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Assessing relative differences in smoke exposure from prescribed, managed, and full suppression wildland fire

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Abstract

A novel approach is presented to analyze smoke exposure and provide a metric to quantify health-related impacts. Our results support the current understanding that managing low-intensity fire for ecological benefit reduces exposure when compared to a high-intensity full suppression fire in the Sierra Nevada of California. More frequent use of fire provides an opportunity to mitigate smoke exposure for both individual events and future emission scenarios. The differences in relative exposure between high-intensity, low-intensity, and prescribed burn were significant (P value < 0.01). Suppressing fire not only appears to shift the health burden of the emissions to a future date but also increases the intensity and number of people exposed in a single exposure. Increased use of ecologically beneficial fire may further be optimized to reduce human exposure through advantageous use of good dispersal conditions and incorporating a mitigation strategy that includes poor dispersal when smoke is largely over wilderness or other natural areas. Accepting naturally occurring fire typical of the environmental system benefits forest health and reduces public exposure to smoke.

Introduction

Wildland fire smoke exposure is an important risk factor to be considered for public health (Johnston et al. 2012; Kollanus et al. 2017). Emissions impacting large geographic areas elicit widespread concern principally regarding human health (Reid et al. 2016) leading to a desire by the public to put fire out when air quality is affected (Kneeshaw et al. 2004) despite the important role it plays in the sustainability of natural systems (Bowman et al. 2009).

Fire has an integral role in the ecological health of the Sierra Nevada of California including controlling species composition

and age structure of the forest (Kilgore 1973). These environmental systems are reliant on various fire frequencies and severities (Steel et al. 2015). California wildlands burned annually approximately 1.8 million ha prior to European settlement with emissions during this time creating smoky conditions likely similar to present "extreme" years (Stephens et al. 2007). Fire occurred regularly in much of California pre-European settlement. A policy of fire suppression throughout the twentieth century created an over-abundance of fuels and a backlog of smoke (Dellasala et al. 2004).

Fuel treatments such as logging can be used to help create conditions where fire can occur without the manifesting in a large high-intensity destructive fire, but logging to expedite suppression decreases burned area in the short term while increasing the area burned under extreme conditions (Reinhardt et al. 2008). Carbon stock is decreased in logged forests with the merchantable biomass carbon primarily emitted within 3 years (Keith et al. 2014). Reducing surface and small diameter fuels with logging can help create fire resistance forests maximizing carbon sequestration (North et al. 2009). Minimizing emissions from wildland fire is paradoxically dependent on fire as a natural process.

Communities in and around fire-prone areas can have a good understanding of relative impacts to air quality from wildland fire smoke and burning for ecological benefit (Cisneros et al. 2017).

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The public tends to favor using fire and mechanical treatment for fire management (Vining and Merrick 2008). Nonetheless, public perception can be an obstacle to wildland fire as messaging and information can lack accurate messaging of smoke impacts (Cisneros and Schweizer 2018).

It is extremely important for fire managers to provide objective information and engage the public in fuel treatment options (Shindler and Toman 2003). There are many effective ways to outreach and communicate with the public (Champ et al. 2012). Formal nuisance complaint programs can be effective for the public to communicate their concerns to land managers (Cisneros et al. 2018). Smoke management is evolving to incorporate more data and communication with the public of the trade-offs of exposure under differing fire management scenarios.

Large high-intensity wildland fire can transport smoke long distances and expose large populations (Zu et al. 2016). Understanding spatial and temporal differences in human exposure is an important component to assess air pollutant impacts. In the continental USA, between 2008 and 2012, 10% of the population lived in areas where smoke contributed significantly to annual average $PM_{2.5}$ (Rappold et al. 2017). Wildland fire smoke exposure is largely dependent on fire size. Prescribed fires that are much smaller in size than full suppression megafires decrease smoke exposure (Williamson et al. 2016), but can also produce significant exposure (Hu et al. 2008). While all fire produces smoke, smoke from megafires produces impacts that could largely be avoided at a single site in a fire-prone area by simply burning within the historic range of variability (Schweizer et al. 2017). There is currently no metric to determine if smoke from wildland fire within the natural range of variability increases or decreases health impacts over a large geographic area.

It is difficult for fire policy to incorporate long-term risks (Stephens et al. 2016) even though natural processes, such as fire, are necessary for sustainable forest health at the landscape level (Stephens et al. 2010). Since the early twentieth century, full suppression has been the default action when managing wildland fire in America. Recognizing the failure full suppression has on forest health in a fire-prone ecosystem (Dale 2006), fire policy now allows for a more flexible response to wildland fire from immediate full suppression to reintroduction of fire, particularly in wilderness and other protected natural areas (Calkin et al. 2015). Managed, or ecologically beneficial, and prescribed fires are proactive strategies allowing fires to burn at desired locations and times to maximize benefits to forest health while managing smoke with good dispersal and timed release (Schweizer and Cisneros 2014). Current policy includes the use of natural ignition fire for ecological benefit. In California, and throughout the USA, smoke exposure occurs from full suppression wildland fires, fires allowed to burn for fuel reduction and ecological benefit, and prescribed fires. Smoke exposure comparisons from the distinct fire management strategy options are nonexistent.

Although the first priority of fire management is life and property protection, fire can be beneficial to forest health. But fire management policy is biased to suppression of all smoke when no life and property are threatened (Schweizer and Cisneros 2017). Suppression policy has created both a smoke emissions backlog and an unsustainable expectation of no smoke in a fire-prone area that is an impending and avoidable health crisis (Schweizer and Cisneros 2017). Ecologically beneficial and prescribed fires are assumed to pose as much smoke exposure risk as suppression fires, leading to little support in their implementation over large geographic areas. This challenges air regulators and public health officials when trying to evaluate short- and long-term trade-offs. Human health concerns from immediate smoke exposure often take precedence over future effects of fire suppression. There are few assessments of how management actions influence smoke exposure and typically focus on large suppression fires using complicated dispersion models that lack precision and accuracy.

Our analysis uses wildland fire in the California Sierra Nevada. We use fine particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) to compare smoke exposure from fires with desired ecological impacts, prescribed burns, and large high-intensity fires on federally managed lands. We use remote sensing data coupled with census information to determine smoke exposure. A new exposure assessment metric for forest fire smoke is presented.

Methods

Location

The Sierra Nevada is located to the east of the California Central Valley and is largely composed of federally managed lands. Fires selected were from the central and southern Sierra Nevada east of the Central Valley cities of Fresno and Bakersfield from Yosemite National Park to Sequoia National Forest. We looked at all fires that burned in this area for the years 2010–2016. These fires predominantly burned on federal lands managed by the National Park Service (Yosemite, Kings Canyon, and Sequoia National Parks) and the US Forest Service (Stanislaus, Sierra, and Sequoia National Forests).

Fire size, growth, burn rate, and intensity categorization

Fire size, growth, burn rate, and intensity are driven by multiple factors including meteorological conditions, climate, fuel moisture, vegetation type, and topography. Maximum fire size has increased rapidly in the Sierra Nevada since the 1970s with an 11-year moving average of near 20,000 ha (Miller et al. 2009). Multiple fires have been successfully managed

in the Sierra Nevada for natural resource objectives that have been over 8000 ha with daily growth rates of up to 300 ha (Schweizer and Cisneros 2014; Meyer 2015).

Fire size was grouped into mega fire (greater than 19,000 ha) large (10,000–19,000 ha), medium (1000–10,000 ha), and small (less than 1000 ha). Fire growth was calculated as the total burn area for the number of days from the start of the fire to the final day HMS smoke polygons were reported. Start date was the ignition date determined using interagency situation reports (SIT-209), fire and weather data (FAMWEB 2018), and the interagency all-risk incident information management system (InciWeb 2017). Fire burn rates are categorized as prescribed, low, and high. Prescribed fires are intentionally ignited and have pre-determined burn rates and are categorized separately. Low burn rate fires are unplanned (not intentionally ignited) fires less than 250 ha/day. High rates of burn fires are unplanned fires greater than 250 ha/day. Fire Incident Situation Reports (FAMWEB 2018) and incident generated information (InciWeb 2017) were used to determine fire tactics used and inform further fire type (prescribed, low ecologically beneficial, and high full suppression).

Fire intensity, the rate of heat production on the flame front, is estimated using post-fire burn severity, emissions, and incident documentation (SIT-209, fire data, etc.). Estimates of intensity were determined using incident summaries (FAMWEB 2018), the Monitoring Trends in Burn Severity project (MTBS 2016), and the Michigan Tech Research Institute Wildland Fire Emissions Information System Emissions Calculator (WFEIS 2016). Fire burn areas (InciWeb 2017; FAMWEB 2018) were overlaid on Sierra Nevada vegetation (USFS 2016) and National Land Cover Database (NLCD 2014) data for vegetation type. Burn severity was determined for vegetation type using estimated pre-Euro-American fire regime characteristics found by Mallek et al. (2013) and maximum patch size within the natural range of variation of maximum high-severity patch size of 120 ha (Meyer 2015) to determine low-intensity (high severity < 5%), medium-intensity (at or below the estimates of typical), and high-intensity (above the typical) fires. A high-intensity fire had greater than 30% medium- and high-intensity fire, a medium-intensity fire had 70% or more low or unburnt area, and low intensity had below 10% high-intensity burn. Estimates of burn severity were compared to emissions and incident documentation to verify burn severity and daily fire intensity.

Remote sensing and fire selection

Remote sensing data is the Hazard Mapping System Fire and Smoke Product (HMS) from the National Oceanic and Atmospheric Administration (NOAA 2018). HMS data is an estimate of smoke density (low, medium, and high) using visible wavelength generated by NOAA satellite analysts daily (Ruminski et al. 2008). Wildland fire data is from the National Fire and Aviation Management Data Warehouse (FAMWEB 2018). We started with all fires throughout the Sierra Nevada for the available years of HMS polygon data (2010–2016). We selected all fires with nonoverlapping medium- and high-density smoke polygons. This made it possible to attribute each smoke polygon with ground-level impacts to a given fire. Fires typically had to be greater than 250 ha in size to be detected. To determine the relative potential for human exposure, the population within 10 km of the fire was determined along with distance to the nearest urban center defined as an area with a population greater than 20,000. Distance was determined using the closest point from the fire perimeter to the urban center.

Steps to determine smoke extent

There were many more fires in California than were used in this study. All HMS data days from the fire start date to the end date where the fire was declared out by the SIT-209 were checked for HMS smoke detection. This large range was examined, but, as expected, the out date was consistently and frequently well past the last HMS smoke polygon that was detected. HMS smoke polygons were assigned to a fire. HMS smoke polygons were compared to fire activity for the given day to validate smoke assignment to a fire and that smoke was attributable to a single fire. Fires were required to have isolated medium- and high-density polygons that could be completely attributed to a single fire. Individual fires were included, because they were not used for ground-level exposure, if low-density polygons mixed with other larger fires in the region and nationally. The area of low-density polygons was divided between contributing fires when multiple fires contributed. Contributing fires were determined by comparing national and regional fire activity and smoke extent on a given day using Moderate Resolution Imaging Spectroradiometer (MODIS) images (USFS RSAC 2017), SIT-209s (FAMWEB 2018), and author observations with HMS polygons. Low-density polygon mixing was primarily from large fires with isolated large medium- and high-density polygons attributable to a given fire and low-density polygons covering, at times, multiple fires. Each fire was assessed for contributions (e.g., relative size of HMS medium- and high-density polygons, fire growth, and individual fire documentation from smoke management on a given day). The spatial extent of the polygons was determined by comparing fire intensity, size, and growth for each fire and MODIS imagery to determine these contributions to the low-density polygon. The steps are outlined below:

1. Locate the HMS smoke polygon over the fire point of origin for days spanning the origin date to when the fire was declared out in incident documentation.

2. Manually validate HMS data for each day to confirm that polygons can be associated with the selected fire.
3. Assess other fires in the area for potential of contributing to the HMS estimated smoke plume.
4. Divide low-density HMS polygons, when mixed with other regional fires, to represent the relative extent of individual fire contribution.

Polygon sizes for each density (low, medium, and high) are used to assess the overall spatial extent of smoke from each fire.

Exposure assessment

HMS polygons associated with individual fires were used to determine the exposure population (people impacted) using US Census data. Population levels were obtained from the 2010 U.S. Census Tract data from the United States Census Bureau (U.S. Census 2016). To determine the number of people under a given smoke density polygon, the census population was assumed to be equally distributed across each tract. Presence of smoke detected by satellite does not signify ground level smoke. Thus, exposure under each HMS smoke density was determined by the probability of increased $PM_{2.5}$ above the norm for that location and day (Preisler et al. 2015). In Preisler et al. 2015, 7 years of $PM_{2.5}$ data from 13 sites around Central California were used to estimate the expected Daily 96th percentile $PM_{2.5}$ value in the absence of fire. These expected values are referred to as "the norms." The regression model used to estimate the norms included daily weather conditions (wind speed and direction, temperature, and relative humidity) and seasonal patterns of each site as explanatory variables. Next, these norms were used to ascertain whether an observed $PM_{2.5}$ value for a given day and location exceeds the norm. With this model, the probability of exceeding the norm on any given day is expected to be around 5%. However, what we saw is that the probability of exceeding the norm was as high as 36.5% (significantly higher than the expected 5%) on days when there was high-density smoke above the site. Consequently, we concluded that any observed exceedances from the norm on days with observed high level of smoke above a site can be attributed to impact of fire with high confidence. Preisler et al. (2015) found surface PM_{25} values on days with low smoke density were not significantly different from the norm. Therefore, we assumed the probability of exposure to $PM_{2.5}$ levels above the norm on low HMS smoke density days to be zero and a measure of smoke aloft. For days with medium and high HMS smoke densities, the probabilities of increased surface $PM_{2.5}$ above the norm were on average 17.2% and 36.5%, respectively (Preisler et al. 2015). Elevated exposure levels attributed to fire were determined

as a weighted average of the impacted number of people per day, with weights 0, 17.2, or 36.5 depending on the smoke density level on that day. Specifically,

$$Ex_j = \sum_{i=1}^{I_j} \left(0.172 \times N_{1ij} + 0.365 \times N_{2ij}\right) \tag{1}$$

where

Ex_j	number of person-days potentially exposed to elevated $PM_{2.5}$ levels above the norm for that location and day during fire event j
N_{1ij}, N_{2ij}	number of people under medium- or high-level smoke polygons on day i during fire j
I_j	number of days impacted by medium or high level of smoke during fire event j

Exposure, as defined by [1] above, is highly correlated with fire size, with a 0.96 correlation between Ex and fire size. In order to study the effect of other fire characteristics (e.g., fire intensity) on exposure levels, we used the following relative exposure (REx) metric:

$$REx_j = Ex_j / S_j \tag{2}$$

where Sj = total burn area of the jth fire. This metric is a measure of the amount of exposure per unit (hectare) of fire size.

We used simple linear regression to assess the effects of each of the variables, fire intensity, or rate of burn, alone on the relative rate of exposure (RExj). All analyses were done within the R-statistical package (R Core Team 2018).

Results

Fire characteristics

We found a total of 7012 fire starts in the central and southern Sierra Nevada of California east of the Central Valley cities of Fresno and Bakersfield from Yosemite National Park to Sequoia National Forest. There were 85 fires larger than 250 ha, 24 larger than 5000 ha, and 13 larger than 10,000 ha. To isolate the exposure assessment to an individual fire, all fires presented here have no medium- or high-density HMS polygons that overlap from another fire. This produced a total of 15 fires that burned primarily on federally managed lands in the Sierra Nevada from 2010 to 2016 that were found to have isolated HMS polygons that could be attributed to a fire. These fires were spaced throughout the Sierra Nevada. The largest urban areas (population > 10,000) are between 57 and 98 km west (W) to south-southwest (SSW) of the Sierra Nevada in the Central Valley from Merced to Bakersfield (see Supporting Information (SI) Fig. S1). The population within 10 km of each fire was between 4508 and 17,170 (Table S1). Two fires (Slope and Vernon) burned during the same time

and were considered one managed fire (Slope/Vernon). Two fires were prescribed, five burned at a low rate, and seven had a high rate of burn. The largest fire was the Rough Fire at 61,360 ha, and the smallest was the Redwood Mt. Fire (prescribed) at 254 ha. Using the definitions of levels of intensity in the "Methods" section, we noted that fires that burned at a high rate were all high-intensity except for one with medium intensity, low rates of burn fires were low- to medium-intensity, and prescribed fires were low-intensity (Table S1). HMS data was available for each day for most fires with the Slope/Vernon and Aspen Fires having four missing days. Light density polygons overlapped with other fires for a maximum of 16 days during the Rough Fire (Table S2).

Fire impact on smoke

The total area of smoke coverage for all densities was largest for the Rough Fire. Area covered (ha) by high- and medium-density smoke per hectare burned was between 129 ha (Slope/Vernon Fire) and 4677 ha (Rough Fire). The total area coverage of low, medium, and high levels of smoke density for each fire was correlated with the area burned per day (Fig. 1). The rate of increase in smoke coverage with increasing fires size (slope of the line) was the same for all three smoke intensities (hypothesis that slopes are the same P value = 0.2); however, the overall fire sizes (intercept of the lines) were significantly different (hypothesis that intercepts are the same P value < 0.01) with the highest coverage for low-density smoke. When the total area under a given smoke density during the fire, or "smoke extent," was compared for different levels of fire intensity and rate of burn, smoke extent was highest for high-intensity and high burn rates (Fig. 1). The differences in high-density coverage per ha burned were typically largest for the high burn rate (> 250 ha/day) fires (Table S3).
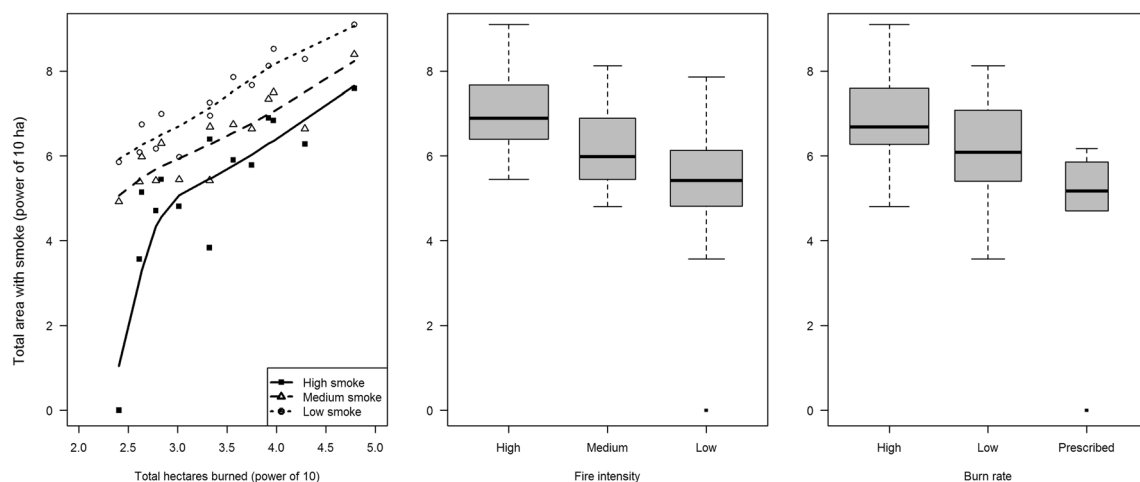
The largest fire (Rough) covered the highest overall area for total low-, medium-, and high-density HMS smoke levels and also had the largest maximum daily smoke density polygon size (Table S3) illustrating the obvious importance of fire size on smoke extent. The Aspen, Lion, Motor, and Erskine Fires had maximum high-density smoke areas that were 65%, 50%, 39%, and 31% of the Rough Fire while the smaller, slower burn rate, less intense fires reduced the maximum high-density smoke area to below 8% of what the Rough Fire produced. While HMS low-density smoke is not associated with increased ground level $PM_{2.5}$ in Central California (Preisler et al. 2015), high rate of daily burn area also had the largest impact on visible (low-density HMS) smoke over the population with a mean of 5875 person-days/ha. Visibility impacts (low-density HMS) for low rate of burn fires were 1976 person-days/ha and prescribed was 124 person-days/ha. While the Erskine Fire burned quickly at 3887 ha/day, it, along with the other southernmost fires (Nicolls and Shirley) had low relative exposure. These fires burned more actively at night possibly reducing the effectiveness of HMS detection which could subsequently limit the value of comparing relative exposure with the more northern fires.

Relative smoke exposure to people from fire size and intensity

Smoke from high rate of burn and larger burn area fires transported over much larger distances while the total smoke area for each hectare burned during a given fire was more consistent (see SI). Intensity and burn rates of fires are highly correlated, making it not possible to estimate the combined effects on relative exposure to smoke. However, fire intensity alone accounted for more of the between fire variability in relative exposure (adjusted $R^2 = 0.6$) than rate of burn

Fig. 1 Total observed smoke area versus (1) total hectares burned. Smooth curves through the points were generated by fitting separate nonparametric spline functions for high, medium, and low smoke density cases (left panel), (2) distributions per fire intensity (middle panel), and (3) distributions per fire burn rate (right panel). Widths of the boxes in middle and right panels are proportional to sample size

(adjusted $R^2 = 0.4$, Fig. 2). High burn rate and high-intensity fires resulted in the largest relative exposures (Figs. 2 and 3, Table 1). Lower burn rate and lower-intensity fires appeared to reduce transport and result in exposure being reduced. On average, high-intensity fire exposure was 83 person-days/ha, compared with low intensity of 15 person-days/ha (Table 1). Prescribed fire exposure was on average 5.5 person-days/ha. The two prescribed fires had low-intensity and burn rates. Although many prescribed fires occurred over these years, only two produced isolated plumes. This is largely due to the small size and short duration of prescribed fires. Further study is needed to determine if the exposure estimates from these fires are applicable when larger areas are burned.

Our results seem to indicate that high daily rate of burn has the most impact on exposure because they burn with higher intensity. Fires that burned at a low daily rate or intensity, on average, reduced exposure to ~10% of the high burn rate or high-intensity fires. The latter implies that fires with high rate of burn or high intensity increased exposure for each hectare burned by almost 10 times when compared to low burn rate or intensity fires.

Discussion

Fire is integral to the landscape of the Sierra Nevada, California (Baker 2014). Suppression of all fires is not viable or desirable (Calkin et al. 2015). Ecologically appropriate fire regimes need to be integrated into the landscape or impacts to society (e.g., lost homes and lives, suppression cost, damage to ecosystem services) from suppression policy will continue to grow (Moritz et al. 2014). The Sierra Nevada is a fire-prone ecosystem with large areas of federally managed land that include designated Wilderness. Managing for future forest health in this area must include fire (Stephens et al. 2016). This setting epitomizes the challenges of active fire

management near a high-density urban population experiencing adverse health impacts from anthropogenic emissions (Penn et al. 2016).

Smoke impacts from wildland fire in the Sierra Nevada are largely managed on a per fire basis using predictive modeling. There is little assessment of the veracity of this process protecting human health in and around a fire-prone ecosystem particularly over multiple years. The risks of wildland fire smoke exposure must include a comprehensive understanding of all costs to human health (Johnston et al. 2016). Trade-offs between different smoke regimes from prescribed, managed (ecologically beneficial), and suppression policies must be understood to accurately assess health impacts (Williamson et al. 2016).

Managing fires for resource benefit can reduce the rate of fire spread and the spatial distribution of smoke. Similar to other findings of positive effects of reducing fire spread rates (Schweizer and Cisneros 2014; Meyer 2015), daily fire growth below 250 ha/day can reduce relative exposure to smoke (Figs. 2 and 3). Allowing a measured amount of emissions provides an opportunity to manage smoke for public health benefit while still allowing for increased burn area.

It is straightforward that larger fires and the subsequent increased emissions impact a larger area and more people. A more difficult concept to quantify is the importance of fire acting as a natural process and reducing impacts over time. It is easy to understand the allure of suppressing smoke by suppressing all fire now. Removing today's emissions to an unwilling public has little or no consequences since future impacts from smoke to the decision process are not considered and often suppression is the easiest policy route (North et al. 2015). This effectively shifts the burden of smoke exposure to the future.

The Sierra Nevada provides a relatively simple example of smoke transport where smoke exposure from wildfires at lower-intensity and burn rates limit the smoke extent and

Fig. 2 Relative smoke exposure to fine particulate matter ($PM_{2.5}$) for rate of burn and fire intensity
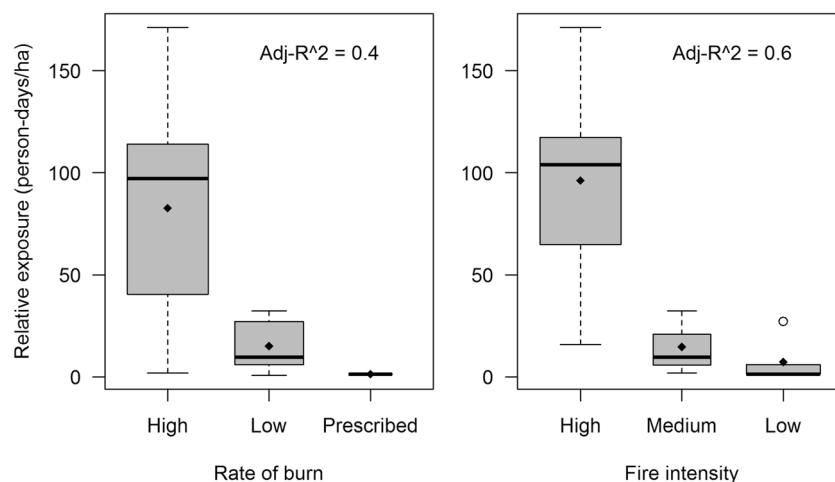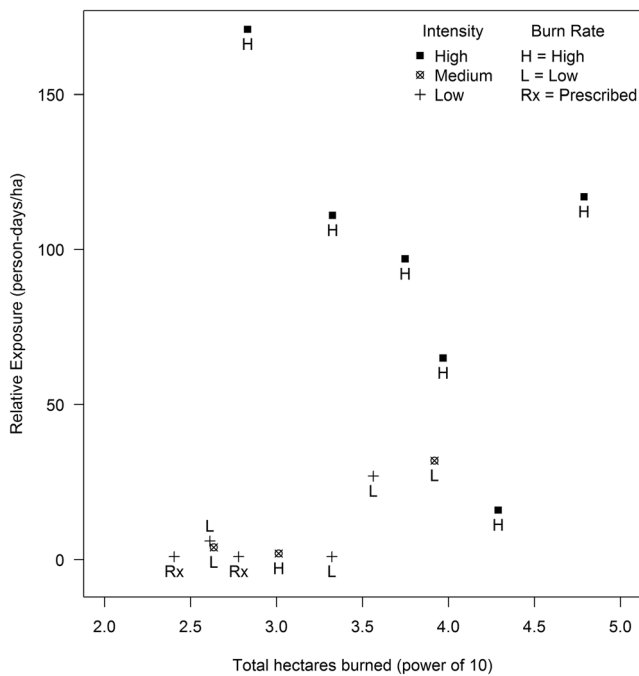
Fig. 3 Total burn area and relative exposure for burn rate and intensity

largely capture emission on forest land while large high-intensity fires transport further and impact large high-density populations (Fig. S2). Smoke from prescribed and ecologically beneficial fire is largely limited to wilderness areas where filtration from the forest canopy (Chen et al. 2016) can occur. While smoke can still impact adjacent communities, these impacts remain below federal air quality standards and transport to more distant and densely populated areas is limited (Schweizer and Cisneros 2014). Limiting smoke aloft using desired conditions to reduce intensity and growth maximizes canopy capture of pollutants and can reduce spatial distribution and exposure.

Smoke exposure from wildland fire is dependent on how the emissions are released. Prescribed fire in and around the wildland urban interface are particularly meaningful to fire managers as smoke impacts may be substantially reduced in a community adjacent to a burn by using prevailing winds away from the community. Smoke management during these specific

scenarios requires decisions to include local conditions that may sustain plume transport away from sensitive receptors and residences. Plume transport during these fires can, at times, better reduce exposure than parameters such as injection height and gross transport. Further away from developed areas, specific prescribed parameters to manage smoke transport can be dependent on overall transport if the goal is to limit human exposure. Surface entrainment of smoke can greatly impact downwind concentrations (Colarco et al. 2004). Further study is needed to understand if the decreased injection height of lower-intensity fire significantly increases smoke entrainment in the forest and the ensuing benefits of pollutant removal. MODIS satellite imagery (USFS RSAC 2017) and HMS smoke data demonstrate differences in spatial distribution of smoke between prescribed fire, large high-intensity burns, and fire managed for resource benefit and trade-offs of smoke extent between fire management actions (Figs. S3 and S4). A visual comparison helps to show the potential for limiting smoke exposure by controlling spatial extent through more frequent fire. Air and land managers, health officials, and the public are confronting this challenge with a near absence of research in relative exposure differences.

Smoke management decisions often do not include any assessment of exposure from delaying emissions. The importance of returning fire to this landscape comes with increased emissions and impacts from smoke that have largely been absent during the era of suppression. Fire will return to this area either from reintroduction through prescribed and managed fire or when suppression fails. Understanding the trade-offs between fire types and the relative extent of public exposure to smoke from these emissions provides a metric to assess possible health outcomes from fire management policy and actions.

Comparative risk of exposure analysis from different fire management practices is essential. Attempting to understand smoke exposure from different types of fire is difficult. We have compared relative exposure to wildland fire smoke from multiple fires while attempting to control for general transport and emissions by using remote sensing of smoke from fires in a similar area and time of year. There are many weaknesses to this approach (e.g., remote sensing data is only during daylight, remote sensing data and ground concentration agreement is not perfect, atmospheric conditions and fuel types are never exactly the same, detection may fail with cloud cover or with large emissions at night). However, the use of HMS data does provide a physical measurement of smoke identified exclusively in the visible wavelength manually generated by satellite analysts (Ruminski et al. 2008) and is not reliant on the veracity of a dispersion or transport model. It has been shown that HMS-detected smoke has a greater than 95% success rate in detecting an increase in $PM_{2.5}$ above the norm that is attributable to fire, at least in the Sierra Nevada, California (Preisler et al. 2015).

Table 1 Relative exposure summary

	Level	Person-day/ha	Interquartile range	Percentage of high
Fire intensity	Low	1.4	1.3–5.9	1.3%
	Medium	10	6–21	9.2%
	High	103	64–117	–
Burn rate	Prescribed	1.32	1.29–1.35	1.4%
	Low	10	6–27	9.7%
	High	97	40–114	–

Location is critical to smoke impacts. It is important when comparing fires to select an area with similar smoke transport to populated areas. Exposure estimates from the Sierra Nevada will likely not be the same as other areas. A fire directly upwind of a densely populated area will obviously have a larger impact than one further away and well dispersed. The fires included in this study were chosen to standardize transport as much as possible and provide context for impacts from fire in a largely undeveloped area. Comparing similar fires and situations is important to understanding the differences between fire management actions. In this case, forest fires of the Sierra Nevada were used to analyze smoke impacts. This-fire prone ecosystem provides a model example applicable to other areas where fire exclusion does not have such obvious impacts.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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