground level air quality may be higher than a natural background from the increased fuel loading and climate change (Hurteau et al., 2014). The backlog of fuels created through years of fire suppression has likely created an emissions deficit that will be confronted in the near future by an increasing population. Thus it is imperative to address the issue of smoke and public health with proactive policy that considers the dilemma of withholding smoke emissions that are to be saddled on the public in the future.

Mortality impacts attributed to smoke from wildland fire are only recently beginning to be understood. Sastry (2002) only consistently found a mortality impact at high particulate matter levels (PM_{10} above 210 μg m^{-3}). Lower levels ($PM_{2.5}$ level below 48 μ gm^{-3}) were not found to create a significant mortality impact (Vedal and Dutton, 2006). Kochi et al. (2012) found a threshold effect for mortality in densely populated areas of San Bernardino County during the large wildfires of 2003 in southern California (PM_{10} levels over 360 μg m^{-3} and $PM_{2.5}$ levels over 100 μg m^{-3}) but did not find significant mortality impacts in less densely populated areas with similar levels or in densely populated areas with milder levels. Johnston et al. (2013) reported that decreased air pollution from biomass smoke was associated with reductions in mortality. Smoke management in a fire adapted ecosystem must incorporate both the immediate and long term smoke impacts to public health including the spatial scale of smoke impacts under different fire management scenarios.

1.2. Public perception of smoke

Without an understanding of smoke impacts from altering the fire regime, a strong incentive exists to suppress and delay emissions to the future. This is in part due to public perception of fire and fire management being complex and belief based (Bright et al., 2007) likely reflecting the complexity of fire, evolving fire management techniques (Brown et al., 2004; Dellasala et al., 2004), and public perceptions (Gauchat, 2012) and awareness (Murphy et al., 2007) in particular when attempting to understand the role of fire for ecologic and human health. Public health officials and the general public are biased to offsetting smoke emissions to some future date to limit the pollutants today. This is especially true in areas of high anthropogenic pollution and where smoke impacts directly impact the local economy. This creates a dilemma for fire managers where it is easier to suppress fire for the immediate benefits than to actively manage for forest health. Healthy relationships between stakeholders are integral to healthy forests and public understanding of smoke from wildland fires (Champ et al., 2012).

Compounding public perception of risk from smoke is the high visibility of smoke from wildland fires in the Sierra Nevada. The Sierra Nevada rise from the California Central Valley, perching

Sierra Nevada wildland fires above major urban areas. Plumes from wildland fires in the Sierra Nevada are almost always visible from at least one urban area in the Central Valley. Additionally, prevailing winds typically move west to east dispersing smoke over the Owens Valley frequently reducing visibility in this tourist based economy. Even though smoke from wildland fire is innately a part of the Sierra Nevada and as essential as floods, blizzards, wind storms and other natural processes, agency and public perceptions, beliefs, and attitudes are variable (Steelman and McCaffrey, 2011) and include a belief that smoke free air in the mountains of the Sierra Nevada is a standard condition instead of an anthropogenic bi-product of fire suppression that is not sustainable.

1.3. Fire policy as perceived by Land Management Agencies in the Sierra Nevada

Large areas of the Sierra Nevada are managed by federal agencies. The U.S. Department of the Interior National Park Service (NPS) and the U.S. Department of Agriculture Forest Service (USFS) are the primary land management agencies in the Sierra Nevada west of the crest. Although these two agencies are quite often confused by the general public, their founding missions are fundamentally different. The NPS is a conservation organization where anthropogenic impacts are eliminated to the greatest extent possible while the USFS allows for regulated sustainable use of the forest ecosystem. On USFS managed land, human activities such as logging, hunting, mountain biking, motorized vehicle use, etc. are typically less restricted than on NPS managed land.

Both the USFS and the NPS manage designated Wilderness Areas. The Wilderness Act is the legislation intended to guide management of these areas for federal land managers (FLMs). The Wilderness Act restricts the development of these areas and requires FLMs to protect and preserve the natural conditions. FLMs are largely restricted from using invasive techniques such as mechanical thinning in Wilderness Areas. The goal is to have a naturally functioning ecosystem to provide the public with a place of solitude connected to the natural world, a connection with the historic value of the American wilderness, and an area set aside for the conservation of plant and animal species for all to enjoy. Natural areas also have the capacity to enhance air and water quality though restricting development and allowing the natural system to act as a pollution sink and natural buffer to anthropogenic impacts (Hurteau and North, 2009; Fule, 2008; Hurteau et al., 2009; Hurteau and North, 2010).

Nowhere do these lofty goals come in more conflict than smoke management from a natural ignition wildland fire in a Wilderness Area Not only is it well understood that fire plays an essential role in the health of the Sierra Nevada (Beaty and Taylor, 2008; Nesmith et al., 2011) but it is also understood that wildland fire is necessary to reduce fuels that have accumulated from past fire suppression policies to a degree which threaten the ecological integrity of these forests (Reinhardt et al., 2008) while attempting to mitigate potential increases in fire activity from climate change (Liu et al., 2010; Spracklen et al., 2009). But, FLMs are not only regulated by the Wilderness Act, they are also regulated by a myriad of other laws, acts, and policies including the Clean Air Act (CAA, 2011) and the Regional Haze Rule (1997). The public, public health officials, representatives of tourist based economies, and smoke sensitive residents pressure LMAs to fully suppress these fires.

Land management policy objectives and the current understanding of ecological benefits provide clear direction to manage these fires on the landscape while air regulation policy through the Clean Air Act (2011), Regional Haze Rule (1997), etc. attempt to restrict anthropogenic emissions. Economic interests compete for these emission thresholds and the overall capacity of an air shed to disperse and buffer pollutants. Wildland fire emissions to the air shed, even though a natural process emission, are typically managed as an anthropogenic emission. This provides conflicting policy and direction where regulator coordination has been difficult (Arbaugh et al., 2009) and public opinion is heavily weighted through the use of complaint programs. Additionally through policies such as the Exceptional Events Rule (2007), air regulators have more latitude for compliance with air quality standards when natural events can be determined to have caused air quality violations. Although in practice this has been complicated by how to document the contribution from a wildfire and the interpretation of what is a natural event wildfire (California Title 17 (California Code of Regulation, 2014) considers a natural ignition fire as a PB). Land managers are thus in the conundrum of mitigating smoke impacts during a natural ignition fire with little public support or suppressing all fire which withholds emissions until a MF with full suppression occurs where air quality impacts are marginalized by the more immediate concerns of loss of life and property from the fire itself.

1.4. National and California Ambient Air Quality Standards and smoke management

Air quality in the U.S.A. is regulated through a multifaceted approach using Federal, State, and local laws to assure compliance with clean air requirements established by the CAA.

The CAA was passed in 1963 and establishes the regulatory framework for air pollution prevention and control in the United States of America. The primary goal of the CAA is pollution prevention through "… reasonable Federal, State, and local governmental actions" (CAA, 2011). The CAA (2011) was established to "protect and enhance" the air resources of the United States, expand and improve research of air pollution, provide national assistance to State and local governments for air pollution control and prevention, and to foster regional air pollution control and prevention programs. The U.S. Congress, recognizing that the U.S. population was increasingly located in expanding urban areas and "that the growth in the amount and complexity of air pollution brought about by urbanization, industrial development, and the increasing use of motor vehicles, has resulted in mounting dangers to public health and welfare" (CAA, 2011), found "… Federal financial assistance and leadership is essential for the development of cooperative Federal, State, regional, and local programs to prevent and control air pollution." (CAA, 2011) The primary responsibility of prevention, reduction, and elimination of air pollution at its source lies with the States and local governments. Pollution prevention is expected with cooperation of all levels of government through Federal, State, and local laws. Federal standards provide basic requirements which State and local law can make more stringent. Cooperation has not fulfilled this standard. Because this cooperation is essentially based in regulating anthropogenic pollutants natural sources of pollutants are not willingly accepted into a polluted air district. When emissions from economically advantageous industries are by necessity being regulated, natural emissions are an easy target to eliminate. There is no incentive in the CAA to allow for natural source emissions providing a difficultly in allowing wildland fire.

The CAA establishes a framework of uniform laws with federal enforcement. In addition to regulating air pollutants, the CAA includes guidance on visibility, prevention of significant deterioration of air quality and visibility, in wilderness areas, emissions and fuel standards, noise pollution, and stratospheric ozone protection. Compliance to the CAA is primarily administered by the U.S. Environmental Protection Agency (EPA). The EPA establishes National Ambient Air Quality Standards (NAAQS) as benchmark levels of criteria pollutants and ensures compliance with these standards. Areas below the NAAQS are considered "attainment areas" while areas above are "nonattainment areas". Meeting the NAAQS is delegated to the state. Individual states are granted primary responsibility for assuring air quality by the establishment of a State Implementation Plan (SIP). The SIP specifies how the state will achieve the national primary and secondary ambient air quality standards.

A 1977 amendment to the CAA established regulatory protection for visibility in wilderness and other natural, scenic, and historic areas. Wilderness areas managed by federal land management agencies are now provided addition protection with a "prevention of significant deterioration of air quality" (CAA, 2011) from additional anthropogenic point source emissions (i.e. power plants).

For human health protection, the EPA has established primary standards for 6 criteria pollutants (Particulate Matter (PM_{10}, $PM_{2.5}$), Ozone (O_3), Sulfur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), and Lead (Pb)). The California Clean Air Act (1988) established additional more stringent standards for these criteria pollutants and also established standards for sulfates, hydrogen sulfide, vinyl chloride, and visibility reducing particles with the California Ambient Air Quality Standards (CAAQS). Areas in compliance with the standards are considered "attainment" areas, while those areas not in compliance are considered "non-attainment" areas.

In California, the California Air Resources Board (CARB) is the responsible state agency. CARB further delegates this responsibility to local Air Pollution Control Districts or Air Quality Management Districts. The Districts have the primary responsibility for meeting the requirements of the CAA (Fig. 1). Emissions from both MF and prescribed fire are considered air pollutants with regulatory oversight by CARB and the Districts. This causes a dilemma for a fire like the Lion Fire to be implemented as a MF as it is perceived as a PB and there is no incentive for an air district to accept additional emissions from fire. Additional emissions create disincentives including nuisance complaints and possible enhancement of standard violations in a non-attainment area to air regulators. Additionally, public health officials necessarily will discourage smoke emissions as any smoke subjects the public to exposure which will inevitably lead to public health issues particularly for the young, elderly, and other sensitive groups. In an anthropogenic polluted air basin it is particularly difficult to confront some smoke today when it can be postponed to some undetermined future date.

Emissions from wildland fires impact air quality and contribute to air pollutant concentrations (Langmann et al., 2009). Smoke from wildland fires impact visibility locally and regionally (McMeeking et al., 2006). Anthropogenic emissions in the California create widespread air quality impacts with approximately 28% of the land area of California and 26 million (70%) of its residents living in areas designated as nonattainment of the federal standards for $PM_{2.5}$. This includes the California Central Valley which is one of the most polluted air sheds in the world. $PM_{2.5}$ is a significant problem for air quality in this area and is a component of smoke generated from fires. This has led the Air regulatory agencies to be even more stringent when it comes to putting fire back on the landscape.

Exposure to smoke has adverse impacts to human health (Kochi et al., 2010). Large uncontrolled wildland fires on public lands can have significant impacts on air quality in urban areas (Viswanathan et al., 2006) with an increased exposure to smoke causing an increase risk to human health (Tham et al., 2009; Kunzli et al., 2006). Current health research also underlines the impacts of smoke at low doses and differing socio-economic factors (Rappold et al., 2012) which will undoubtedly yield a better understanding of smoke mitigation in the ensuing years that will provide air and fire managers better insight into smoke impacts on all communities from multiple fire scenarios using PB, MF, and full suppression. Understanding impacts from wildland smoke are further confounded by location in California where chronic $PM_{2.5}$ exposure is highly dependent on location. Exposure to high concentrations of $PM_{2.5}$ is typical in the Central Valley while concentrations typically are much lower as elevation increases and population density

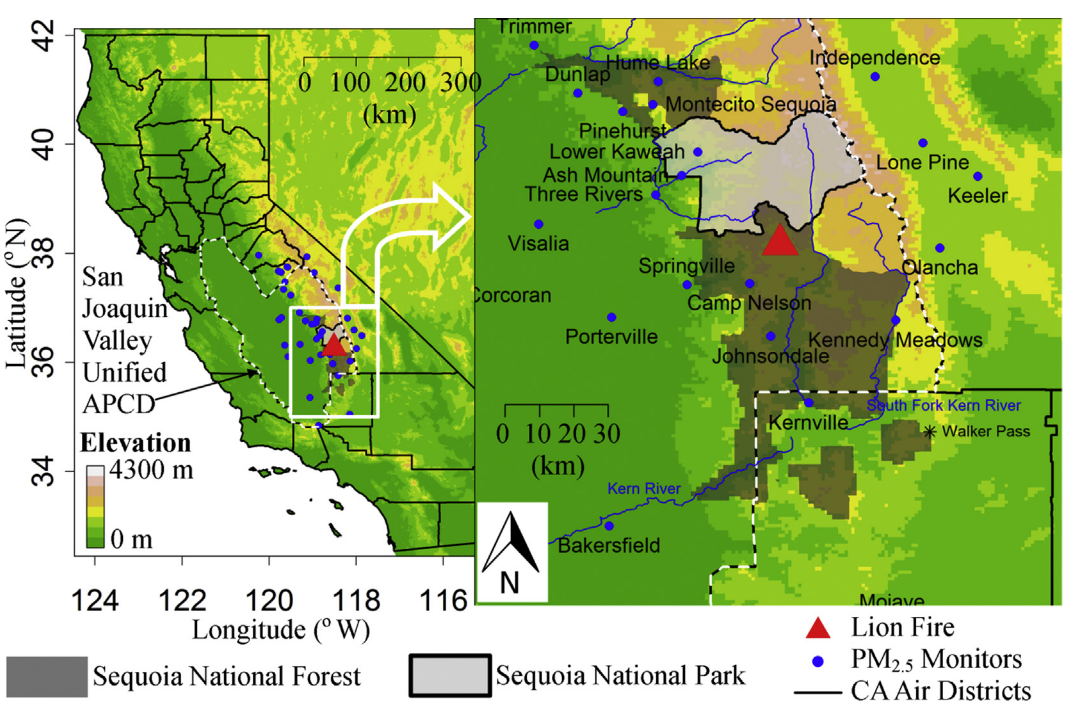

Fig. 1. California air district boundaries and Particulate Matter less than 2.5 microns ($PM_{2.5}$) monitoring site locations.

decreases (Cisneros et al., 2014). Excess mortality from wildland smoke is similar to general estimates for urban PM (Hanninen et al., 2009) suggesting federally developed health standards would accurately represent relative risk for a given population.

1.5. Competing priorities in smoke management: the balancing act

Federal land managers and air regulators attempt to balance competing priorities between fire and air quality. Advances in wildfire simulation and predictive models are helping to frame federal wildland fire policy and operations by implementing a risk management framework to support the decision making process (Calkin et al., 2011a; Vadrevu et al., 2010; Calkin et al., 2011b) but there is an inherent unpredictability in wildfire behavior and uncertainty in prioritizing value to ecological and human health impacts (Brugnach et al., 2011; Thompson and Calkin, 2011). This again leads to air policy through the CAA being invoked to discourage MF because the risk of a larger than predicted smoke event can essentially stop an active fire management program for many years.

Smoke transport and the unpredictability of wildland fire and the subsequent emissions makes MF very difficult to conduct because of smoke management. Smoke impacts to air quality are dependent on weather (i.e. wind speed and direction), seasonal timing, and emissions (i.e. fuel loads, fire intensity) (Tian et al., 2008). There is an opportunity to use MF to better control these emissions and potentially mitigate some smoke impacts to public health with better control of the timing and intensity of emissions. Large uncontrolled fires with burn intensities greater than the historic normal will produce major air quality impacts while fires burning within normal fire intensity in the Sierra Nevada have less impact over a smaller area. Increasing MF ideally would reduce the spatial extent of smoke impacts by controlling fire intensity and size but would also likely increase localized exposure to some smoke as more fires in a given area are allowed to burn.

This manuscript will test that hypothesis that the Lion Fire did not significantly impact air quality and provide insight and information about the conflicting policies connected to this case study. Thus data presented in this paper are assumed to be representative of a conservative estimate of ground level concentrations of $PM_{2.5}$ from a wildland fire in the southern Sierra Nevada and representative of other areas where fire suppression has left an unnatural fuel load. Smoke impacts to public health are evaluated during the event and analyzed to understand the significance of a fire this size on local and regional air quality. This study uses air quality concentrations of $PM_{2.5}$, one of the criteria pollutants under the National Ambient Air Quality Standards (NAAQS), collected during the fire to identify impacts. Current Federal fire policy with respect to public and ecological health is discussed to help balance the conflict between air and land management as it relates to wildland fire and ultimately to determine if smoke impacts to air quality are minimized successfully when allowing active use of wildland fire as a tool for land managers.

2. Material and methods

2.1. Fire location and description

The Lion Fire started near Lion Meadow in the Golden Trout Wilderness on the Sequoia National Forest (36° 16′ 5″ N, 118° 30′ 40″ W) and primarily burned in the Golden Trout Wilderness of Sequoia National Forest. The fire burned a total of 8,370 ha from 7/8/2011 to 9/7/2011. 7,920 ha burned in the Sequoia National Forest and 450 ha in Sequoia National Park (Fig. 1). Fire information data for the Lion Fire and other wildland fire emission sources during this period were obtained from the National Interagency Fire Center (2012) additional local fire information was obtained from the Sierra Wildland Fire Reporting System (2012) and Forest and National Park Service staff.

The ignition point was near Lion Meadow approximately three quarters of a mile north-northeast of the confluence of the Little Kern River and Lion Creek. The fire initially burned north and east toward the Great Western Divide which in this area separates the Little Kern and the Kern River drainages. The fire then progressed generally north and west; up the Little Kern River and Pecks Creek drainages. After ignition on July 8, 2011 the fire grew at less than 150 ha per day until July 17. Over the next three days the fire grew about 1,500 ha, followed by 2 days of slower growth. Reported fire size increased by over a 4,600 ha from July 23 to July 28, and then growth slowed to 206 and 334 ha. After July 30 the fire did not increase by more than 136 ha per day. Areas of the fire with high severity primarily occurred 7/19–20 and 7/25–28.

2.2. Data collection

$PM_{2.5}$ data from 34 monitoring sites (Table 1) was compiled and used to assess smoke exposure to human health. Site locations ranged from approximately 16.6 km–242.8 km from the ignition point of the Lion Fire.

Data for regulatory sites in California was obtained from the California Air Resources Board (CARB) Air Quality and Meteorological Information System (2012). Data from tribal lands (Lone Pine and Bishop) is from the Tribal Environmental Exchange Network (2012). Data from Nevada is from Clark County Department of Air Quality (2012). Smoke emissions from wildland fire in the Sierra Nevada 7/8–9/7/2012 (during the Lion Fire) were almost entirely from the Lion Fire with no other fire burning over 40 ha. Wildland fires that occurred during this time (excluding the Lion Fire) exhibited short term (typically less than 1 day) and localized smoke impacts. Newly ignited wildland fires throughout the Sierra Nevada during this time were actively suppressed reducing or eliminating smoke impacts from other wildland fires at all monitoring sites. Levels of $PM_{2.5}$ at sites where smoke from the Lion Fire was not present were within normal variations typical in the Sierra Nevada (Cisneros et al., 2014).

Met One Instruments, Inc. (Oregon, U.S.A.) Beta Attenuation Monitors BAM-1020 (BAM) were used at permanent monitoring sites where data was collected year round, and Met One Instruments, Inc. Environmental Beta Attenuation Monitors (EBAM) were used at the non-regulatory temporary monitoring sites (see Table 1 for dates of operation). The BAM can be used as a Federal Equivalent Method (FEM) for measuring $PM_{2.5}$. FLMs BAMs do not adhere to the EPA FEM requirements and therefore the $PM_{2.5}$ data is not appropriate for compliance determination. The EBAM is designed for temporary and quick deployment. The EBAM has not been designated by the EPA as an FEM. BAM hourly measurements have a resolution of ± 0.1 $\mu g\ m^{-3}$. EBAM accuracy is $\pm 10\%$ of the indicated value for hourly measurements with data resolution of 1.0 $\mu g\ m^{-3}$. The BAM (EBAM) hourly lower detection limit, set by twice the standard deviation of the hourly zero noise, is less than 4.8 $\mu g\ m^{-3}$ (6.0 $\mu g\ m^{-3}$). The BAM (EBAM) 24-h average lower detection limit is less than 1.0 $\mu g\ m^{-3}$ (1.2 $\mu g\ m^{-3}$) (Met One Instruments, Inc, 2008a; Met One Instruments, Inc., 2008b).

2.3. Data calculations

Annual $PM_{2.5}$ calculations are based on the *Guideline on Data Handling Conventions for the PM NAAQS* (US EPA, 1999). Calculations and graphics were made using the R statistical environment (R Core Team., 2012; Carslaw and Ropkins, 2012) FLM air monitoring sites

Table 1
Site Information arranged by distance from the fire.

Site	Latitude (N)	Longitude (W)	Regulatory	Temporary site dates	Distance (km) and direction from lion fire	
Camp Nelson	36.14105	118.60876	No	7/14–10/4/2011	16.6	SW
Springville	36.13625	118.81070	No	Permanent site	30.7	WSW
Johnsondale	35.96970	118.54090	No	7/14–10/6/2011	33.2	S
Three Rivers	36.42792	118.91230	No	7/8–10/7/2011	40.2	WNW
Lower Kaweah	36.56580	118.77720	No	7/19–10/19/2011	40.6	NW
Ash Mountain	36.48940	118.82920	No	Permanent Site	40.8	NW
Kennedy Meadows	36.02135	118.13690	No	6/15–10/28/2011	43.4	SE
Olancha	36.25534	117.99390	No	7/29–9/7/2011	46.5	E
Lone Pine	36.59556	118.04917	Yes	Permanent site	55.1	NE
Porterville	36.03183	119.05500	Yes	Permanent site	55.5	WSW
Kernville	35.75506	118.41740	No	Permanent site	57.5	S
Pinehurst	36.69731	119.01880	No	Permanent site	62.1	NW
Keeler	36.48791	117.87111	Yes	Permanent site	62.4	ENE
Montecito Sequoia	36.71900	118.92200	No	7/7–7/22/2011	65.9	NW
Independence	36.80994	118.20370	No	7/14–9/6/2011	66.1	NE
Hume Lake	36.79447	118.90490	No	7/7–8/11/2011	68.2	NW
Visalia	36.33250	119.29100	Yes	Permanent site	70.4	W
Dunlap	36.75695	119.16531	No	7/8–7/20/2011	79.9	NW
Corcoran	36.10222	119.56583	Yes	Permanent site	96.7	W
Trimmer	36.91119	119.30600	No	6/16–10/6/2011	100.8	NW
Hanford	36.31472	119.64333	Yes	Permanent site	101.8	W
Bakersfield	35.35667	119.06278	Yes	Permanent site	112.7	SW
Bishop	37.36667	118.41667	Yes	Permanent site	122.2	N
Clovis	36.81944	119.71639	Yes	Permanent site	124.1	WNW
Fresno	36.78194	119.77306	Yes	Permanent site	126.6	WNW
Mojave	35.05035	118.14811	Yes	Permanent site	139	SSW
North Fork	37.23300	119.50600	No	6/16–10/29/2011	139.1	NW
Oakhurst	37.33989	119.66700	No	8/12–9/7/2011	157.5	NW
Mammoth Lakes	37.64729	118.96430	No	8/14–9/6/2011	158.3	NNW
Lebec	34.84167	118.86056	Yes	Permanent site	161.4	SSW
Lebec2	34.84150	118.86050	Yes	Permanent site	161.4	SSW
Yosemite Valley	37.74861	119.58694	No	Permanent site	190.2	NW
Lee Vining	37.93979	119.12840	No	8/14–9/6/2011	193.5	NNW
Tuolumne	37.96199	120.23920	No	8/13–9/6/2011	242.8	NW

are typically not regulatory monitors and the data presented here is for comparative purposes to help better understand regulatory compliance and smoke impacts at more rural mountain communities in the southern Sierra Nevada. FOFEM6 (2013), a first order fire effects model, was used to calculate $PM_{2.5}$ emissions throughout the fire. Primary cover types used were Ponderosa Pine, Red Fir, and Sierra Nevada Mixed Conifer.

Air Quality Index (AQI) is a system of reporting daily air quality established by the U.S. Environmental Protection Agency (EPA). AQI has 6 categories (good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous) with thresholds depending on a given pollutant. EPA breakpoints (0–12, 12.1–35.4, 35.5–55.4, 55.5–150.4, 150.5–250.4, 250.5–500 $\mu g\ m^{-3}$) are used when determining the AQI for the daily or 24-h $PM_{2.5}$ concentration. Daily human health impacts are also assessed by comparing one hour $PM_{2.5}$ concentrations to the standards set by the California Office of Environmental Health and Hazard Assessment (2013) for public health officials. The 1–3 h average breakpoints from good to hazardous are 0–38, 39–88, 89–138, 139–351, 352–526, >526 $\mu g\ m^{-3}$ respectively. These standards have not been implemented as regulatory standards but are routinely used by public health officials and land managers in California to assess smoke exposure and issue appropriate smoke advisories during a wildland fire.

Established regulatory NAAQS thresholds are used to determine long term health impacts from smoke exposure during the Lion Fire. Annual $PM_{2.5}$ statistics for permanent non-regulatory sites (Table 1) are calculated using the NAAQS data handling conventions and are compared to both regulatory standards and the urban regulatory monitoring sites.

NAAQS data handling convention protocol require the 98th percentile to be calculated as a rank value. All daily concentrations over a given year are ranked from highest to lowest. The 98th percentile is then determined dependent on the number of daily samples obtained. Daily samples are required to be representative of the entire year so that high concentrations are not missed due to sample timing. If less than 50 days are sampled equally throughout the year, the highest (1st) daily concentration is the 98th percentile for the year. With more samples, the rank increases until the 8th highest day of a given year is used when 351 or more days are recorded. Because temporary sites used in the Lion Fire did not collect full year data and were sampling every day, we used the 5th highest concentration as a conservative estimate of the annual 98th percentile. Using the 5th highest concentration by NAAQS data handling conventions would mean 201–250 of the daily mean concentrations for the year were recorded or 3 of the highest daily concentrations occurred when data was not being collected. Temporary monitoring site locations were located at elevations where $PM_{2.5}$ concentrations are highest in the summer and with maximum concentrations typically occurring during a smoke event (Cisneros et al., 2014). We believe using the 5th highest concentration, rather than the 8th highest concentration, is a conservative estimate of the 98th percentile for these temporary sites because the highest $PM_{2.5}$ concentrations for the year were likely during the Lion Fire. Use of the 5th highest concentration allows for 3 daily high concentrations to be missed during the segment of the year when $PM_{2.5}$ was not monitored and concentrations were likely lower. This ensures at least 55% of the highest daily readings for the year were captured at temporary sites during the Lion Fire thus leading to a conservative (low) valuation of the 98th percentile.

Annual federal standards are 3-year mean concentrations. Exceeding the federal threshold on a given day or for a year does not inevitably result in exceeding the federal standard.

3. Results

3.1. Smoke transport

Emissions estimates of $PM_{2.5}$ were approximately 24,000 Mg for the entire fire with the 3 highest emissions days being 7/26 (3,300 Mg), 7/25 (2,980 Mg), and 7/27 (2,600 Mg).

Upper air winds were typically from the west and generally moved smoke that was aloft to the east. HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) forward trajectories (NOAA Air Resources Laboratory, http://ready.arl.noaa.gov/HYSPLIT.php) frequently predicted air transport to the south or southeast and north through the Owens Valley in the mornings and northeast in the afternoons (Fig. 2). Satellite imagery including smoke density data from the Hazard Mapping System (HMS) Fire and Smoke Product (NOAA National Environmental Satellite, Data, and Information Service http://satepsanone.nesdis.noaa.gov/FIRE/fire.html) and web cameras show the typical transport pattern from the fire was east and northeast across the Owens Valley into Nevada during the day (Fig. 2) and would sink into local river drainages (primarily the Kern River drainage) at night.

Smoke was transported throughout the Sierra Nevada and east into and beyond the Owens Valley. The complex topography of the Sierra Nevada dictated timing and location of the largest $PM_{2.5}$ impacts as smoke frequently settled into and was transported through drainages. The Kern River drainage dominated the ground level transport of smoke from the fire. Night-time conditions drew smoke from the Lion Fire down the Little Kern River drainage into the Kern River drainage south to Lake Isabella and east towards Walker Pass. This pattern was typical of smoke patterns documented by ground observations and $PM_{2.5}$ monitoring during the fire.

3.2. $PM_{2.5}$ AQI during the Lion Fire

Air quality impacts to $PM_{2.5}$ from the Lion Fire as determined by AQI were localized, and extended furthest in the major transport corridor of the Kern River drainage. Effects from the Lion Fire could not be determined to impact the Central Valley. Sites nearer the fire typically saw increased concentrations into the good or moderate category.

Monitoring sites with the largest impacts from the Lion Fire $PM_{2.5}$ were Johnsondale, Camp Nelson, and Kernville. Camp Nelson

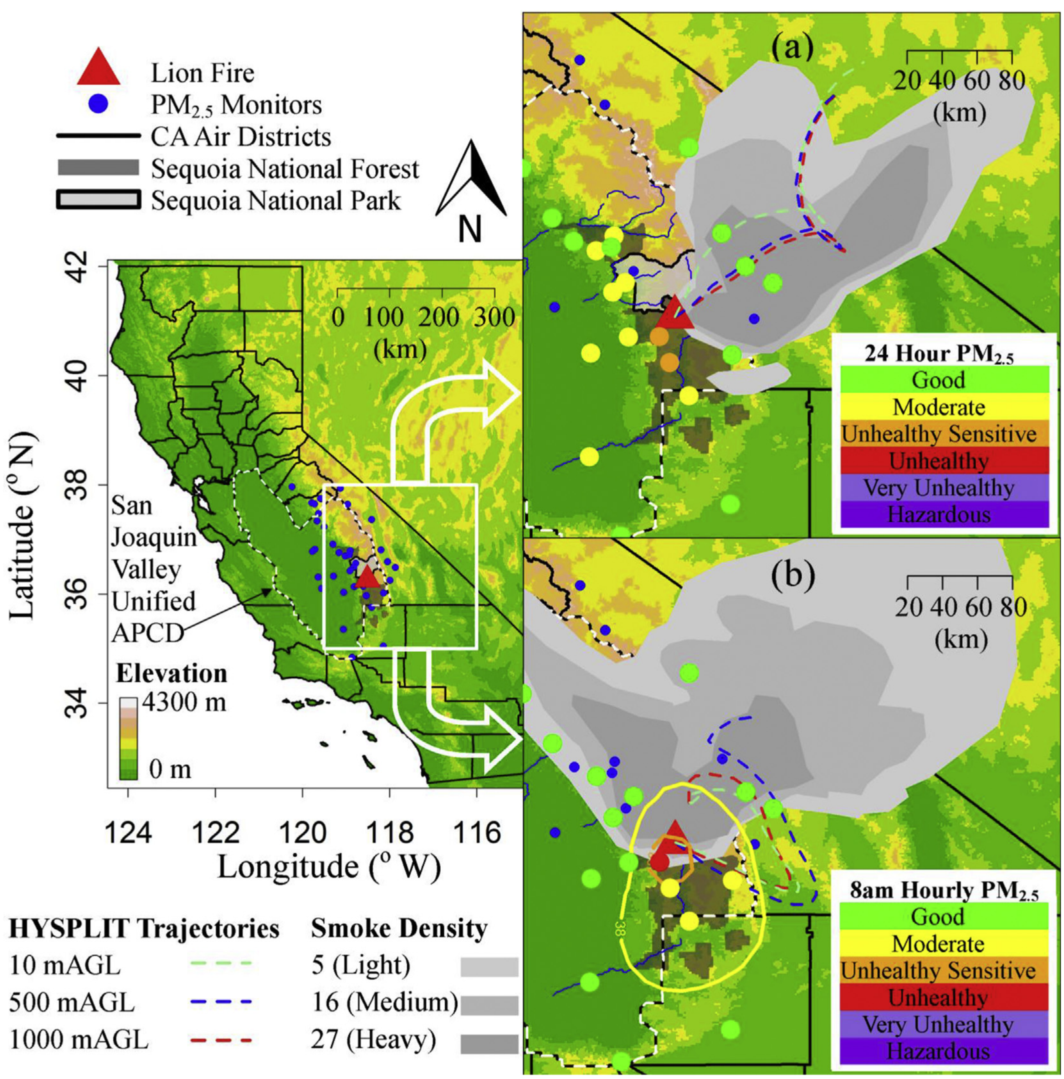

Fig. 2. Smoke dispersal patterns using monitoring site data, Hazard Mapping System (HMS) data, fitted trend surface using hourly ground based data, and HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) forward trajectories for (a) afternoon 7/18/2011 1600 with daily Air Quality Index (AQI) for each site (fitted trend surface modeled using the hourly data was good for entire area) and (b) morning (7/26/2011 0800) with 1-h AQI for each site.

experienced the highest levels of $PM_{2.5}$ (376 μg m^3 max hourly and 166.7 μg m^3 max 24-h) but had only 17 days (24-h mean) above and AQI of good. Both Kernville (211 μg m^3 max hourly and 68.4 max 24-h) and Johnsondale (333 μg m^3 max hourly and 95.8 μg m^3 max 24-h) did not have such high single day concentrations, but both experienced more days above an AQI of good (38 and 35 days respectively) than Camp Nelson (Table 2).

Highest concentrations of $PM_{2.5}$ at Kernville typically come from the south and southeast (Fig. 3a). During the Lion Fire the highest $PM_{2.5}$ concentrations at Kernville were from the north and northeast as smoke transport down the Kern River canyon dominated (Fig. 3b). Smoke sank into the Kern River drainage and was transported down drainage to Kernville during the night and was reflected in the higher $PM_{2.5}$ concentrations from the north (Fig. 3c). The Kernville area then vented in the afternoon subjecting the Kernville area to smoke exposure primarily between 5 am and 11 am (Fig. 4) with afternoon emissions from the fire lofted and generally transported east over the Owens Valley. Highest hourly concentrations at Kernville were in the unhealthy range. Hourly concentrations of $PM_{2.5}$ were normally lower at Kernville than Johnsondale (Fig. 5) which was further up the Kern River drainage and nearer to the Lion Fire. At Kernville, AQI was unhealthy for 10 total hours and 1 day (Table 2) and unhealthy for sensitive for 33 total hours and 5 days.

Smoke was transported from the Lion Fire to Johnsondale from the east through the South Creek drainage with highest concentrations in the morning. Hourly and 24-h rolling concentrations at Johnsondale were typically highest in the morning with maximums in the unhealthy category. Fifteen hours on 6 different days with 1 daily AQI of unhealthy occurred at Johnsondale and 19 h and 3 days were unhealthy for sensitive (Table 2).

The nearest monitor was approximately 16.6 km southwest at Camp Nelson. Camp Nelson was generally upwind of the fire as smoke typically was blown east during the day and settled into drainages east of Camp Nelson at night keeping concentrations generally low punctuated by a few hours of very high concentrations on 3 separate days. The Camp Nelson site recorded both the highest hourly (376 μg m^{-3}) and highest daily (167 μg m^{-3}) mean $PM_{2.5}$ concentrations during the Lion Fire (Fig. 5) illustrating the impacts of nearness to the emissions source. Camp Nelson had hourly $PM_{2.5}$ in the good category for some time during every day monitored during the Lion Fire. For 2 h on 7/31/2011 hourly $PM_{2.5}$ was very unhealthy. The 22 h of unhealthy occurred over 7 days with 8 of those hours also occurring on 7/31/2011. On 7/31/2011 hourly $PM_{2.5}$ was good for 10 h. AQI at Camp Nelson was very unhealthy for 2 h, unhealthy for 14 h and 2 days, and unhealthy for sensitive for 7 h and 2 days (Table 2).

At the Kennedy Meadows site, $PM_{2.5}$ concentrations typically are highest with winds from the west but were highest from the south during the Lion Fire as smoke from the Kernville area was transported up the South Fork of the Kern River. At Kennedy Meadows, $PM_{2.5}$ concentrations were moderate or good with 4 h unhealthy for sensitive.

East side monitors in the Owens Valley at Olancha and Independence reached maximums in the moderate category for $PM_{2.5}$.

Central Valley sites in Bakersfield, Visalia, and Fresno were moderate or good which is typical for this time of year in these urban sites during the fire. These sites were similar to other sites throughout the entire Central Valley.

3.3. $PM_{2.5}$ compliance with federal standards

Although smoke impacts to mountain communities can be ascertained through temporary event drive monitoring, this is at best an incomplete assessment of public health impacts. To determine the impacts to public health from smoke in a fire and smoke adapted ecosystem, it is necessary to have some understanding of air quality over time. Federal air quality standards for $PM_{2.5}$ are a way to determine air quality in an area over time. Mountain communities throughout the Sierra are located in areas where prior to Euro-American settlement, smoke was present through most of the summer. These areas are not typically monitored for routine air quality because the populations are too small to warrant EPA monitoring sites. With the ability of land managers to suppress fire and fire becoming an inevitability that needs to be managed to mitigate impacts, background levels of pollutants generated from smoke must be incorporated into long term air management goals.

$PM_{2.5}$ monitoring in Kernville from 2006 to 2012 have highest concentrations typically coinciding with wind from the south and southeast from Lake Isabella with typical transport likely up the Kern River drainage from the Bakersfield area (Fig. 3a). Annual three year mean (8.0–10.0 μg m^3) and 98th percentile (23–24 μg $m^{3)}$ concentrations of $PM_{2.5}$ at Kernville have been below federal standards since monitoring began in 2005 (Table 3). Monitors at Springville and Pinehurst, also ran year round, showing similar $PM_{2.5}$ readings. This illustrates that $PM_{2.5}$ in these areas is typically lower than the Central Valley. Although these areas are in federal and state nonattainment areas, the complications and limitations of air quality monitoring over an entire air basin is clear. Mountain communities of the Sierra Nevada have some capacity to

Table 2
Estimated 98th percentile Particulate Matter less than 2.5 microns ($PM_{2.5}$) for 2011 (3-year mean), mean $PM_{2.5}$ during and after the Lion Fire, and daily and hourly Air Quality Impacts (AQI) arranged by distance from the fire.

Site	98th per. $PM_{2.5}$ (μg m^{-3})	Mean $PM_{2.5}$ μg m^{-3} during[a] fire (SD[c])	Mean $PM_{2.5}$ μg m^{-3} after[b] fire (SD[c])	AQI category number of days (number of hours)					
				Good	Moderate	Unhealthy sensitive	Unhealthy	Very unhealthy	Hazardous
Camp Nelson	28.0[d]	16.0 (31.1)	9.0 (7.1)	39 (1226)	13 (41)	2 (7)	2 (14)	0 (2)	0 (0)
Springville	37.7 (30)	18.9 (8.1)	13.2 (7.5)	0 (1386)	57 (29)	0 (1)	1 (0)	0 (0)	0 (0)
Johnsondale	35.0[d]	17.8 (26.9)	7.4 (6.6)	22 (1227)	31 (113)	3 (19)	1 (15)	0 (0)	0 (0)
Kennedy Meadows	17.6[d]	8.3 (10.5)	4.1 (4.8)	53 (1431)	8 (19)	0 (4)	0 (0)	0 (0)	0 (0)
Olancha	7.4[d]	6.2 (6.4)	No Data	33 (849)	1 (7)	0 (0)	0 (0)	0 (0)	0 (0)
Kernville	34.0 (23)	20.1 (24.5)	8.6 (6.6)	22 (1230)	32 (118)	5 (33)	1 (10)	0 (0)	0 (0)
Pinehurst	19.8 (19)	11.6 (5.8)	11.8 (7.0)	40 (1436)	20 (5)	0 (0)	0 (0)	0 (0)	0 (0)
Independence	14.8[d]	6.9 (9.5)	No Data	41 (1111)	6 (24)	0 (0)	0 (0)	0 (0)	0 (0)
Trimmer	12.4[d]	8.6 (6.2)	9.7 (6.0)	56 (1451)	2 (1)	0 (1)	0 (0)	0 (0)	0 (0)
North Fork	12.2[d]	7.7 (6.4)	7.4 (6.6)	54 (1385)	2 (2)	0 (0)	0 (0)	0 (0)	0 (0)

[a] 7/9–9/7/2011.
[b] 9/8–11/7/2011.
[c] Standard deviation.
[d] 24-h average estimates using 5th highest daily mean.

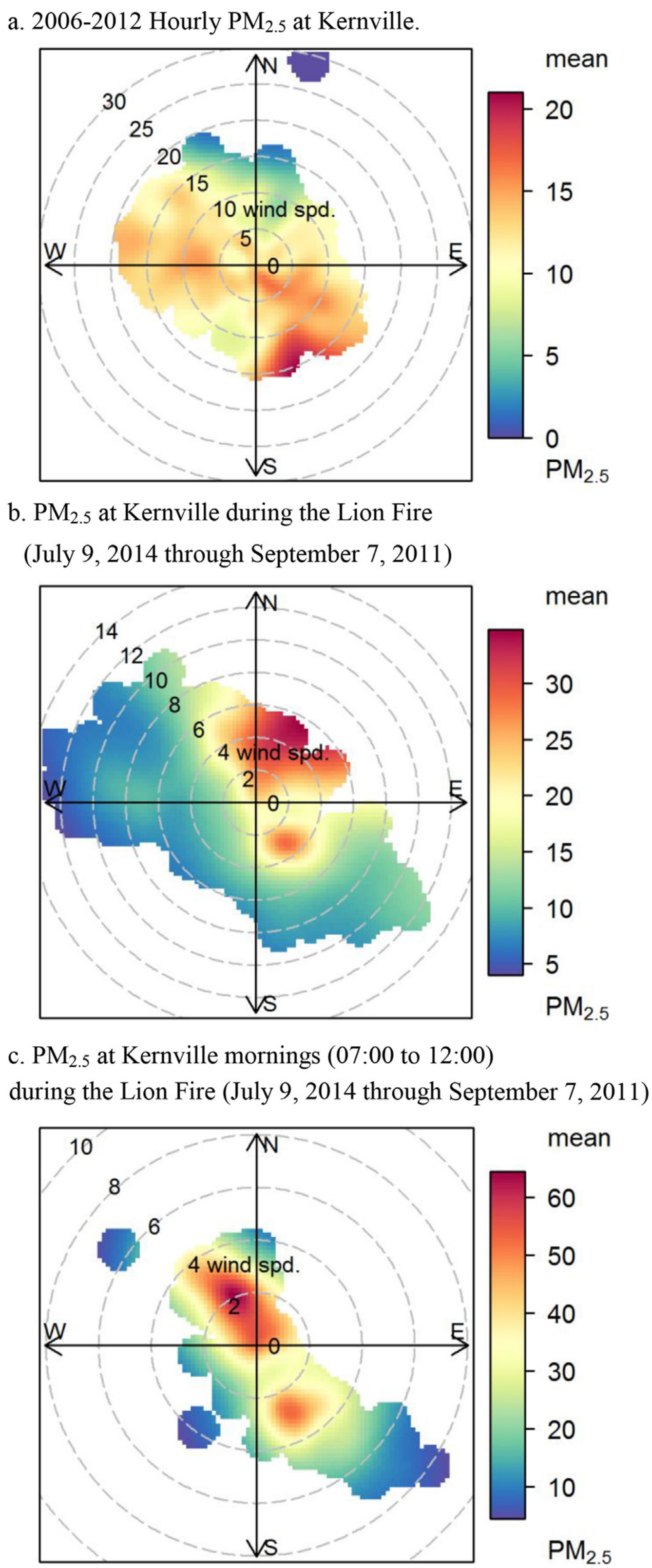

Fig. 3. Particulate Matter less than 2.5 microns ($PM_{2.5}$) showing concentration by wind speed and direction at the Kernville monitoring site for (a) all hourly data (2006–2012), (b) hourly $PM_{2.5}$ concentrations during the Lion Fire (July 9, 2014 through September 7, 2011), and (c) hourly $PM_{2.5}$ concentrations mornings (07:00–12:00) during the Lion Fire (July 9, 2014 through September 7, 2011).

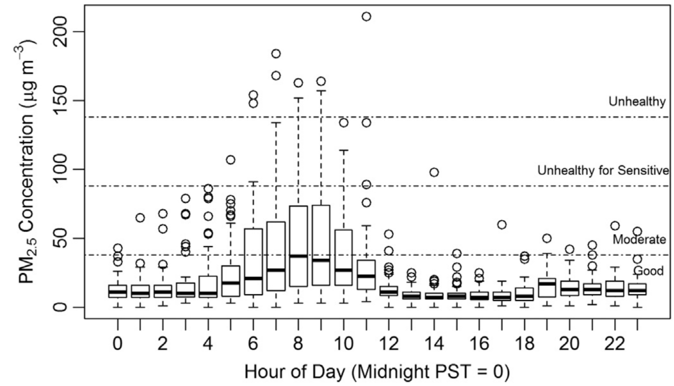

Fig. 4. Modified boxplot (where the box is defined by the first quartile as the lower edge of the box, second quartile (median) as the black line, and 3rd quartile as the upper extent of the box, lower extent of data (minimum) are the horizontal lines below the box (lower whisker), the upper extent are the largest data point less than 1.5 times the interquartile distance (upper whisker), and outliers are represented by empty circles) showing diurnal pattern of Particulate Matter less than 2.5 microns ($PM_{2.5}$) concentrations at Kernville during the Lion Fire (7/9–9/7/2011).

allow for both some smoke impacts and still remain below federal and state thresholds for $PM_{2.5}$. The difficulties and challenges to administer air quality regulations where fire and urban pollution compete for use of the air basin are clear.

The concentrations of $PM_{2.5}$monitored at Kernville are representative of the higher elevation temporary sites set up to monitor air quality during the Lion Fire. Other monitoring throughout this area of the Sierra Nevada typically is similar to that at Kernville unless there are localized smoke impacts. Post fire $PM_{2.5}$ concentrations were similar between all sites once the smoke had subsided. Kernville and the other monitors run over multiple years at elevations above ~1,500 msl in the southern Sierra Nevada have shown that annual $PM_{2.5}$ concentrations are generally low (less than 12 μg m^3)with smoke impacts from wildland fire typically producing the highest concentrations of $PM_{2.5}$ during the summer (Cisneros et al., 2014).

4. Discussion

4.1. Summary of $PM_{2.5}$ and smoke impacts from the Lion Fire

Hourly $PM_{2.5}$ concentrations during the Lion Fire (7/9–9/7) were typically good regionally with unhealthy for sensitive days going to near zero for sites in the Sierra Nevada out of the direct transport of the smoke (Table 2). AQI for daily exposure to $PM_{2.5}$ was generally good or moderate throughout the fire with 4–6 days unhealthy for sensitive or higher in the most impacted sites of Kernville, Johnsondale, and Camp Nelson (Table 2). Four unhealthy 24-h averages were measured (1 at both Johnsondale and Kernville and 2 at Camp Nelson). Three of these readings occurred on 7/31/2011 at the three sites of Kernville (68 μg m^{-3}), Johnsondale (95 μg m^{-3}), and Camp Nelson (138 μg m^{-3}) with the additional day at Camp Nelson (63 μg m^{-3} on 7/28). This was at the end of the most active period for the fire where the average reported acres burned was over 660 ha per day for the preceding week. Exceeding the unhealthy threshold helps to illustrate the importance of transport and distance which is particularly important when managing the lower emissions of a MF. Camp Nelson, the closest site to the fire, was typically upwind of the fire, but the nearness reduced the transport distance and the smoke would be more concentrated. Therefore when smoke was present, ground level concentrations of $PM_{2.5}$ were higher than other monitoring sites due to less mixing and dispersion during transport.

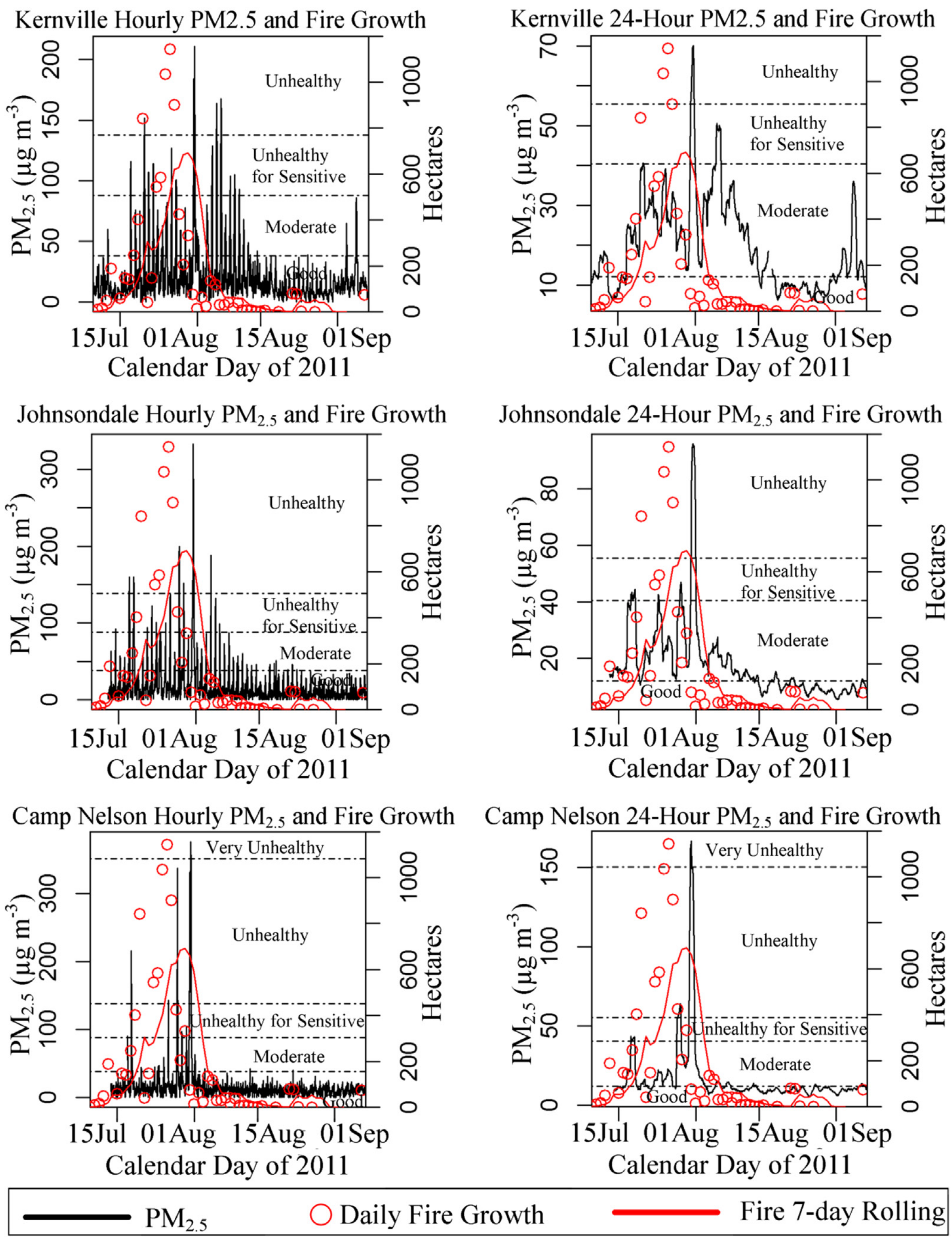

Fig. 5. Hourly and 24-Hour Particulate Matter less than 2.5 microns ($PM_{2.5}$) with Air Quality Index (AQI) breakpoints and reported daily and 7-day rolling fire size at Kernville, Johnsondale, and Camp Nelson during the Lion Fire (July 9, 2011 through September 7, 2011).

Johnsondale was in the predominant direction of smoke transport as seen from the increased moderate and higher daily and hourly impacts. Typical nighttime transport of smoke into and down the Kern River drainage exposed the Kernville area to more smoke even though this location was further away than many other sites thus exposing the Kernville area to lower hourly concentrations but over more hours.

Kernville, the only year round site that recorded smoke impacts saw an increase in annual $PM_{2.5}$ in 2011 of approximately 1 μg m^{-3} from 2010 to 2009 but was .6 μg m^{-3} lower than 2012. At Kernville, the 2011 annual mean was 8.1 μg m^{-3} with a 3-year annual mean of 7.4 μg m^{-3}. Annual mean has been below the federal standard since 2008 with 3-year mean consistently below the standard. This is similar to the other $PM_{2.5}$ monitoring sites operated by the USFS in the wildland urban interface of the western slopes of the Sierra Nevada (Table 3). Annual mean $PM_{2.5}$ at Kernville below the EPA annual mean standard (12 μg m^{-3}) in 2011 when the Lion Fire occurred and again in 2012 indicates the potential for a MF of this size in this area to be conducted without causing violations to the federal standards.

The federal standard (98th percentile) was not exceeded for 2011 (Lion Fire year) at any site. Springville, the only site where the 98th percentile estimate is above the 3-year standard, had only 1 of the ten highest days occurring during the Lion Fire (Table 2) showing the influence of anthropogenic impacts on this lower elevation site nearer to the populated Central Valley. Most of the

Table 3
National Ambient Air Quality Standards (NAAQS) calculated for U.S. Forest Service year round monitoring sites.

Site	2012	2011	2010	2009	2008	2007	2006
$PM_{2.5}$ ($\mu g\ m^{-3}$) annual mean (3-year mean)							
Kernville	8.7 (8.0)	8.1 (7.4[a])	7.2 (10.0[a])	7	15.9		
Pinehurst	7.9 (8.1)	8.0 (7.5)	7.9 (7.7)	6.2 (7.5)	9.1 (8.0)	7.2	7.8
Springville	9.7 (11.6)	14.1 (11.7)	9.1 (11.8)	10.0 (13.7)	16.2 (14.6)	14.8	12.8
$PM_{2.5}$ ($\mu g\ m^{-3}$) annual 98th percentile (3-year mean)							
Kernville	18.8 (23)	34.0 (23[a])	17.3 (24[a])	17.7[a]	36.3	34.9[a]	37.3[a]
Pinehurst	16.8 (18)	19.8 (19)	18.5 (24)	17.3 (25)	34.6	22.1	22.9[a]
Springville	31.9 (31)	37.7 (30)	21.1 (35)	28.6 (43)	54.9 (48)	44	44.1

[a] At least one quarter does not meet NAAQS requirement for number of valid daily averages.

sites monitored for the Lion Fire did not go above the federal standard for even a single day. Kernville, Johnsondale, and Camp Nelson all had days (7, 6, and 3 respectively) above the 35 $\mu g\ m^{-3}$ annual standard from smoke. The federal annual 98th percentile at Kernville for both the Lion Fire year of 2011 (34.0 $\mu g\ m^{-3}$) and the 3-year mean (23 $\mu g\ m^{-3}$) were below the federal standard (Table 3). $PM_{2.5}$ exposure including sites with estimated 98th percentile all remained below the federal standard for 2011.

4.2. Implications of wildland fire smoke

Wildland fire and subsequent smoke impacts have been an evolutionary pressure in the Sierra Nevada that is integral to this forest ecosystem. As people have moved into this area, smoke impacts to human health have become a pressing political issue. Historic wildfire suppression has erased the cultural memory of fire and smoke in this area leading regulators and the general public to have little tolerance to smoke and unrealistic expectations for continued suppression of fire in the face of climate change and unnatural fuel loading. Additionally, because smoke can be sensed at low levels, any smoke in this area leads to the assumption that air quality has been hazardously compromised. Although emissions from wildland fire undoubtedly have adverse impacts to human health during a fire, there has been little interest in future impacts to air quality and public health through fire suppression. Because weighing beneficial impacts to air quality from a healthy forest ecosystem is difficult, it is typically ignored for event driven reactionary land and air management. This strategy is likely leading to a less healthy and resilient Sierra Nevada ecosystem (Miller, 2012) which is more susceptible to other stressors such as climate change which in turn may lead to larger more intense fires. Additionally, the current excessive fuel loadings will produce increased emissions and smoke impacts when burned. Fuel loads can be expected to increase unless the use of fire is increased leading to the possibility that smoke in the future will significantly impact large portions of the region including the heavily populated Central Valley when this area inevitably burns.

The Sierra Nevada is further restricted by current air regulatory policy and alignment. While areas throughout the Sierra Nevada (similar to sites in this study) are likely in attainment of federal $PM_{2.5}$ standards (Cisneros et al., 2014), these areas, in the regulatory environment, are in a non-attainment area. Fire in any portion of a non-attainment area will necessarily be under greater scrutiny for any emissions with current air quality, even at distant sites with little to no impacts from the fire, anywhere within the air basin being the primary factor for MF decisions. Regulators will find it difficult or impossible to consider long term consequences and impacts to air quality when air quality standard is being exceeded in the Central Valley urban areas of the air district.

Smoke from the Lion Fire impacted air quality both visibility and public health as was apparent in the high hourly concentrations and over a month of some levels of smoke in many areas, but in regard to current federal standards for annual (12 $\mu g\ m^{-3}$) and 98th percentile (35 $\mu g\ m^{-3}$), Kernville (and likely much of the surrounding area) were in compliance. Without an increase in anthropogenic emissions in this area, a fire of the size and intensity of the Lion Fire could be allowed to progress naturally every three years with little chance of exceedance of federal regulatory standards for $PM_{2.5}$ in the Kernville area. The relatively few days and hours of unhealthy AQI during the Lion Fire can be contrasted to the McNally Fire. The McNally Fire was a full suppression high intensity fire in this area of the Sierra Nevada in 2002. Smoke from the McNally Fire impacted the Owens Valley (Cisneros et al., 2012). Fire of this magnitude and intensity and the subsequent increased emissions can be expected to increasingly impact large urban centers if smoke emissions are not managed more efficiently. Timing and quantity of smoke emissions have no opportunity to be managed during a high intensity wildfire in the Sierra Nevada. Options to control or mitigate smoke impacts from the large high-intensity Rim Fire (2013 – Stanislaus National Forest and Yosemite National Park) were virtually non-existent. High intensity fires with full suppression send large amounts of smoke long distances impacting a much more extensive and populated area.

Smoke causes a myriad of impacts to human health. Suppression policies appear to not only be moving these impacts to future generations but with increased fire size and intensity smoke impacts can be expected to have increasing mortality impacts and the associated social cost (Kochi et al., 2012). $PM_{2.5}$ air quality impacts from the Lion Fire were primarily moderate or good using current thresholds, showing the potential for mitigating future impacts from a larger more intense fire using MF. Additionally, with a return to the natural fire regime in the Sierra Nevada more typical of the size and intensity of the Lion Fire there is the potential to use MF to control both the timing and amount of smoke to adhere to present federal air quality standards.

Smoke from fire will be experienced by people living or recreating in the Sierra Nevada. Only the timing, extent, and intensity of smoke exposure can reasonably be managed. Air quality impacts from emissions from the Lion Fire were under current NAAQS for $PM_{2.5}$.

4.3. Policy recommendations

More case studies are necessary to understand the complex interaction between fire emissions and public health in the Sierra Nevada. The Lion Fire illustrates that while there were no violations to the annual federal $PM_{2.5}$ standards, smoke exposure to a small proportion of the public did occur which likely impacted public health (Delfino et al., 2009), particularly for sensitive groups (Elliot et al., 2013). Thus, managing a fire of this magnitude and intensity in the Sierra Nevada is possible without extreme smoke impacts typical of large high intensity suppression fires.

Current policy and regulatory enforcement is designed to concentrate protection on immediate impacts. This works well with anthropogenic emissions but is in effect pushing the onerous impacts of smoke exposure to subsequent years. Fuel loading, increases in wildland urban interface, and climate change are coalescing to limit the proactive use of fire for ecological and thus public health benefit. Fire managers are near to having no alternative but to be reactive to fire which will limit their effectiveness to control emissions.

Although satellite imagery, dispersion models, other products designed to evaluate potential smoke impacts are useful tools (Price et al., 2012), they typically over-predicted the ground level concentrations and extent during this event leading to an increased perceived risk of smoke exposure (Fig. 2). These tools should be used with caution for projecting real ground level concerns about air quality for smaller fires in complex terrain such as the Sierra Nevada and should not be substituted for ground based measurements if at all possible.

A large high intensity fire in the Sierra Nevada, the McNally Fire in 2002, impacted a much larger area and caused federal standards to be exceeded (Cisneros et al., 2012). During the McNally Fire, monitoring for coarse particulate matter (particulate matter less than 10 microns in diameter) recorded concentrations that were in the hazardous range. A large high intensity fire in this area has the potential to increase public health impacts to local communities, the Owens Valley, and the Central Valley. Current policy should be altered to encourage fire of historic size and intensity to be managed in the Sierra Nevada even during times of poor air quality in the Central Valley. Future emissions potential including considering emissions from large high intensity fires and the increased impact to public health should not be ignored. Failure to confront this difficult air quality conundrum necessarily leaves the impacts to future generations. Management of naturally occurring fires during advantageous meteorological and ecological conditions should be prioritized to limit future air quality impacts.

Managing smoke impacts from fire on a landscape level in the Sierra Nevada is a complex policy problem. A possible scenario under current air quality conditions would be to manage $PM_{2.5}$ to remain below current federal thresholds. This would provide policy managers the opportunity for managing smoke emissions and consider current and future levels of exposure possibly cycling MFs into and out of an area over multiple years to provide landscape level forest restoration while exposing the public to years with and without MF. Fire size can also be managed more easily during a MF possibly managing total area burned where feasible to take advantage of good dispersal days. Smoke impacts were difficult to determine from the reported burn area. This is possibly due to the difficulty of timely estimating the area during a fire. Reported hectares were a poor indicator of localized smoke impacts but impacts typically went over unhealthy for sensitive at the monitoring sites when more than 300 ha were reported for the day. The 7-day rolling average of hectares burned (Fig. 5) was a better predictor of $PM_{2.5}$ impacts ($r^2 = .34$). This likely was because the longer average helped to reduce the error in reported fire size and also included some matrix for areas still burning and is an area that needs additional research. Considering fire size and duration has the potential to be a simple way to create trigger points where a progressive program of outreach could protect the public from smoke exposure during a fire.

5. Conclusions

Managing smoke from wildland fire is complex with no simple way to approach the myriad of decisions required. Quantifying impacts to air quality from a smoke event help to inform these decisions. The smoke from large high intensity fires, because of their widespread and highly detrimental impacts to air quality and public health are the focus of much of the current research. These fires were not typical and are a product of anthropogenic activities. Smoke impacts from wildland fire the size and intensity typical of the ecosystem such as the Lion Fire are not well documented. Without this understanding, smoke regulatory agencies necessarily must take a conservative approach where impacts must be predicted and assumed to be as widespread and intense as a large high intensity fire. Measured smoke impacts from the Lion Fire suggest this should not be the assumption.

Smoke from the Lion Fire was present for 1–2 months in small rural and mountain communities close to the fire in the Sierra Nevada. There were impacts to air quality, particularly to sensitive groups that must be mitigated if future fires of this size are allowed to burn. Impacts for the Lion Fire were localized and below federal thresholds for $PM_{2.5}$ at sites closest to the fire. $PM_{2.5}$ concentrations at urban sites in the Central Valley remained low and typical of other years without fire throughout the fire duration. Smoke from the Lion Fire did not appear to impact $PM_{2.5}$ at Central Valley sites. $PM_{2.5}$ concentrations were found to be below federal and state standards for air quality at all monitoring sites during the Lion Fire.

The potential exists to manage fire at the intensity and extent historically seen in the Sierra Nevada while risks to public health from smoke are minimized with air quality impacts held below regulatory standards. This opportunity to manage smoke by mitigating public health impacts to federal regulatory standards also provides a framework for assessing the tradeoff between short- and long-term impacts of smoke to public health through assessing smoke impacts over 1–3 years instead of only considering hours or days. Recognizing and mitigating short term exposure, particularly to sensitive populations is obviously essential but should not be the only factor considered in this complex decision. Wildland fires should not all be treated the same where the avoidance of short term smoke impacts are the only consideration. Avoidance of major air quality impacts from large high intensity fire and future public health benefits of allowing some emissions must be considered. Policy needs to allow flexibility to manage air quality impacts from a fire the size and intensity of the Lion Fire historically experienced in the Sierra Nevada including allowing wildland fire at times of poor air quality in the Central Valley. Allowing smoke events of this magnitude has potential to reduce regional smoke impacts to air quality.

Acknowledgments

Funding for this project was provided by the University of California at Merced. The authors would like to thank the U.S. Forest Service Region 5 Air Management and staff of the Sequoia National Forest for their support in the collection of the smoke monitoring data.

References

Air Quality and Meteorological Information System, 2012. http://www.arb.ca.gov/aqmis2/aqmis2.php (accessed 08.02.12.).

Arbaugh, M.J., Procter, T., Esperanza, A., 2009. Managing air pollution impacted forests of California. Dev. Environ. Sci. 8, 567–582.

Beaty, R.M., Taylor, A.H., 2008. Fire history and the structure and dynamics of a mixed conifer forest landscape in the northern Sierra Nevada, Lake Tahoe Basin, California, USA. For. Ecol. Manag. 255, 707–719.

Bright, A.D., Newman, P., Carroll, J., 2007. Context, beliefs, and attitudes toward wildland fire management: an examination of residents of the wildland-urban interface. Hum. Ecol. Rev. 14, 212–222.

Brown, R.T., Agee, J.K., Franklin, J.F., 2004. Forest restoration and fire: principles in the context of place. Conserv. Biol. 18, 903–912.

Brugnach, M., Dewulf, A., Henriksen, H.J., van der Keur, P., 2011. More is not always better: coping with ambiguity in natural resource management. J. Environ. Manag. 92, 78–84.

California Code of Regulations (CCR), 2014. Title 17-Division 3. Public Health. Chapter 1. Air Resources Board. Subchapter 2. Smoke Management Guidelines for Agricultural and Prescribed Burning. Sections 80100–80330. http://www.oal.ca.gov/ccr.htm (accessed 15.04.14.).

California Office of Environmental Health and Hazard Assessment, 2013. Wildfire Smoke a Guide for Public Health Officials Revised July 2008 (with 2012 AQI Values). http://oehha.ca.gov/air/risk_assess/wildfirev8.pdf (accessed 13.02.14.).

Calkin, D.C., Finney, M.A., Ager, A.A., Thompson, M.P., Gebert, K.M., 2011a. Progress towards and barriers to implementation of a risk framework for US federal wildland fire policy and decision making. For. Policy Econ. 13, 378–389.

Calkin, D.E., Thompson, M.P., Finney, M.A., Hyde, K.D., 2011b. A real-time risk assessment tool supporting wildland fire decision making. J. For. 109, 274–280.

Carslaw, D.C., Ropkins, K., 2012. openair – an R package for air quality data analysis. Environ. Modell. Softw. 27–28, 52–61.

Champ, J.G., Brooks, J.J., Williams, D.R., 2012. Stakeholder understandings of wildfire mitigation: a case of shared and contested meanings. Environ. Manag. 50, 581–597.

Cisneros, R., Schweizer, D., Preisler, H., Bennett, D.H., Shaw, G., Bytnerowicz, A., 2014. Spatial and seasonal patterns of particulate matter less than 2.5 microns in the Sierra Nevada, California. Atmos. Pollut. Res. 5, http://dx.doi.org/10.5094/APR.2014.067 (in press).

Cisneros, R., Schweizer, D., Zhong, S., Hammond, K., Perez, M.A., Guo, Q., Traina, S., Bytnerowicz, A., Bennett, D.H., 2012. Analyzing the effects of the 2002 McNally fire on air quality in the San Joaquin Valley and southern Sierra Nevada, California. Int. J. Wildland Fire 21, 1065–1075.

Clark County Department of Air Quality, 2012. http://ccaqapps5m.co.clark.nv.us/ (accessed 01.03.12.).

Clean Air Act (CAA) 42 U.S.C. Sec 7401-7626, 2011. FDsys. U.S. Government Printing Office, 2014. http://www.gpo.gov/fdsys/pkg/USCODE-2008-title42/pdf/USCODE-2008-title42-chap85.pdf (accessed 02.02.14.).

Delfino, R.J., Brummel, S., Wu, J., Stern, H., Ostro, B., Lipsett, M., Winer, A., Street, D.H., Zhang, L., Tjoa, T., Gillen, D.L., 2009. The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. Occup. Environ. Med. 66, 189–197.

Dellasala, D.A., Williams, J.E., Williams, C.D., Franklin, J.F., 2004. Beyond smoke and mirrors: a synthesis of fire policy and science. Conserv. Biol. 18, 976–986.

Exceptional Events Rule 40 U.S.C. Sec 50.14, 2007. U.S. Government Printing Office, 2014. http://www.ecfr.gov/cgi-bin/text-idx?SID=c203a60eb1ef06f943b24cdc0944981d&node=40:2.0.1.1.1.0.1.14&rgn=div8 (accessed 11.04.14.).

Elliot, C.T., Henderson, S.B., Wan, V., 2013. Time series analysis of fine particulate matter and asthma reliever dispensations in populations affected by forest fires. Environ. Health-Glob. 12, 11.

Ferrenberg, S.M., Schwilk, D.W., Knapp, E.E., Groth, E., Keeley, J.E., 2006. Fire decreases arthropod abundance but increases diversity: early and late season prescribed fire effects in a Sierra Nevada mixed-conifer forest. Fire Ecol. 2, 79–102.

FOFEM6, 2013. http://www.firelab.org/science-applications/fire-fuel/111-fofem (accessed 15.04.13.).

Fule, P.Z., 2008. Does it make sense to restore wildland fire in changing climate? Restor. Ecol. 16, 526–531.

Gauchat, G., 2012. Politicization of science in the public sphere: a study of public trust in the United States, 1974 to 2010. Am. Sociol. Rev. 77, 167–187.

Hanninen, O.O., Salonen, R.O., Koistinen, K., Lanki, T., Barregard, L., Jantunen, M., 2009. Population exposure to fine particles and estimated excess mortality in Finland from an East European wildfire episode. J. Expo. Sci. Env. Epid. 19, 414–422.

Hurteau, M.D., Westerling, A.L., Wiedinmyer, C., Bryant, B.P., 2014. Projected effects of climate and development on California wildfire emissions through 2100. Environ. Sci. Technol. 48, 2298–2304.

Hurteau, M.D., North, M., 2010. Carbon recovery rates following different wildfire risk mitigation treatments. For. Ecol. Manag. 260, 930–937.

Hurteau, M., North, M., 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Front. Ecol. Environ. 7, 409–414.

Hurteau, M.D., Koch, G.W., Hungate, B.A., 2009. Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. Front. Ecol. Environ. 6, 493–498.

Johnston, F.H., Hanigan, I.C., Henderson, S.B., 2013. Evaluation of interventions to reduce air pollution from biomass smoke on mortality in Launceston, Australia: retrospective analysis of daily mortality, 1994–2007. BMJ 346, e8446.

Keeley, J.E., McGinnis, T.W., Bollens, K.A., 2005. Seed germination of Sierra Nevada postfire chaparral species. Madrono 52, 175–181.

Kilgore, B., 1981. Fire in ecosystem distribution and structure: western forests and scrublands. In: Mooney, H.A., Bonnicksen, T.M., Christensen, N.L. (Eds.), Proceedings of the Conference: Fire Regimes and Ecosystem Properties. USDA Forest Service, pp. 58–89. General Technical Report WO-GTR-26.

Kochi, I., Champ, P.A., Loomis, J.B., Donovan, G.H., 2012. Valuing mortality impacts of smoke exposure from major southern California wildfires. J. For. Econ. 18, 61–75.

Kochi, I., Donovan, G.H., Champ, P.A., Loomis, J.B., 2010. The economic cost of adverse health effects from wildfire-smoke exposure: a review. Int. J. Wildland Fire 19, 803–817.

Kunzli, N., Avol, E., Wu, J., Gauderman, W.J., Rappaport, E., Millstein, J., Bennion, J., McConnell, R., Gilliland, F.D., Berhane, K., Lurmann, F., Winer, A., Peters, J.M., 2006. Health effects of the 2003 Southern California wildfires on children. Am. J. Resp. Crit. Care 174, 1221–1228.

Langmann, B., Duncan, B., Textor, C., Trentmann, J., van der Werf, G.R., 2009. Vegetation fire emissions and their impacts on air pollution and climate. Atmos. Environ. 43, 107–116.

Liu, Y., Stanturf, J., Goodrick, S., 2010. Trends in global wildfire potential in a changing climate. For. Ecol. Manag. 259, 685–697.

McMeeking, G.R., Kreidenweis, S.M., Lunden, M., Carrillo, J., Carrico, C.M., Lee, T., Herckes, P., Engling, G., Day, D.E., Hand, J., Brown, N., Malm, W.C., Collett Jr., J.L., 2006. Smoke-impacted regional haze in California during the summer of 2002. Agr. For. Meteorol. 137, 25–42.

Met One Industries, Inc, 2008a. BAM 1020 Particulate Monitor Operation Manual BAM-1020 Rev G. Grant Pass, Oregon.

Met One Industries, Inc, 2008b. E-BAM Particulate Monitor Operation Manual E-BAM-9800 Rev L. Grant Pass, Oregon.

Miller, C., 2012. The hidden consequences of fire suppression. Park Sci. 28, 75–80.

Miller, J.D., Safford, H.D., Crimmins, M., Thode, A.E., 2009. Quantitative evidence for increasing Forest fire severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. Ecosystems 12, 16–32.

Moreira, B., Tormo, J., Estrelles, E., Pausas, J.G., 2010. Disentangling the role of heat and smoke as germination cues in Mediterranean Basin flora. Ann. Bot. Lond. 105, 627–635.

Murphy, A., Abrams, J., Daniel, T., Yazzie, V., 2007. Living among frequent-fire forests: human history and cultural perspectives. Ecol. Soc. 12, 17.

National Interagency Fire Center, 2012. http://www.nifc.gov/fireInfo/fireInfo_main.html (accessed 05.03.12.).

Nesmith, J.C.B., Caprio, A.C., Pfaff, A.H., McGinnis, T.W., Keeley, J.E., 2011. A comparison of effects from prescribed fires and wildfires managed for resource objectives in Sequoia and Kings Canyon National Parks. For. Ecol. Manag. 261, 1275–1282.

Parmeter Jr., J.R., Uhrenholdt, B., 1975. Some effects of pine-needle or grass smoke on fungi. Phytopathology 65, 28–31.

Price, O.F., Williamson, G.J., Henderson, S.B., Johnston, F., Bowman, D.M.J.S., 2012. The relationship between particulate pollution levels in Australian cities, meteorology, and landscape fire activity detected from MODIS hotspots. PLOS ONE 7, e47327.

R Core Team, 2012. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0. URL. http://www.R-project.org/.

Rappold, A.G., Cascio, W.E., Kilaru, V.J., Stone, S.L., Neas, L.M., Devlin, R.B., Diaz-Sanchez, D., 2012. Cardio-respiratory outcomes associated with exposure to wildfire smoke are modified by measures of community health. Environ. Health Glob. 11, 71.

Regional Haze Rule 40 U.S.C. Sec 51, 1997. U.S. Government Printing Office, 2014. http://www.epa.gov/ttn/caaa/t1/fr_notices/rhfedreg.pdf (accessed 11.04.14.).

Reinhardt, E.D., Keane, R.E., Calkin, D.E., Cohen, J.D., 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. For. Ecol. Manag. 256, 1997–2006.

Sastry, N., 2002. Forest fires, air pollution, and mortality in Southeast Asia. Demography 39, 1–23.

Sierra Wildland Fire Reporting System, 2012. http://sierrafire.cr.usgs.gov/ (accessed 05.03.12.).

Spracklen, D.V., Mickley, L.J., Logan, J.A., Hudman, R.C., Yevich, R., Flannigan, M.D., Westerling, A.L., 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. J. Geophys. Res. Atmos. 114, 27.

Steelman, T.A., McCaffrey, S.M., 2011. What is limiting more flexible fire management – public or agency pressure? J. For., 454–461. December 2011.

Stephens, S.L., Millar, C.I., Collins, B.M., 2010. Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. Environ. Res. Lett. 5, 024003.

Stephens, S.L., Martin, R.E., Clinton, N.E., 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. For. Ecol. Manag. 251, 205–216.

Swetnam, T.W., Baisan, C.H., Caprio, A.C., Brown, P.M., Touchan, R., Anderson, R.S., Hallett, D.J., 2009. Multi-millennial fire history of the Giant Forest Sequoia National Park, California, USA. Fire Ecol. 5, 120–150.

Tham, R., Erbas, B., Akram, M., Dennekamp, M., Abramson, M.J., 2009. The impact of smoke on respiratory hospital outcomes during the 2002–2003 bushfire season, Victoria, Australia. Respirology 14, 69–75.

Thompson, M.P., Calkin, D.E., 2011. Uncertainty and risk in wildland fire management: a review. J. Environ. Manag. 92, 1895–1909.

Tian, D., Wang, Y., Bergin, M., Hu, Y., Liu, Y., Russell, A.G., 2008. Air quality impacts from prescribed forest fires under different management practices. Environ. Sci. Technol. 42, 2767–2772.

Tribal Environmental Exchange Network, 2012. http://trexwww.ucc.nau.edu/ (accessed 01.03.14.).

US EPA, 1999. Guideline on Data Handling Conventions for the PM NAAQS. United States Environmental Protection Agency Office of Air Quality, Planning and Standards, Research Triangle Park, NC 27711. EPA-454/R-99–008 April 1999.

Vadrevu, K.P., Eaturu, A., Badarinath, K.V.S., 2010. Fire risk evaluation using multicriteria analysis-a case study. Environ. Monit. Assess. 166, 223–239.

Van de Water, K.M., Safford, H.D., 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. Fire Ecol. 7, 26–58.
Vedal, S., Dutton, S.J., 2006. Wildfire air pollution and daily mortality in a large urban area. Environ. Res. 102, 29–35.
Viswanathan, S., Eria, L., Diunugala, N., Johnson, J., McClean, C., 2006. An analysis of effects of San Diego wildfire on ambient air quality. J. Air Waste Manag. 56, 56–67.
Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313, 940–943.
Yao, J., Henderson, S.B., 2014. An empirical model to estimate daily forest fire smoke exposure over a large geographic area using air quality, meteorological, and remote sensing data. J. Expo. Sci. Env. Epid. 24, 328–335.
Zimmerman, G.T., Laven, R.D., 1987. Effects of forest fuel smoke on dwarf mistletoe seed germination. Gt. Basin Nat. 47, 652–659.