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Research article

Using National Ambient Air Quality Standards for fine particulate matter to assess regional wildland fire smoke and air quality management

Don Schweizer [a, *], Ricardo Cisneros [b], Samuel Traina [c], Teamrat A. Ghezzehei [d], Glenn Shaw [e]

[a] Environmental Systems Graduate Group, University of California, Merced, 5200 N. Lake Road, Merced, CA, 95343, USA
[b] School of Social Sciences, Humanities and Arts, University of California, Merced, 5200 N. Lake Road, Merced, CA, 95343, USA
[c] Office of Research, University of California, Merced, 5200 N. Lake Road, Merced, CA, 95343, USA
[d] School of Natural Sciences, University of California, Merced, 5200 N. Lake Road, Merced, CA, 95343, USA
[e] Department of Geological Engineering, Montana Tech of the University of Montana, 1300 West Park Street, Butte, MT, 59701, USA

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ABSTRACT

Wildland fire is an important ecological process in the California Sierra Nevada. Personal accounts from pre-20th century describe a much smokier environment than present day. The policy of suppression beginning in the early 20th century and climate change are contributing to increased megafires. We use a single particulate monitoring site at the wildland urban interface to explore impacts from prescribed, managed, and full suppression wildland fires from 2006 to 2015 producing a contextual assessment of smoke impacts over time at the landscape level. Prescribed fire had little effect on local fine particulate matter ($PM_{2.5}$) air quality with readings typical of similar non-fire times; hourly and daily good to moderate Air Quality Index (AQI) for $PM_{2.5}$, maximum hourly concentrations 21–103 μg m^{-3}, and mean concentrations between 7.7 and 13.2 μg m^{-3}. Hourly and daily AQI was typically good or moderate during managed fires with 3 h and one day reaching unhealthy while the site remained below National Ambient Air Quality Standards (NAAQS), with maximum hourly concentrations 27–244 μg m^{-3}, and mean concentrations 6.7–11.7 μg m^{-3}. The large high intensity fire in this area created the highest short term impacts (AQI unhealthy for 4 h and very unhealthy for 1 h), 11 unhealthy for sensitive days, and produced the only annual value (43.9 μg m^{-3}) over the NAAQS 98th percentile for $PM_{2.5}$ (35 μg m^{-3}). Pinehurst remained below the federal standards for $PM_{2.5}$ when wildland fire in the local area was managed to 7800 ha (8–22% of the historic burn area). Considering air quality impacts from smoke using the NAAQS at a landscape level over time can give land and air managers a metric for broader evaluation of smoke impacts particularly when assessing ecologically beneficial fire. Allowing managers to control the amount and timing of individual wildland fire emissions can help lessen large smoke impacts to public health from a megafire.

1. Introduction

Wildland fire is an important ecological process in fire prone ecosystems such as the California Sierra Nevada (Keeley et al., 2011; Kilgore et al., 1979). Pre-European settlement, the Sierra Nevada had much more wildland fire and smoke (Stephens et al., 2007). Changing climate and fuel build up through policies of suppression contribute to the increase in large high intensity fires (megafires) uncharacteristic of this landscape. Wildland fire is increasing in frequency and size with longer fire durations since pre-European settlement and the era of suppression (Schwartz et al., 2015; Westerling et al., 2006). Although large scale fuel reduction programs can help reduce megafires (Williams, 2013), restoring forest heterogeneity is not simply dependent on reducing fuels and fire severity (Baker, 2014). Fire management is a complex undertaking (Thompson and Calkin, 2011; Vining and Merrick, 2008) with

* Corresponding author.
E-mail addresses: dschweizer@ucmerced.edu (D. Schweizer), rcisneros@ucmerced.edu (R. Cisneros), straina@ucmerced.edu (S. Traina), taghezzehei@ucmerced.edu (T.A. Ghezzehei), gshaw@mtech.edu (G. Shaw).

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entrenched agency disincentives (North et al., 2015b; Topik, 2015) and robust debate (Boer et al., 2015; North et al., 2015a; Thompson and Calkin, 2011).

Smoke from wildland fire is associated with risk of respiratory and cardiovascular disease (Liu et al., 2015). Smoke from large high intensity fires can impact large areas long distances from the actual fire (Le et al., 2014) with research attempting to provide tools for reducing public exposure to smoke (Huff et al., 2015). Prescribed burning can limit the exposure and transport distance but these more localized smoke impacts are also a concern for health (Haikerwal et al., 2015). Smoke exposure in a fire prone community cannot be completely eliminated by suppression.

Policy and public support are needed for large scale use of managed fire. Visibility and the ability to smell smoke at low levels of exposure can easily bias public health concerns. Whether fire comes as a megafire or is managed for forest health with prescribed and managed natural ignition is largely a matter of policy and land and air managers' willingness to allow wildland fire for ecological benefit.

While other pollutants present in wildland fire smoke (e.g. carbon monoxide in the immediate areas of burn and ozone formation through plume chemistry) are of concern (Bytnerowicz et al., 2016), particulate matter less than 2.5 μm ($PM_{2.5}$) is a good indicator of impacts because its dominance as an air quality pollutant in wildland fire smoke makes it a leading health risk factor (Fantke et al., 2015; Hänninen et al., 2009; Lim et al., 2012).

$PM_{2.5}$ Air Quality Index (AQI) is used to determine impacts or nuisance levels (e.g. a given day or hour may be impacted by smoke). National Ambient Air Quality Standards (NAAQS) provide $PM_{2.5}$ thresholds that are used to protect public health. NAAQS are threshold levels of $PM_{2.5}$ designed to protect public health where a location is in "attainment" if below the threshold and if above are in "non-attainment".

Therefore, managing smoke from wildland fires in the vicinity of densely populated areas must address the competing needs for maximizing ecological benefits of fires while minimizing smoke exposure. The Sierra Nevada, which is adjacent to the densely populated Central Valley of California, provides an important case study for this challenging problem. The Central Valley, which is in an already compromised airshed from anthropogenic sources such as vehicle emissions and agriculture, is in non-attainment to a number of air pollutants including $PM_{2.5}$. In contrast, monitoring sites that are close to wildland fire smoke throughout the Sierra Nevada are below these standards (Cisneros et al., 2014). Thus, it appears that wildland fire in the Sierra Nevada has little impact on Central Valley sites even though smoke can be remotely sensed over these locations (Preisler et al., 2015).

Mountain communities located closest to the fire are often the most impacted. Managing air quality impacts from smoke at these mountain sites between the wilderness and developed areas provides a metric to better assess tradeoffs from suppression policy and ecological benefits from the reintroduction of fire to the landscape.

This study investigates whether continued wildland fire suppression policy and the subsequent large high intensity wildland fires (wildfire) on federally protected forests in the Sierra Nevada produce a greater adverse impact on air quality than prescribed or managed wildland fire used for ecological benefit.

Emissions from fire are considered and assessed almost solely on their immediate impacts to air quality. We propose a much simpler approach where smoke impacts are managed to NAAQS standards. The NAAQS thresholds allow for a more comprehensive evaluation of air quality impacts through longer (3 year) analysis. We assess wildland fire smoke impacts on air quality using the AQI for short term (hourly and daily) exposure. NAAQS for $PM_{2.5}$ are calculated to investigate whether health impacts can be reduced through a timed release of smoke that more closely replicates historic fire emissions.

2. Methods

A $PM_{2.5}$ monitoring site located between federally protected land and the urban Central Valley is used to assess wildland fire smoke impacts for the years 2006–2015. The implications of landscape level use of ecologically beneficial wildland fire and smoke management are discussed. The objective of this analysis is to provide a context for linking air quality impacts from wildland fire smoke to fire management policy and is intended to provide insight into the tradeoffs in air quality and human health protection from full suppression and managed fire.

2.1. Site description

The Pinehurst site (Latitude 36.69731; Longitude −119.01880; elevation 1246 masl) is located in the western slopes of the Sierra Nevada in Fresno County, California. Pinehurst is a small rural foothill community (population <1000) located approximately 0.5 km east of the Sequoia National Forest boundary and approximately 2.5 km west of the boundary to Kings Canyon National Park on the ridge between the Mill Creek and Dry Creek basins (Fig. 1). Pinehurst is located in the San Joaquin Valley Air Pollution Control District (SJVAPCD) and is considered for regulatory purposes to be in non-attainment of $PM_{2.5}$.

Pinehurst is situated east of the Central Valley of California (low elevation in Fig. 1) at mid-elevation on the western slope of the Sierra Nevada with the nearest point on the crest (>3000 masl) 55 km to the east. Pinehurst is in the fire prone Sierra Nevada. Immediately east is almost exclusively federally protected land (Sequoia and Kings Canyon National Parks, Sierra National Forest, and Sequoia National Forest with Inyo National Forest east of the crest) with a history of frequent fire (van de Water and Safford, 2011). The city of Fresno, California is located approximately 60 km west of Pinehurst while Visalia is 45 km southwest. The closest point on the Central Valley floor (<150 masl) is about 25 km WSW (Orange Cove). Atmospheric transport is generally from west to east although ground level transport at Pinehurst is influenced by the major drainages of the Kings and Kaweah Rivers.

2.2. Monitoring equipment

Meteorological data is collected by a Remote Automatic Weather Station (RAWS) A Met One Instruments, Inc. Beta-attenuation monitor (BAM) was used to collect hourly $PM_{2.5}$. BAMs can be used as a Federal Equivalent Method (FEM) for regulatory compliance and are widely used throughout California. The BAM at Pinehurst is operated similar to California compliance monitors but is not used for federal compliance monitoring. BAM inspections were performed once every two weeks and included checks for the integrity of the flow (leak check), atmospheric pressure, temperature, and flow rate. Hourly data was considered valid if there were no errors logged by the instrument and all audits were passed. Hourly data was validated by ensuring internal relative humidity (RH) was at or below the internal threshold set at 40% with and flow was 16.7 ± 5% lpm. To correct for the noise band of several micrograms on the BAM (Met One Instruments, 2008), the occasional negative values for the BAM were set as zero for all calculations. Daily (24 h) averages required a minimum of 16 valid hours (U.S. Environmental Protection Agency, 1999).

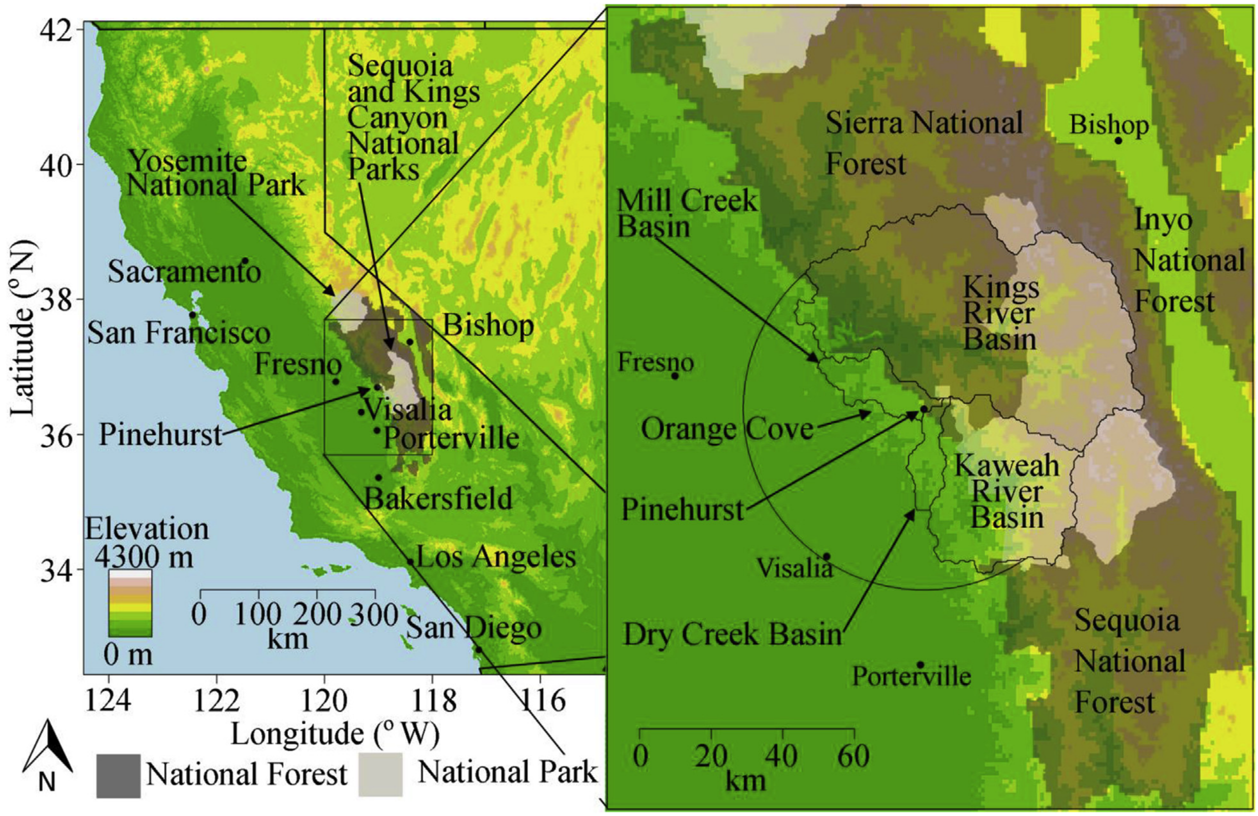

Fig. 1. Site location overview with federally protected National Forest and Park Service land in the Sierra Nevada along with Pinehurst region enlarged and displaying local area drainages and foothill bounding area (semi-circle to the west) into the Central Valley.

2.3. Wildland fire and emission calculations

Wildland fire data were obtained from the National Interagency Fire Center (NIFC, 2016) and the National Fire and Aviation Management web applications data warehouse (FAMWEB, 2017). Fire start date was used to compile monthly statistics. Individual fire size and rate of growth as reported in daily reports was used when assessing smoke impacts for a specific day or days. Individual fires were categorized for fire management action (prescribed, managed, and suppression). Prescribed were planned fires ignited by the managing agency. Managed fires were unplanned natural ignition (lightning) fires where land managers had determined conditions were advantageous for ecological benefit and the fires were not fully suppressed (suppression). Wildland fire was assessed for all 42 million ha of California, regionally (3.97 million ha), and locally (862,400 ha). Local wildland fires were further subset (see Fig. 1) to Mill Creek (32,400 ha), Dry Creek (19,900 ha), Kaweah River (147,100 ha), and Kings River (396,800 ha) drainages and an area west of the drainages (foothills) defined as within 50 km (266,300 ha). Regional fires included all fires within the bounding box (Latitude −120, −118; Longitude 35.7, 37.7) which is the area of enlargement in Fig. 1. Pre-historic area burned was calculated using high and median fire return intervals for California vegetation types established by Stephens et al. (2007).

2.4. Data handling

Air quality in this paper is determined using hourly and 24 h impacts as defined by the Air Quality Index (AQI) for $PM_{2.5}$. The 6 AQI categories (good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous) are used to indicate the level of air quality for $PM_{2.5}$. EPA 24-h (daily mean concentration) breakpoints for AQI are: 0–12, 12.1–35.4, 35.5–55.4, 55.5–150.4, 150.5–250.4, 250.5–500 $\mu g\ m^{-3}$. California Office of Environmental Health and Hazard Assessment for public health officials (Lipsett et al., 2013) 1–3 h average breakpoints for AQI (0–38, 39–88, 89–138, 139–351, 352–526, >526 $\mu g\ m^{-3}$) are used for hourly measurements.

NAAQS thresholds for $PM_{2.5}$ (3 year average annual mean of 12.0 $\mu g/m^3$; 3 year mean 98th percentile 35 $\mu g/m^3$) were calculated using the *Guideline on Data Handling Conventions for the PM NAAQS* (U.S. Environmental Protection Agency, 1999). NAAQS data handling for $PM_{2.5}$ require a minimum number of daily samples each quarter of the year for accurate representation for the entire year. A rolling 3 year mean of each annual value is the standard. Annual mean is a mean of all days while the 98th percentile is calculated as a rank value. The NAAQS annual (3 year annual mean) and the NAAQS 24 h (3 year mean of the 98th percentile) are defined as the calculated federal standards while the annual mean and annual 24 h are the individual year average and 98th percentile respectively. Data was processed using R (R Core Team, 2016) and the Openair package (Carslaw and Ropkins, 2012).

In addition to using fire start and end dates, satellite imagery for smoke (MODIS, 2017), National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System Fire and Smoke Product (HMS) data (NOAA, 2016), Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) forward and back trajectories (HYSPLIT, 2016), U.S. Forest Service BlueSky modeling framework (BlueSky, 2016), and personal observations were used to determine smoke transport and to determine the presence or absence of smoke from individual fires.

3. Results

3.1. Typical patterns of $PM_{2.5}$, meteorology, and smoke transport

Prevailing winds for California are generally from the W or NW for most of the year. Upper air winds at Pinehurst are generally from the west or northwest (Air Resources Lab, 2016). Ground level wind patterns are largely terrain driven as the mountain ranges throughout the state modify upper air patterns at ground level. The complex terrain includes river drainages at points over 1000 m deep. Prevailing wind direction in Fresno is from the NW March through November and the E/ESE December through February (WRCC, 2016). Localized transport includes nighttime subsidence of air masses from higher elevation and upslope afternoon winds. Although there was daily variance, general transport for the Pinehurst area consistently followed these general patterns between the years.

Pinehurst has monthly mean concentrations of $PM_{2.5}$ below the federal annual standard of 12 $\mu g\ m^{-3}$. Maximums typically occur from July through September (Fig. 2) and winter lows (below 6 $\mu g\ m^{-3}$) from December to March. The Central Valley has overall higher concentrations and a winter high pattern that is often disconnected to Pinehurst (Cisneros et al., 2014). There is minimal daily and hourly variation in $PM_{2.5}$ at Pinehurst that can be attributed to anthropogenic emissions (Fig. SI 1 and 2).

Summer highs at Pinehurst coincide with the typical wildland fire season. Fire season normally begins about mid-summer and ends with the first significant rain or snow event in the late fall or early winter. Wildland fire can occur any month of the year but the typical wet winters preclude much fire activity until May with most fires starting in July (Fig. 2). In October, the shorter days and cooler temperatures slow fire activity until winter storms bring increased precipitation and end the fire season. Higher $PM_{2.5}$ concentrations in May through September typically is when ground level wind is from the direction of a fire as illustrated by Fig. 3 where the highest concentrations occur when ground level winds are from the direction (northeast) of the 2015 Rough and 2008 Tehipite fires (locations shown in Fig. SI 3). Wildland fire smoke was an important contributing source to $PM_{2.5}$ at Pinehurst.

3.2. Wildland fire

Wildland fire burns regularly throughout California with a median of 8095 wildland and 657 prescribed fires per year (2006–2015). The largest fires in the Pinehurst region were on federal US Forest Service and National Park Service land (Fig. SI 3). The years 2006–2015 in California burned from a low of 73,691 ha (2010) to a 604,074 ha (2008) high (Fig. SI 4(a)). While 2008 had the largest total area burned, this overall burn area may be much more typical of the historic cycle (Stephens et al., 2007). 2015 was the highest local burn year for Pinehurst (Fig. SI 4(b)) due to the full-suppression Rough Fire (61,360 ha). The local Pinehurst burn area for 2006 to 2014 was an order of magnitude below 2015 with 2008 being the next largest (Fig. SI 4(c)). The Pinehurst regional and local area is an active area of wildland fire ignitions (Fig. SI 5(a)) where the number of regional fire starts and ignitions in the foothills exceeded 1000 in both 2006 and 2007. Federally protected local land had 50-70 annual wildland fire starts (Fig. SI 5(b)). Both Dry Creek (14 fires) and Mill Creek (107 fires) had no fire over 200 ha and much of the fire in the foothills area (871 fires total) was small with only 3 fires larger than 200 ha (Table SI 1). The Kaweah River drainage had 218 fires between 2006 and 2015 with 8 fires over 200 ha. The Kings drainage had 382 total fires and the largest burned area during the Hidden Fire (Table SI 1). Regionally, there were an additional 61 fires over 200 ha. Four prescribed fires in the Kaweah drainage were the closest of all the fires to Pinehurst (7–13 km E). The Sheep Fire was the closest managed fire (23–32 km ENE). The Rough (14–35 km NE) and Hidden (17–23 km ESE) fires were the closest suppression fires (Fig. SI 3).

3.3. Smoke transport

Drainage transport was important to smoke impacts at Pinehurst. Smoke from wildland fires in the Pinehurst local area often

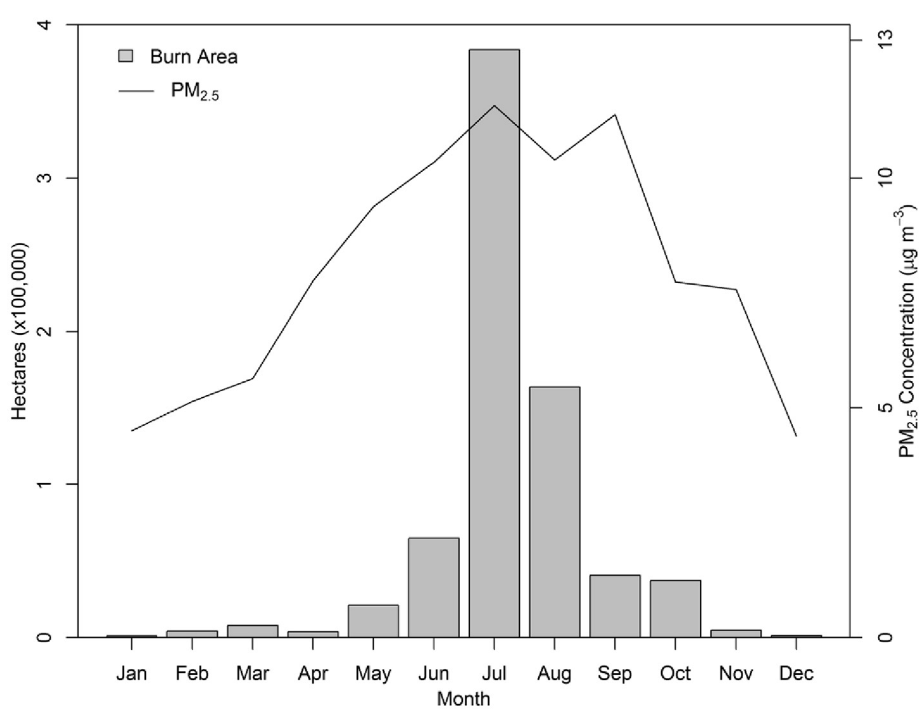

Fig. 2. Hectares of wildland fire burned in the Pinehurst region from 1970 to 2014 and monthly mean fine particulate matter ($PM_{2.5}$).

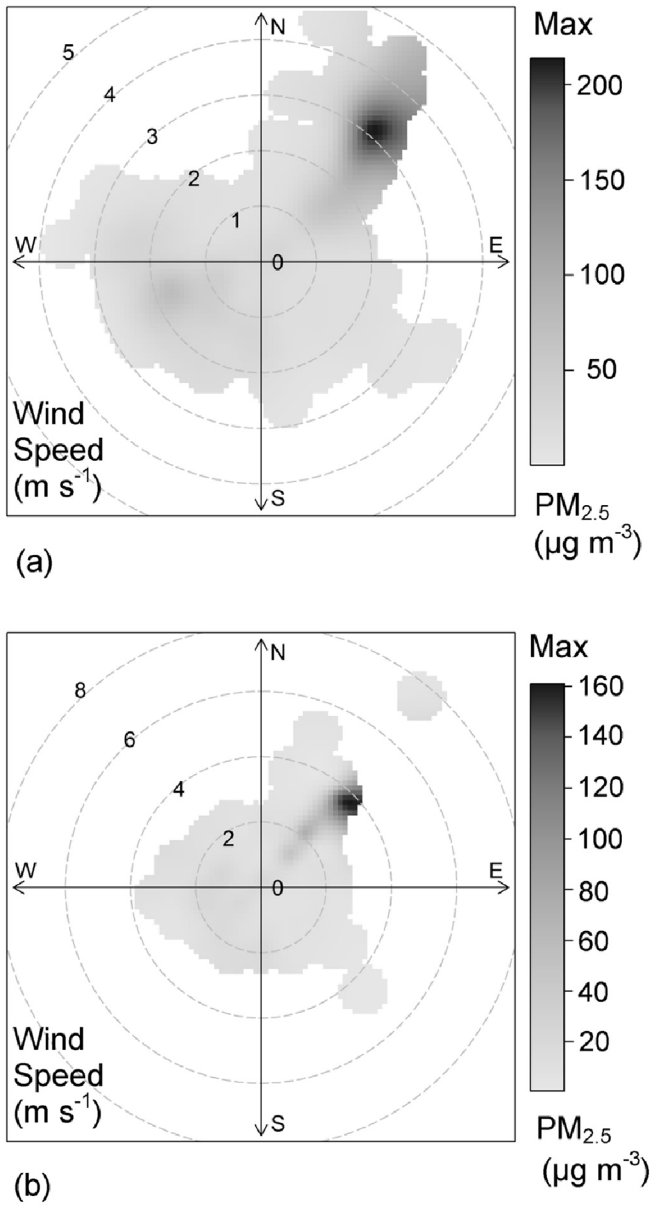

Fig. 3. Ground level wind speed (m s^{-1}) and direction and maximum hourly $PM_{2.5}$ (μg m^{-3}) at Pinehurst during the (a) Rough Fire from September 10 to October 8, 2015 and (b) Tehipite Fire from August 18 to October 8, 2008.

settled into drainages during the evening and night as fire intensity reduced. Wildland fire smoke in the Sierra Nevada followed the general east transport as illustrated by the managed 2011 Lion Fire (Fig. 4). Similarly, the 2010 Sheep Fire was widespread across the Sierra Nevada (Fig. SI 6). HMS data also indicated some of the drainage transport with this fire where smoke from the Sheep Fire was transported west from the fire through the Kings River drainage. The 2015 Rough Fire and the larger emissions from this megafire increased spatial smoke impacts (Fig. 5) and also resulted in the highest hourly readings at Pinehurst (455 and 251 μg m^{-3}). The Rough Fire accounted for 31 of the 51 hourly concentrations at Pinehurst that exceeded 100 μg m^{-3}. The daily concentration of $PM_{2.5}$ was above the NAAQS 24 h threshold 19 times from 2006 to 2015 with 11 during the Rough Fire.

Satellite imagery and modeling was useful only for the larger (~>1000 ha) managed and full suppression fires. Typically the greatest impacts were on federal lands east of these fires.

3.4. Vegetation and historic fire return

Land use and vegetation in the Pinehurst region (see Fig. 1) is primarily developed for agriculture (27%) with Ponderosa (9%) and mixed conifer (9%). The western foothill region is primarily agricultural (57%) with 31% Blue Oak and Valley Oak woodland. Moving up in elevation, Dry and Mill Creek are primarily Blue Oak and Valley Oak (40% and 37% respectively) with both having 37% Chaparral. The Kings and Kaweah River drainages, encompassing mid-to high-elevation federally protected lands included more timber. The Kaweah River drainage has 37% Ponderosa Pine, 24% Chaparral, and 22% Red Fir. The Kings River drainage major vegetation types were Red Fir (36%) and Ponderosa Pine (15%).

Pre-historic fire was estimated to be between 35,300 ha and 92,400 ha annually for the Pinehurst local area with regional fire from 132,600 to 347,900 ha annually (Table 1). Wildland fire in this area is well below the estimated pre-historic levels. Although 2015, due to the Rough Fire, exceeded the high fire return interval estimate for local fires, it was only 66% of the median pre-historic fire extent. Total fire size regionally was below pre-historic estimates. The Rough Fire contributed 2 to over 5 times the expected fire area for the Kings River. Other years were below the calculated estimates. 2008, with managed fires in the Kings and Kaweah River drainages, was 8–22% of the expected. The other high local fire years (2006 and 2010) were between 4-10% and 5–12% of calculated fire area.

The Dry and Mill Creek drainage areas did not experience much fire from 2006 to 2015 typically below 1% of the estimated area. The Foothills area burned 11.1–28.3% during 2006. The Kaweah River drainage area burned 11.6–29.4% of the estimated area in 2008. The 2008 Tehipite Fire (managed) burned 17.4–45.8% (high fire return-median fire return) of the estimated total for the King River area while the 2010 Sheep Fire (managed) burned 12.3–32.6% of the estimated total for the Kings River drainage.

3.5. $PM_{2.5}$ and AQI at Pinehurst

Hourly AQI for $PM_{2.5}$ at Pinehurst is largely good with 2015 having the worse hourly AQI and 2008 having the most unhealthy hours (Table SI 2). The highest hourly AQI from 2006 to 2015 was very unhealthy. The highest hourly concentration of $PM_{2.5}$ (455 μg m^{-3}) was on 8/28/2015 and caused by the Rough Fire. The Rough Fire accounted for all the 2015 hourly AQI that were unhealthy for sensitive groups, unhealthy, and very unhealthy and additionally accounted for 137 of the Moderate hourly readings for the year. The Rough Fire had the largest impact both in quantity and level of air quality impact accounting for 31 of the 51 h above 100 μg m^{-3} and 11 of the 19 days above 35 μg m^{-3}. The managed Sheep and Tehipite Fires also had impacts to air quality but were much less in both number of hours and level of impact. $PM_{2.5}$ reached an hourly high at Pinehurst of 136 μg m^{-3} (unhealthy sensitive AQI) during the Sheep Fire with 30 hourly readings above 35 μg m^{-3}. The highest daily concentration at Pinehurst during the Sheep Fire was 24.4 μg m^{-3} (moderate AQI). $PM_{2.5}$ during the Tehipite Fire had an hourly high of 181 μg m^{-3} (unhealthy AQI), with 5 h above 100 μg m^{-3} and 35 h above 35 μg m^{-3} resulting in 5 h of unhealthy AQI. The highest daily concentration of $PM_{2.5}$ at Pinehurst during the Tehipite Fire was 33.8 μg m^{-3} (moderate AQI). Local prescribed fires including the nearest significant burns (Whitaker Rx, Redwood Mt., Upper Redwood, and Hart) had hourly $PM_{2.5}$ AQI typically good with 1 h of unhealthy for sensitive. These prescribed burns contributed to a total of 12 moderate hours. Hours with the highest AQI at Pinehurst were almost exclusively caused

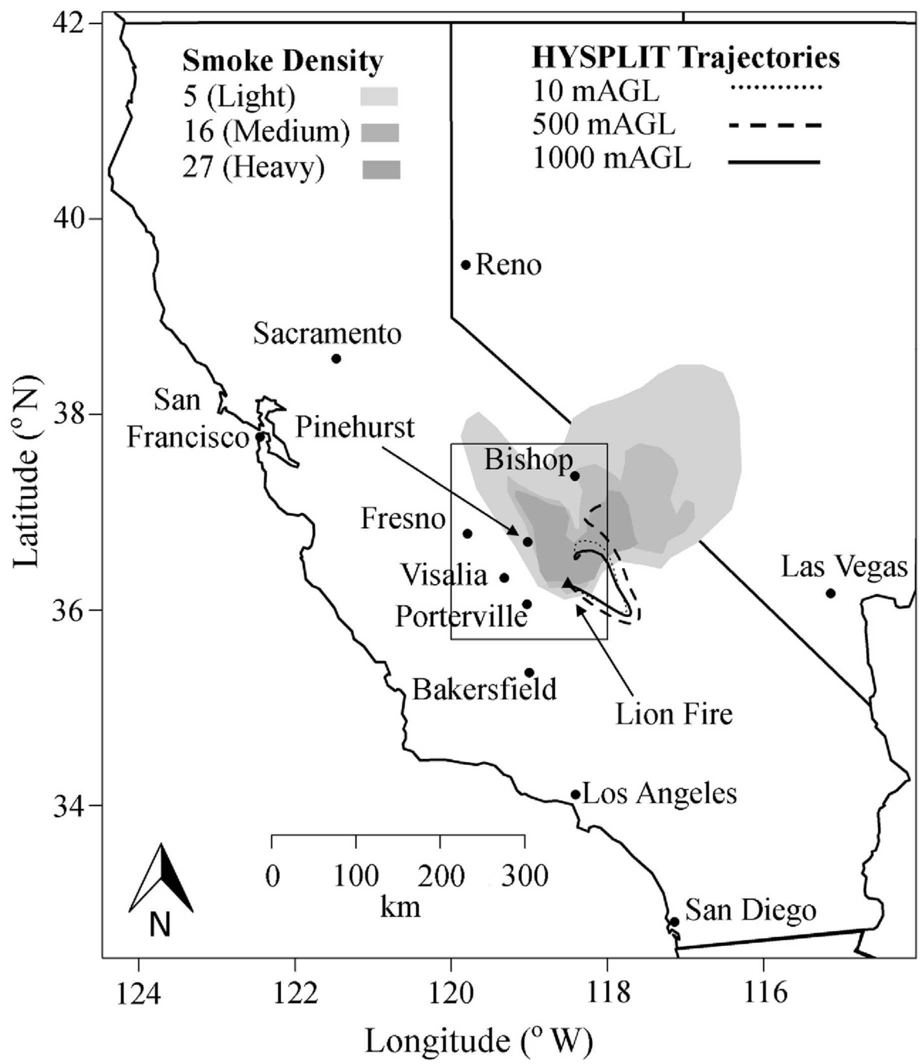

Fig. 4. Smoke transport as described by the Hazard Mapping System Fire and Smoke Product (HMS) smoke density and Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) forward trajectories from the Lion Fire on 7/26/2011 with Pinehurst regional bounding box.

by wildland fire.

Hourly AQI was good during both large regional fires (Round and Cabin) during 2015. Neither the Round Fire to the northeast or the Cabin Fire to the south-southeast impacted Pinehurst (all hours good AQI). During 2008, all hourly unhealthy values and 2 unhealthy for sensitive occurred during the Tehipite Fire. The Tehipite Fire also contributed to the increased $PM_{2.5}$ at Pinehurst resulting in moderate AQI for 62 h 2008 was an active fire year in California with smoke covering most of the state. Before the start of the Tehipite Fire, large fires in northern California created high $PM_{2.5}$ in many areas across the state, including Pinehurst, during late June (25–30). As the smoke moved more northerly, $PM_{2.5}$ returned to normal but increased again in the Pinehurst area from about July 7 to 11. This June statewide smoke was associated with 70 moderate and 1 unhealthy for sensitive AQI hours while the July episode added 24 moderate hours. The Sheep Fire (2010) caused the 1 unhealthy for sensitive and contributed to 23 of the 30 moderate AQI hours.

Daily AQI was generally good with the highest AQI being unhealthy for sensitive for $PM_{2.5}$ (Table 2). The Rough Fire had the largest impact to AQI with 11 unhealthy for sensitive and 22 moderate days. The Tehipite Fire smoke contributed to 1 unhealthy for sensitive and 34 moderate days. Air quality for $PM_{2.5}$ during the Sheep Fire never went above moderate 24-h AQI (42 days). The June 2008 period produced 3 moderate and 3 unhealthy for sensitive days with no days of good 24-h AQI. The July 2008 period of smoke also had no good days with 4 moderate a 1 unhealthy for sensitive. Local prescribed and smaller fires did not go above moderate and typically remained in the good category. Larger fires in the local area (Rough, Tehipite, Sheep, Lion, and Aspen) all impacted Pinehurst and often increased the 24-h AQI to moderate.

Impacts from smoke to $PM_{2.5}$ air quality at Pinehurst were generally low for smaller fires (less than ~1500 ha) even when burning in the immediate area. Prescribed fires in the area, while typically closest to the Pinehurst monitor, were not associated with a pronounced increase in $PM_{2.5}$. Mean $PM_{2.5}$ concentrations for the days of the four closest fires (7–13 km away), the Whitaker, Redwood Mountain, Upper Redwood, and Hart prescribed fires, were all within $-3.0\ \mu g\ m^{-3}$ and $+4.2\ \mu g\ m^{-3}$ of the mean concentrations during the same days for all other years and hourly maximums from $-53\ \mu g\ m^{-3}$ to $+54\ \mu g\ m^{-3}$ (Table 3). Impacts to $PM_{2.5}$ from prescribed fire smoke were largely within the variation typical of this site for the time of year.

The larger managed fires (Sheep and Tehipite) had an impact on

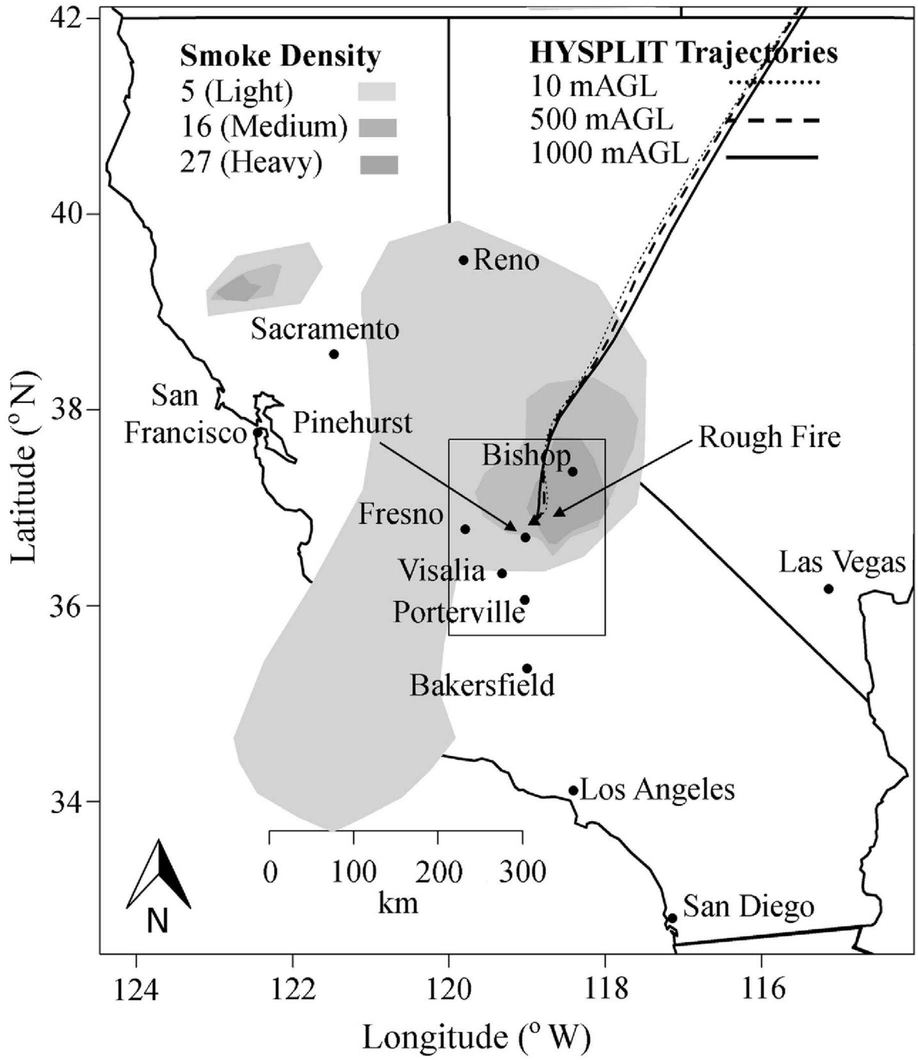

Fig. 5. Smoke transport as described by the Hazard Mapping System Fire and Smoke Product (HMS) smoke density and Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) forward trajectories from the Rough Fire on 9/2/2015 with Pinehurst regional bounding box.

air quality as was seen in the hourly and daily AQI and resulted in maximum concentrations at Pinehurst of 136 μg m^{-3} during the Sheep Fire and 144 μg m^{-3} during the Tehipite Fire (Table 4). Smoke impacts to $PM_{2.5}$ were largely over a few hours (1–6) and at the same time of day. $PM_{2.5}$ concentrations over the entire fire were from −3.8 μg m^{-3} to +1.9 μg m^{-3} for mean concentrations during other years (Table 4). Excluding the 2015 Rough Fire impacts to $PM_{2.5}$, mean concentrations ranged from −2.8 μg m^{-3} to +2.5 μg m^{-3} with maximum hourly concentrations lower except during the Tehipite Fire (Table 4).

$PM_{2.5}$ mean concentrations during full suppression fires were −3.0 μg m^{-3} to +10.8 μg m^{-3}. The Rough Fire increased mean $PM_{2.5}$ at Pinehurst to 20.4 μg m^{-3} with a maximum hourly concentration or 455 μg m^{-3} while the next closest suppression fire (Hidden) had a maximum of 181 μg m^{-3} (Table 5).

3.6. $PM_{2.5}$ and NAAQS health standards at Pinehurst

NAAQS annual and NAAQS 24 h (these values are the rolling 3 year mean of the annual values) are both below the attainment threshold at the Pinehurst monitor from 2008 to 2015 (Fig. 6). NAAQS annual is consistently below the federal threshold with 2015 having the highest NAAQS annual (8.5 μg m^{-3}) and annual mean (9.3 μg m^{-3}). NAAQS 24 h is also below the federal compliance threshold with the highest being 2015 (30 μg m^{-3}). Annual mean values have a low correlation ($R^2 = 0.33$; $p = 0.082$) to the area burned in the local bounding areas. Annual 24 h is strongly correlated ($R^2 = 0.73$; $p = 0.002$) the local area burned. The annual

Table 1
Pre-historic high (longer time between fires) and median fire return interval burn area estimates and the actual largest (2006–2015) burned areas (ha) with year for the Pinehurst region and local area.

Bounding area	Fire return interval estimate (ha)		Actual	
	High	Median	Max (ha)	Year
Foothills	13,600	36,200	679	2006
Dry Creek	1500	3800	11	2007
Mill Creek	2400	6100	28	2009
Kaweah River	6400	16,200	1884	2008
Kings River	11,400	30,100	61,389	2015
Total Local	35,300	92,400	61,445	2015
Regional (excluding local)	97,300	255,500	24,986	2011
Total Regional	132,600	347,900	69,887	2015

Table 2
Number of days of Air Quality Index (AQI) categories at Pinehurst from 2006 to 2015.

Year	NA (days)	Good (days)	Moderate (days)	Unhealthy for Sensitive Groups (days)	Unhealthy (days)	Very Unhealthy (days)	Hazardous (days)	Daily Max $PM_{2.5}$ ($\mu g\ m^{-3}$)
2015	34	267	53	11	0	0	0	53.5
2014	12	274	78	1	0	0	0	45.7
2013	33	263	69	0	0	0	0	23.7
2012	23	283	59	1	0	0	0	36.4
2011	9	273	83	0	0	0	0	25.0
2010	36	239	90	0	0	0	0	24.4
2009	54	285	26	0	0	0	0	29.8
2008	10	269	82	5	0	0	0	53.9
2007	35	285	44	1	0	0	0	43.3
2006	68	248	49	0	0	0	0	34.2

Table 3
Fine particulate matter concentrations at Pinehurst during prescribed fire for the same days during other years (2006–2015) in order of nearness to Pinehurst with closest at top and furthest at bottom of list.

Fire	Start Date	End Date	Mean ($\mu g\ m^{-3}$)		Hourly Max ($\mu g\ m^{-3}$)	
			During	Other years	During	Other years
Whitaker	6/21/2012	6/24/2012	9.8	9.3	68	55
Redwood Mountain	7/10/2011	8/16/2011	13.2	10.5	58	112
Upper Redwood	7/5/2006	7/9/2006	11.0	12.6[a]	103	44[a]
Hart	7/5/2009	7/9/2009	9.6	12.6[a]	50	44[a]
Davenport	11/18/2008	11/20/2008	11.6	7.4	87	52
Mosquito	10/20/2014	10/24/2014	7.7	7.9	21	43

[a] Does not include 2006 or 2009.

24 h for 2015 at 43.9 $\mu g\ m^{-3}$ is the only single year above the federal threshold with the next highest in 2008 (33.8 $\mu g\ m^{-3}$). For Pinehurst to remain in NAAQS compliance (3 year mean of the annual mean values) for $PM_{2.5}$ in 2016, the annual 24 h cannot exceed 34.8 $\mu g\ m^{-3}$. For 2017 to remain in compliance both 2016 and 2017 need to average 30.5 $\mu g\ m^{-3}$ or less.

Table 4
Fine particulate matter concentrations at Pinehurst during managed fire for the same days during other years (2006–2015) in order of nearness to Pinehurst with closest at top and furthest at bottom of list.

Fire	Start Date	End Date	Mean ($\mu g\ m^{-3}$)		Hourly Max ($\mu g\ m^{-3}$)	
			During	Other years	During	Other years
Sheep	7/16/2010	10/25/2010	10.9	10.0 (9.3[a])	136	455 (181[a])
Tehipite	7/25/2008	12/12/2008	9.2	9.0 (8.4[a])	244	455 (185[a])
Roaring	7/23/2006	12/15/2006	7.5	9.1 (8.6[a])	52	455 (244[a])
Cedar Bluffs	10/17/2008	10/21/2008	6.7	7.8 (7.9[a])	49	73 (73[a])
Burnt	7/21/2006	8/1/2006	9.0	11.0 (11.4[a])	27	72 (72[a])
Horse	7/19/2009	10/12/2009	7.3	10.7 (9.8[a])	73	455 (181[a])
Lion	7/8/2011	11/8/2011	11.7	9.8 (9.2[a])	58	455 (185[a])
Cabin	7/19/2015	7/30/2015	7.4	11.2	31	72

[a] Excluding 2015 Rough Fire.

Table 5
Fine particulate matter concentrations at Pinehurst during suppression fire for the same days during other years (2006–2015) in order of nearness to Pinehurst with closest at top and furthest at bottom of list.

Fire	Start Date	End Date	Mean ($\mu g\ m^{-3}$)		Hourly Max ($\mu g\ m^{-3}$)	
			During	Other years	During	Other years
Rough	7/31/2015	10/1/2015	20.4	9.7	455	181
Hidden	9/10/2008	10/8/2008	11.9	9.8	181	192
Stokes	8/17/2010	8/19/2010	11.5	11.9	21	251
W	6/24/2006	6/26/2006	15.2	12.9	26	104
Avocado	5/20/2008	5/22/2008	7.9	9.4	24	24
Windy	8/23/2013	8/26/2013	10.6	11.1	42	124
Aspen	7/22/2013	9/9/2013	11.6	10.7	42	455
French	7/28/2014	8/18/2014	11.6	10.1	72	251
Round	2/6/2015	2/10/2015	2.5	4.1	9	60
Clover	5/31/2008	6/7/2008	6.5	9.8	25	40
Bull	7/26/2010	8/31/2010	12.0	10.4	28	455
Telegraph	7/25/2008	9/15/2008	11.0	11.0	178	455
Inyo	7/6/2007	7/11/2007	11.2	14.0	20	103
John	9/13/2011	9/18/2011	13.4	11.3	24	110

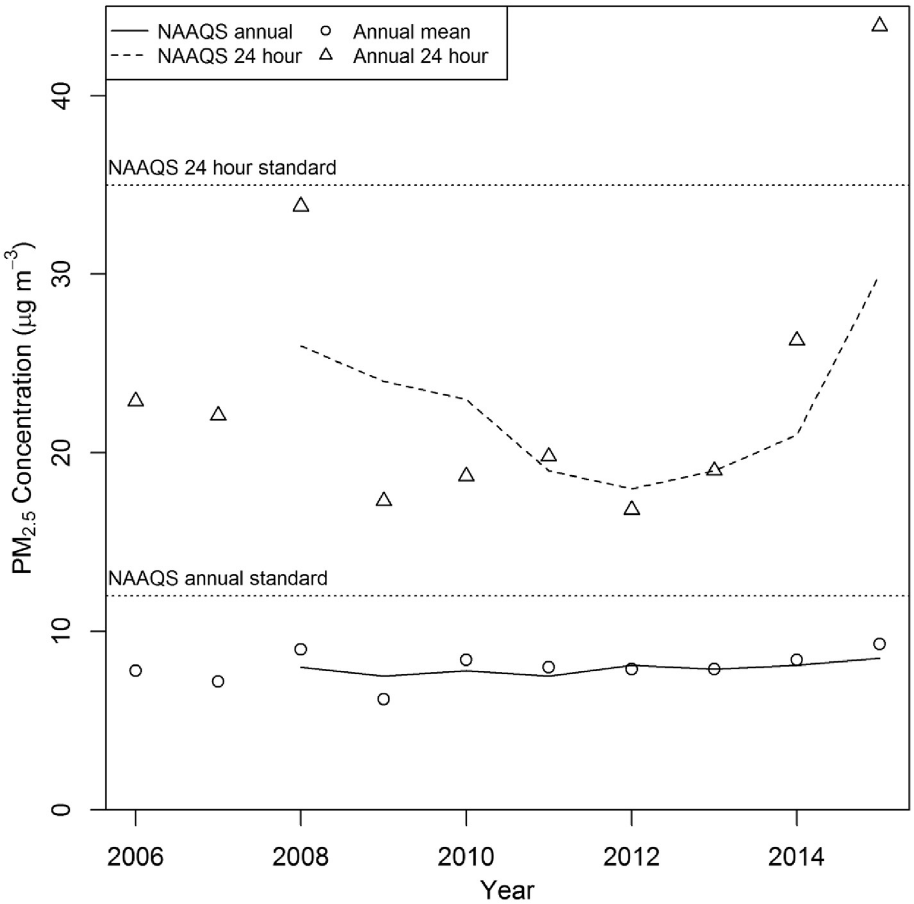

Fig. 6. Fine particulate matter ($PM_{2.5}$) at Pinehurst for annual and 24 h compliance to federal attainment standards.

Daily concentrations of $PM_{2.5}$ exceeded the NAAQS 24 h standard (35 µg m^{-3}) 19 times from 2006 through 2015. The statewide smoke in California during 2008 accounted for 4 of these days while 11 occurred while the Rough Fire was active. The managed Tehipite Fire (2008) was active for one while the other 3 occurred when there were no other wildland fires in the area and no large fires in the region.

Compliance with NAAQS 24 h is an excellent indicator of smoke at Pinehurst. Smoke accounted for 39% of the highest 10 days for each year. The Rough Fire accounted for the all of the highest 10 days during 2015. Smoke from the Sheep Fire (2010) was associated with the number 1, 2, 4, and 5 highest days. The Tehipite Fire (2008) accounted for 2 in the top 10 while the statewide smoke during this year caused 7. The only smoke from a prescribed fire in the highest days was during the Redwood Mountain burn in 2011 (the Lion Fire also contributed). The highest single day for 2011 was 25.0 µg m^{-3}.

4. Discussion

Wildland fire is a difficult natural process to manage. Smoke from wildland fire is a complex component to using fire for ecological benefit and fuel reduction. Suppression of fire in the Sierra Nevada has led to increased fuel build-up and contributed to an increased number and severity of megafires (Williams, 2013). Smoke impacts from large high intensity full suppression fires such as the 2013 Rim (Peterson et al., 2015) and 2002 McNally (Cisneros et al., 2012) in the Sierra Nevada suggest these fires can be expected to widely distribute significant amounts of smoke that impact large populations. Tradeoffs between releases of emissions through these high intensity fires versus release from self-regulated fire more typical of this forest system (Parks et al., 2015) must be confronted if the impacts to human health are to be accurately assessed. These self-limiting fires can be used as a form of natural suppression. Natural suppression fires burn into previous burns, streams, rock barriers, etc. Natural suppression fires in wilderness areas can reduce the cost of control and exposure of firefighters to unnecessary risk by allowing fire to sustain forest health.

Fire and air quality policy has created an atmosphere that is not conducive to mitigating the risks to public health in a fire adapted wilderness (North et al., 2015a,b). This may be in large part due to intolerance of regulators to any smoke and where broader acceptability needs public deliberation (Weisshaupt et al., 2005). Suppression is the default for immediate political pressures being felt by air and land managers. Policy is intended to provide long term benefits to society. The policy of suppression of wildland fire has routinely been discredited for ecological health (Backer et al., 2004; Stephens et al., 2016) while ecosystem function and health are integral to human health (Jackson et al., 2013). Smoke impacts from wildland fire can easily be used as a community rallying point to entrench a desire to suppress all fires for a smoke averse population (Shindler and Toman, 2003). A single day of smoke can be used to advance a suppression agenda by relying on perceptions derived from an era where suppression virtually eliminated smoke. But, these emissions are not gone they are simply delayed until suppression is no longer possible (Steel et al., 2015) and additional fuel loading creates smoke events beyond the normal (Gonzalez et al., 2015; Schoennagel et al., 2004). Smoke impacts are inevitable in a fire adapted ecosystem. But, increased population may make a

return to a natural fire regime and the smoke emissions problematic (Dombeck et al., 2004; Hurteau et al., 2014).

Air quality for $PM_{2.5}$ was found to be good for a single site impacted by wildland fire over multiple years. Managed fire in this fire prone area did not cause the monitoring site to exceed the current NAAQS thresholds for $PM_{2.5}$. Smoke from the Tehipite Fire in 2008 and the Sheep Fire in 2010 impacted the Pinehurst site and had larger impacts in the immediate areas adjacent to the fire and in the Kings River drainage but these impacts were largely only unhealthy for sensitive groups and short duration. These ecologically beneficial fires helped sustain this fire adapted forest and reduced fuels with measured emissions and included subsequent benefits to public health from a healthy and resilient ecosystem. In contrast, the Rough Fire (2015) increased air quality impacts to $PM_{2.5}$ to very unhealthy levels and led to an exceedance of the annual NAAQS 24 h. Emissions slowed when the Rough Fire entered the 2010 Sheep Fire perimeter. When the Rough Fire burned in this area, AQI impacts reduced into the good range for a number of days. Later, the fire became more active as it again entered areas of higher fuel loads (caused by a century of fire suppression) and AQI increased in Pinehurst to unhealthy levels. This drop in impacts at the Pinehurst site during the Rough Fire and the implications of benefits to air quality from previous recent ecologically beneficial fire needs further study.

Effective wildland fire policy and smoke management are complex issues. There is no simple solution to smoke management in a fire prone ecosystem. Smoke from wildland fire will likely become an increasingly contentious subject, particularly in the public forum, as long term benefits of managed and prescribed fire challenge the legacy of unsustainable suppression policy and a smoke averse public. While suppression is important, management of fire emissions can be enhanced through timed, measured release from ecologically beneficial fire. It is important to understand the differed risk through suppression of wildland fire and smoke. There are inherent difficulties to determining smoke impacts on air quality from wildland fire. Smoke from any fire will have impacts. These impacts are largely dependent on location of the source and the receptor. Being in direct immediate contact with smoke even from a campfire will exceed air quality standards. Wildland fire smoke is no exception. Indeed, being directly in the plume of a wildland fire of even the smallest size exposes a person to many pollutants. The Pinehurst site was never directly in a plume. Rather, we chose this site because it was not in the plume but more representative of local communities' exposure to $PM_{2.5}$.

Smoke impacted air quality at Pinehurst. Hourly AQI reached very unhealthy on one of the largest growth days (8/28/2015) of the Rough Fire when fire size increased approximately 2900 ha. Fire will always have some impact to air quality. We found that during a prescribed or managed fire, smoke impacts were below federal NAAQS thresholds at the representative site. Smoke impacts typically occurred at the same time of day for a wildland fire. The reliable timing of smoke $PM_{2.5}$ exposure for managed or prescribed fires provides a potential for managing smoke impacts to human health. Impacts from prescribed and managed fires could largely be mitigated through personal choices of when to exercise, move to a different area, etc. The high severity full suppression Rough Fire smoke exposure did not provide this luxury. AQI was the highest and much more pervasive and wide spread throughout the day. Although this is intuitive in that the Rough Fire was much larger, and therefore emitted substantially more smoke, lost is the idea that had the local Pinehurst area burned more nearly to the prehistoric normal this episode may have been avoided.

It is difficult to parse out health impacts and nuisance when determining smoke impacts. Additionally, it is much easier to urge full suppression when confronting any smoke impact. But, this tact assumes that these emissions will not come. In a fire prone area with a fire adapted ecosystem this assumption is flawed. Increased fire size and intensity in the western United States is the new normal (Westerling et al., 2006) as we move into a post suppression era. With most years falling well below what is estimated as typical for even high fire return intervals or the least fire on the landscape, the Sierra Nevada are likely not an exception. These estimates and the increased fuel loads from suppression strongly suggest the Sierra Nevada will have more smoke in the coming years. These emissions can likely be mitigated by increased burning and a slower release of smoke rather than choosing a megafire through suppression policies.

Exceedance of the annual 24 h for 2015 illustrates the type of public health impacts to be expected when full suppression fails to contain a wildland fire with heavy fuel loading and other extreme conditions. Burning in the Pinehurst area could easily be increased while still adhering overall to NAAQS $PM_{2.5}$ thresholds. Air and fire management in a fire prone area particularly one with large tracts of wilderness or other protected natural areas should consider managing to a local basin where a sensitive site or, as Pinehurst, a site located near the wildland urban interface may be used to estimate landscape level air quality. This would help in the assessment and weighing of impacts from a managed fire while allowing regulators to have a metric to decide between public health (NAAQS) and nuisance (AQI, visibility, smell).

5. Conclusions

Wildland fire in the Pinehurst area has been well below historic levels and could be increased using prescribed and managed fire. Prescribed and managed fire exposes the Pinehurst area to less particulate matter and decreases duration from a megafire when full suppression fails. Consistent management of fire on the landscape for fuel reduction and ecological benefit can be accomplished to a much larger magnitude than was done from 2006 to 2014. 2008 had the largest managed and prescribed fire local area amounting to 7800 ha burned while remaining below NAAQS standards for $PM_{2.5}$. Current fire extent could be increased to at least this annual minimum or 8–22% of the historic burn area while likely still remaining below federal health standards. Burning at this rate over all years 2006–2015 would have produced a similar total local burn area as actually occurred (including the megafire in 2015). This approach could reduce the risk of exposing a larger area to higher concentrations similar to those experienced during the 2015 Rough Fire. A simple systematic approach for weighing both short and long term air quality goals for smoke management can be accomplished using a representative monitoring site and current in-place federal standards over multiple years. This would allow for sustainable landscape burning that would largely restrict impacts from the densely populated areas of the Central Valley. Rather than focusing policy on the location of the most impacted air quality, for large protected natural areas, a landscape level understanding of air quality impacts would help provide a more nuanced assessment of smoke impacts and aid in the management of fire prone areas.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.07.004.

References

Air Resources Lab, 2016. National oceanic and atmospheric administration, air Resources laboratory: real-time environmental applications and display system. http://ready.arl.noaa.gov/READYamet.php (accessed 1.20.16).

Backer, D.M., Jensen, S.E., McPherson, G.R., 2004. Impacts of fire-suppression activities on natural communities. Conserv. Biol. 18, 937–946. http://dx.doi.org/10.1111/j.1523-1739.2004.494_1.x.

Baker, W., 2014. Historical forest structure and fire in Sierran mixed-conifer forests reconstructed from General Land Office survey data. Ecosphere 5, 79. http://dx.doi.org/10.1890/ES14-00046.1.

BlueSky, 2016. U.S. Forest Service AirFire research Team. http://www.airfire.org/data/bluesky-daily/ (accessed 2.26.16).

Boer, M.M., Price, O.F., Bradstock, R.A., 2015. Wildfires: weigh policy effectiveness. Science 350, 920. http://dx.doi.org/10.1126/science.350.6263.920-a.

Bytnerowicz, A., Hsu, Y.-M., Percy, K., Legge, A., Fenn, M.E., Schilling, S., Frączek, W., Alexander, D., 2016. Ground-level air pollution changes during a boreal wildland mega-fire. Sci. Total Environ. 572, 755–769. http://dx.doi.org/10.1016/j.scitotenv.2016.07.052.

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

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 Mountains, California. Atmos. Pollut. Res. 5, 581–590. http://dx.doi.org/10.5094/APR.2014.067.

Cisneros, R., Schweizer, D., Zhong, S., Hammond, K., Perez, M.A., Guo, Q., Traina, S., Bytnerowicz, A., Bennett, D.H., 2012. Analysing the effects of the 2002 McNally fire on air quality in the san Joaquin Valley and southern Sierra Nevada, California. Int. J. Wildl. Fire 21, 1065–1075. http://dx.doi.org/10.1071/wf11025.

Dombeck, M.P., Williams, J.E., Wood, C.A., 2004. Wildfire policy and public lands: integrating scientific understanding with social concerns across landscapes. Conserv. Biol. 18, 883–889. http://dx.doi.org/10.1111/j.1523-1739.2004.00491.x.

FAMWEB, 2017. National fire and aviation management data warehouse. https://fam.nwcg.gov/fam-web/.

Fantke, P., Jolliet, O., Evans, J.S., Apte, J.S., Cohen, A.J., Hänninen, O.O., Hurley, F., Jantunen, M.J., Jerrett, M., Levy, J.I., Loh, M.M., Marshall, J.D., Miller, B.G., Preiss, P., Spadaro, J.V., Tainio, M., Tuomisto, J.T., Weschler, C.J., McKone, T.E., 2015. Health effects of fine particulate matter in life cycle impact assessment: findings from the Basel Guidance Workshop. Int. J. Life Cycle Assess. 20, 276–288. http://dx.doi.org/10.1007/s11367-014-0822-2.

Gonzalez, P., Battles, J.J., Collins, B.M., Robards, T., Saah, D.S., 2015. Aboveground live carbon stock changes of California wildland ecosystems, 2001-2010. For. Ecol. Manag. 348, 68–77. http://dx.doi.org/10.1016/j.foreco.2015.03.040.

Haikerwal, A., Reisen, F., Sim, M.R., Abramson, M.J., Meyer, C.P., Johnston, F.H., Dennekamp, M., 2015. Impact of smoke from prescribed burning: is it a public health concern? J. Air Waste Manag. Assoc. 65, 592–598. http://dx.doi.org/10.1080/10962247.2015.1032445.

Hänninen, 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. Environ. Epidemiol. 19, 414–422. http://dx.doi.org/10.1038/jes.2008.31.

Huff, Hoff, R., Kondragunta, S., Zhang, H., 2015. Monitoring the impacts of wildfires on forest ecosystems and public health in the exo-urban environment using high-resolution satellite aerosol products from the visible infrared imaging radiometer suite (VIIRS). Environ. Health Insights 9, 9. http://dx.doi.org/10.4137/EHI.S19590.

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. http://dx.doi.org/10.1021/es4050133.

HYSPLIT, 2016. National oceanic and atmospheric administration, air Resources laboritory: Hybrid single Particle lagrangian integrated trajectory Model. https://ready.arl.noaa.gov/HYSPLIT.php (accessed 2.26.16).

Jackson, L.E., Daniel, J., McCorkle, B., Sears, A., Bush, K.F., 2013. Linking ecosystem services and human health: the Eco-Health Relationship Browser. Int. J. Public Health 58, 747–755. http://dx.doi.org/10.1007/s00038-013-0482-1.

Keeley, J.E., Pausas, J.G., Rundel, P.W., Bond, W.J., Bradstock, R.A., 2011. Fire as an evolutionary pressure shaping plant traits. Trends Plant Sci. 16, 406–411. http://dx.doi.org/10.1016/j.tplants.2011.04.002.

Kilgore, B.M., Taylor, D., Kilgore, B.M., Taylor, D.A.N., 1979. Fire history of a sequoia-mixed conifer forest, 60, 129–142.

Le, G.E., Breysse, P.N., Mcdermott, A., Eftim, S.E., Geyh, A., 2014. Canadian Forest Fires and the Effects of Long-range Transboundary Air Pollution on Hospitalizations among the Elderly, pp. 713–731. http://dx.doi.org/10.3390/ijgi3020713.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.R., Andrews, K.G., Aryee, M., Atkinson, C., Bacchus, L.J., Bahalim, A.N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M.L., Blore, J.D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N.G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R.T., Byers, T.E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H., Chen, J.S., Cheng, A.T.-A., Child, J.C., Cohen, A., Colson, K.E., Cowie, B.C., Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D.C., Devries, K., Dherani, M., Ding, E.L., Dorsey, E.R., Driscoll, T., Edmond, K., Ali, S.E., Engell, R.E., Erwin, P.J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M.M., Flaxman, S., Fowkes, F.G.R., Freedman, G., Freeman, M.K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H.R., Hall, W., Hoek, H.W., Hogan, A., Hosgood, H.D., Hoy, D., Hu, H., Hubbell, B.J., Hutchings, S.J., Ibeanusi, S.E., Jacklyn, G.L., Jasrasaria, R., Jonas, J.B., Kan, H., Kanis, J.A., Kassebaum, N., Kawakami, N., Khang, Y.-H., Khatibzadeh, S., Khoo, J.-P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J.L., Leigh, J., Li, Y., Lin, J.K., Lipshultz, S.E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G.A., Merriman, T.R., Micha, R., Michaud, C., Mishra, V., Mohd Hanafiah, K., Mokdad, A.A., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P.K., Nolla, J.M., Norman, R., Olives, C., Omer, S.B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K.D., Parry, C.D.H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P.M., Petzold, M., Phillips, M.R., Pope, D., Pope, C.A., Powles, J., Rao, M., Razavi, H., Rehfuess, E.A., Rehm, J.T., Ritz, B., Rivara, F.P., Roberts, T., Robinson, C., Rodriguez-Portales, J.A., Romieu, I., Room, R., Rosenfeld, L.C., Roy, A., Rushton, L., Salomon, J.A., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P., Shield, K., Shivakoti, R., Singh, G.M., Sleet, D.A., Smith, E., Smith, K.R., Stapelberg, N.J.C., Steenland, K., Stöckl, H., Stovner, L.J., Straif, K., Straney, L., Thurston, G.D., Tran, J.H., Van Dingenen, R., van Donkelaar, A., Veerman, J.L., Vijayakumar, L., Weintraub, R., Weissman, M.M., White, R.A., Whiteford, H., Wiersma, S.T., Wilkinson, J.D., Williams, H.C., Williams, W., Wilson, N., Woolf, A.D., Yip, P., Zielinski, J.M., Lopez, A.D., Murray, C.J.L., Ezzati, M., AlMazroa, M.A., Memish, Z.A., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet Lond.n, Engl. 380, 2224–2260. http://dx.doi.org/10.1016/S0140-6736(12)61766-8.

Lipsett, M., Materna, B., Lyon Stone, S., Therriault, S., Blaisdell, R., Cook, J., 2013. Wildfire Smoke - a Guide for Public Health Officials. Updated June 2013 2008, p. 54.

Liu, J.C., Pereira, G., Uhl, S.A., Bravo, M.A., Bell, M.L., 2015. A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. Environ. Res. 136, 120–132. http://dx.doi.org/10.1016/j.envres.2014.10.015.

Met One Instruments, 2008. BAM 1020 Particulate Monitor Operation Manual BAM-1020–9800 Rev G. Met One Instruments, Inc., Grants Pass, OR.

MODIS, 2017. National aeronautics and space administration (NASA) moderate resolution imaging spectroradiometer (MODIS) satellite imagery. https://fsapps.nwcg.gov/afm/imagery.php accessed 2.26.16.

NIFC, 2016. National interagency fire center. http://www.nifc.gov/fireInfo/fireInfo_main.html accessed 1.26.16.

NOAA, 2016. National oceanic and atmospheric administration hazard mapping system fire and smoke Product. http://www.ospo.noaa.gov/Products/land/hms.html accessed 10.27.16.

North, M., Stephens, S., Collins, B., Agee, J., Aplet, G., Franklin, J., Fule, P., 2015a. Wildfires–response. Science 350, 920–921. http://dx.doi.org/10.1126/science.350.6263.920-c.

North, M.P., Stephens, S.L., Collins, B.M., Agee, J.K., Aplet, G., Franklin, J.F., Fule, P.Z., 2015b. Reform forest fire management. Science 349, 1280–1281. http://dx.doi.org/10.1126/science.aab2356.

Parks, S.A., Holsinger, L.M., Miller, C., Nelson, C.R., 2015. Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. Ecol. Appl. 25, 1478–1492. http://dx.doi.org/10.1890/14-1430.1.

Peterson, D.A., Hyer, E.J., Campbell, J.R., Fromm, M.D., Hair, J.W., Butler, C.F., Fenn, M.A., 2015. The 2013 Rim fire: implications for predicting extreme fire spread, pyroconvection, and smoke emissions. Bull. Am. Meteorol. Soc. 96, 229–247. http://dx.doi.org/10.1175/BAMS-D-14-00060.1.

Preisler, H., Schweizer, D., Cisneros, R., Procter, T., Ruminski, M., Tarnay, L., 2015. A statistical model for determining impact of wildland fires on Particulate Matter (PM 2.5) in Central California aided by satellite imagery of smoke. Environ. Pollut. 205, 340–349. http://dx.doi.org/10.1016/j.envpol.2015.06.018.

R Core Team, 2016. R: a Language and Environment for Statistical Computing.

Schoennagel, T., Veblen, T.T., Romme, W.H., 2004. The interaction of fire, fuels, and climate across rocky mountain forests. Bioscience 54, 661–676. http://dx.doi.org/10.1641/0006-3568(2004)054.

Schwartz, M.W., Butt, N., Dolanc, C.R., Holguin, A., Moritz, M.A., North, M.P., Safford, H.D., Stephenson, N.L., Thorne, J.H., van Mantgem, P.J., 2015. Increasing elevation of fire in the Sierra Nevada and implications for forest change. Ecosphere 6, 121. http://dx.doi.org/10.1890/ES15-00003.1.

Shindler, B., Toman, E., 2003. Fuel reduction strategies in forest communities: a longitudinal analysis of public support. J. For. 8–15.

Steel, Z.L., Safford, H.D., Viers, J.H., 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. Ecosphere 6, 8. http://dx.doi.org/10.1890/ES14-00224.1.

Stephens, S.L., Collins, B.M., Biber, E., Fulé, P.Z., 2016. U.S. federal fire and forest policy: emphasizing resilience in dry forests. Ecosphere 7, e01584. http://dx.doi.org/10.1002/ecs2.1584.

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. http://dx.doi.org/10.1016/j.foreco.2007.06.005.

Thompson, M.P., Calkin, D.E., 2011. Uncertainty and risk in wildland fire management: a review. J. Environ. Manag. 92, 1895–1909. http://dx.doi.org/10.1016/j.jenvman.2011.03.015.

Topik, C., 2015. Wildfires burn science capacity. Science 349. http://dx.doi.org/10.1126/science.aad4202, 1263–1263.

U.S. Environmental Protection Agency, 1999. Guideline on Data Handling

Conventions for the PM NAAQS.
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. http://dx.doi.org/10.4996/fireecology.0703026.
Vining, J., Merrick, M.S., 2008. The influence of proximity to a national forest on emotions and fire-management decisions. Environ. Manag. 41, 155–167. http://dx.doi.org/10.1007/s00267-007-9041-y.
Weisshaupt, B.R., Carroll, M.S., Blatner, K., Robinson, W.D., Jakes, P.J., 2005. Acceptability of smoke from prescribed forest burning in the northern Inland West: a focus group approach. J. For. 103, 189–193.
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. http://dx.doi.org/10.1126/science.1128834.
Williams, J., 2013. Exploring the onset of high-impact mega-fires through a forest land management prism. For. Ecol. Manag. 294, 4–10. http://dx.doi.org/10.1016/j.foreco.2012.06.030.
WRCC, 2016. Western regional climate center: monthly prevailing wind for California. http://www.wrcc.dri.edu/htmlfiles/westwinddir.html accessed 1.20.16.