

fire & fuels management

Aligning Smoke Management with Ecological and Public Health Goals

Jonathan W. Long, Leland W. Tarnay, and Malcolm P. North

Past and current forest management affects wildland fire smoke impacts on downwind human populations. However, mismatches between the scale of benefits and risks make it difficult to proactively manage wildland fires to promote both ecological and public health. Building on recent literature and advances in modeling smoke and health effects, we outline a framework to more directly quantify and compare smoke impacts based on emissions, dispersion, and the size and vulnerability of downwind populations across time and space. We apply the framework in a case study to demonstrate how different kinds of fires in California's Central Sierra Nevada have resulted in very different smoke impacts. Our results indicate that the 257,314-acre Rim Fire of 2013 probably resulted in 7 million person-days of smoke impact across California and Nevada, which was greater than 5 times the impact per burned unit area than two earlier wildfires, Grouse and Harden of 2009, that were intentionally managed for resource objectives within the same airshed. The framework and results suggest strategies and tactics for undertaking larger-scale burns that can minimize smoke impacts, restore forest ecosystems, and reduce the potential for more hazardous wildfire and smoke events.

Keywords: air quality, California, USA, particulate matter, socioecological systems, wildland fire

Wider use of ecologically beneficial fire has been suggested as a critical tool for increasing the pace and scale of forest restoration and for avoiding extreme wildfires that pose threats to human health (North et al. 2015, Schweizer and Cisneros 2016). A range of constraints, however, have hindered the use of fire to meet resource objectives, whether through prescribed burning or managing wildfires for resource objectives (hereafter called "resource objective wildfires"). Air quality policy and regulations have been particularly significant constraints on intentional use of fire (Carroll et al. 2007, Quinn-Davidson and Varner 2012, Engel 2013).

Tensions reflect long-standing division of responsibilities between forest managers concerned with restoring forests and air regulators concerned with protecting public health (Sneeuwjagt et al. 2013). A recent update to wildfire-smoke policy proposed by the US Environmental Protection Agency (US EPA) recognized the need to restore and maintain more frequent fire regimes through intentional use of fire, while asserting that protecting human health remained the agency's "highest priority" (Office of the Federal Register 2015). Therefore, addressing both forest restoration and air quality objectives remains a central challenge.

This article explores strategies that for-

est managers and air quality regulators can jointly pursue to minimize public health impacts while restoring more natural fire regimes. First, we consider factors that make this challenge so difficult, by examining how the social and ecological context of fire involves scale mismatches that create disincentives for ecologically beneficial use of wildland fire. Second, we outline a more direct framework for quantifying smoke impacts to human populations through monitoring and analysis of daily emissions, the location and density of resulting smoke plumes, and the size and vulnerability of populations within such plumes. We show how the framework can link tools that forest managers, air regulators, and public health experts are already using, but that are often not systematically applied to resource objective wildfires and prescribed fires. Through a case study, we examine how smoke impacts from intentional use of fire are likely to differ from an extreme wildfire targeted for suppression. We focus on the area affected by the Rim Fire, which escaped from a campfire on Aug. 17, 2013, to become the largest fire in the history of the Sierra Nevada. Because this area also had a recent history of prescribed burns and resource objective wildfires, it afforded a distinctive opportunity to consider how working with fire can influ-

Received August 10, 2016; accepted December 12, 2016; published online January 19, 2017.

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Acknowledgments: This article was informed by data and experience by one of the authors as an Air Resource Specialist for Yosemite National Park, as well as support from the Park's fire management and resource management staff. We thank T. Procter, H. Preisler, L. Heath, and A. Bytnerowicz for thoughtful reviews and insights that contributed to this article. The USDA Forest Service Pacific Southwest Research Station and Region 5 Air Quality Program provided support for this research.

ence smoke impacts. Finally, we discuss how this quantitative framework can help managers and regulators implement proactive fire management strategies that align public health and forest restoration objectives. We highlight examples from California's Sierra Nevada, but many of these challenges are common to other parts of the world where increasingly large and severe wildfires are impacting large populations (Williams 2013).

Socioecological Context

The last century of fire suppression in California has caused past and current generations to expect less frequent fire and smoke than was integral to seasonally dry forest ecosystems (Stephens et al. 2007). It has also contributed to less frequent, larger, and more severe wildfires (Stephens and Sugihara 2006, Miller and Safford 2012, Fulé et al. 2014). These extreme fires not only directly threaten lives and property but they also produce enormous quantities of smoke that pose significant health risks, especially when affecting large urban areas (Strand et al. 2012, Moeltner et al. 2013, Schweizer and Cisneros 2016). Important health risks include increased mortality and respiratory morbidities associated with fine particulate matter (less than 2.5 microns, known as PM_{2.5}) (Liu et al. 2015). Wildfires are an unpredictable component of PM_{2.5} pollution in California, contributing only 17,068 tons in 2005, 529,821 tons in 2008, and 53,487 tons in 2011. The wildfire emissions in 2008 represented 68% of all PM_{2.5} emissions in the state, and they caused notable public health impacts (Wegesser et al. 2009, Preisler et al. 2015). Such impacts are likely to worsen in the future, because higher temperatures and accumulated fuels are expected to favor very large fires in fire-prone regions such as California (Barbero et al. 2015). Hurteau et al. (2014) found that under a business-as-usual climate scenario, this escalation in fire potential is likely to increase wildfire emissions in California by 50% by the end of this century unless agencies take a more proactive approach to fire use.

An important spatial mismatch results from the fact that large wildfires can create smoke impacts on distant urban populations. The risk to urban populations from regional-scale smoke impacts has increased as California became the most urbanized state in the United States, with 90% of its population residing within cities that have

Sidebar 1. Glossary of Technical Terminology

Air resource advisors—Personnel with specialized training who are assigned to coordinate air quality monitoring and smoke concentration and dispersion modeling on wildland fires.

Hazard mapping system (HMS) smoke product—A map produced by the National Oceanic and Atmospheric Administration that indicates the location and density of significant smoke plumes.

Prescribed fire—A wildland fire originating from a planned ignition that is intentionally managed to achieve resource objectives.

Push/pull fire tactics—Tactics for speeding or slowing fire spread, which can be used to influence the rate of smoke production.

Resource objective wildfire—A wildland fire originating from an unplanned ignition that is intentionally managed to achieve resource objectives such as reducing fire danger or forest restoration rather than being targeted for suppression. Such fires have also been labeled “resource benefit wildfire,” “wildland fire use,” or “managed wildfire” (see Hunter et al. 2014).

Wildland fire—Any nonstructure fire that occurs in vegetation or natural fuels.

Suppression wildfire—An unplanned wildland fire where the objective is to put the fire out.

more than 50,000 people and another 5% living in smaller urban clusters (US Census Bureau 2015). Many of those urban areas are situated in valleys or basins that have poor air quality due to human activities as well as natural conditions that often trap pollutants (Ngo et al. 2010, Nakayama Wong et al. 2011). For example, the four metropolitan areas in the United States with the highest levels of particle pollution are all located in California's Central Valley (American Lung Association 2015). Because many urban populations already experience poor air quality during the summer, they are particularly vulnerable to health impacts from wildfires (Delfino et al. 2009, Cisneros et al. 2014).

An important temporal mismatch re-

sults from the ability of present generations to pass accumulated fuels that result from fire suppression onto future generations (North et al. 2012, Lueck and Yoder 2015). In the shorter term, current policies have permitted regulators to curtail fires intentionally managed for resource objectives in response to nuisance complaints by a few individuals, despite the potential for such fires to have long-term collective benefits (Engel 2013). Because the impact and likelihood of smoke increase the longer that fire is kept out of the system, extensive fire suppression can result in a vicious cycle that becomes more and more costly to escape until the system fails, as represented by extreme wildfires (Calkin et al. 2015). Many members of the public agree with researchers and

Management and Policy Implications

Forest managers and air quality regulators could better align the dual objectives of restoring forests and protecting human health by using a common framework to quantitatively manage and evaluate the smoke impacts of different kinds of fires on downwind populations. Some smoke management policies discourage managing large fires for resource objectives and risk shunting inevitable emissions into even larger and long-lasting wildfires that expose sizeable human populations to unhealthy concentrations of particulate matter. Managing wildland fires under favorable conditions can help to restore forests, reduce hazardous fuels, and mitigate potentially harmful smoke impacts on downwind populations by decreasing daily emissions and taking advantage of favorable dispersion. Our framework supports smoke management strategies including the following: incentivizing reduction of human exposure to hazardous smoke levels over space and time rather than area burned; pacing fire spread based on airshed capacity to disperse the resulting emissions; and communicating with the public to reduce the exposure of downwind populations and the benefits of managing wildland fires for resource objectives. Advancing these strategies will depend on coordinated efforts by forest and fire managers, air quality regulators, and air resource advisors with specialized skills in evaluating and communicating fire impacts on downwind populations.

**Smoke Impact = f (Emissions \times Dispersion \times Population Vulnerability)
integrated over time and space**

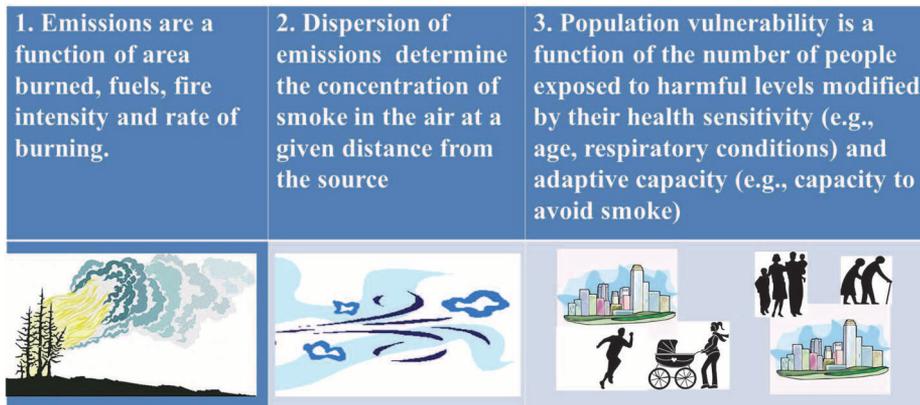


Figure 1. Framework for evaluating smoke impacts using source emissions, dispersal and downwind populations, integrated over time and large areas of fire influence.

managers who have argued that tolerating short-term impacts of prescribed fires may avoid more harmful impacts (Olsen et al. 2014). However, those arguments have not been well aligned with regulatory systems designed to protect public health, visibility, and safety, which vary across and within states (Engel 2013).

Within California, decisions regarding particular fires are generally made on a case-by-case basis by local air districts. These decisions often rely on area burned as a proxy for reporting and evaluating potential smoke impacts from fires and for setting thresholds for providing additional documentation for permits (California Air Resources Board 2015). For example, local regulators have sometimes limited burns to less than 50 acres per day when air quality conditions were considered marginal for dispersing smoke (Carolyn Ballard, Fire Management Officer, Sierra National Forest, pers. comm., April 19, 2016). Because suitable burn windows are often limited to only a few consecutive days, such constraints can make it infeasible to burn the hundreds or thousands of acres needed for landscape restoration. In addition, some air pollution control districts in California have imposed fees for each unit of area burned for prescribed fires and resource objective wildfires, although not for wildfires targeted for suppression (Sneeuwjagt et al. 2013). These fees are used to offset the costs of reviewing smoke plans and monitoring air quality during burns; however, they also provide a disincentive for wildland fires that are managed for resource benefits. For reasons we discuss throughout the article, shifting from an emphasis on area

burned toward more direct measures of smoke impact may afford opportunities to better align public health and ecological restoration.

Measuring Smoke Impacts on Public Health

Smoke and wildfires can impact public health in ways other than particulate pollution, including ozone pollution, increased stress during and after wildfires, and strains on medical services and communication systems (Fowler 2003, Kumagai et al. 2004, Finlay et al. 2012). Despite these broader considerations, public health regulations for smoke typically focus on a 24-hour average of PM_{2.5}. Values that exceed 35 µg/m³ are considered unhealthy for sensitive groups, which include pregnant women, young children, elderly individuals, smokers, and people with chronic respiratory problems such as asthma (Delfino et al. 2009, Kochi et al. 2010, Moeltner et al. 2013). Although this standard is an important quantitative threshold, higher levels of PM_{2.5} are associated with broader and greater health risks, so incorporating concentration-response relationships will improve estimates of smoke impact. Furthermore, exceedances of the 24-hour standard may not signify an actual health impact on a particular day, as forecasting of smoke can help people take steps to reduce their exposure (Rappold et al. 2014). A broad accounting of smoke impacts also should consider other demographic and institutional factors that influence vulnerability and adaptive capacity (Cross 2001, Trainor et al. 2009).

One approach for estimating the smoke impact in economic terms has been to multiply the number of person-days of impact by individuals' willingness to pay to avoid exposure. For example, Richardson et al. (2012) found that individuals in several southern California cities were willing to pay \$84.42 (in 2012 dollars) to avoid a day of wildfire smoke impact resulting from the Station Fire of 2009, during which ground-level conditions exceeded the 24-hour standard for 1–3 days. Jones et al. (2016) found a per capita willingness to pay of \$130 (in 2014 dollars) to avoid wildfire smoke health effects in Albuquerque during the Wallow Fire of 2011.

A Quantitative Framework for Evaluating Smoke Impacts

We outline a quantitative framework (Figure 1) to evaluate smoke impacts that can be applied using existing tools and data sets to improve understanding of potential smoke impacts across large areas over time. Some fire managers routinely conduct the first two steps, quantifying source emissions and downwind concentrations, but they have traditionally compiled summaries over the total size and duration of the burn, rather than tracking the daily variation of emissions relative to dispersion. For both prospective planning and retrospective evaluation of fire outcomes, it is important to quantitatively account for the smoke impacts to public health in space and time.

Source emissions can be estimated based on fuel loads using tools such as the First Order Fire Effects Model (FOFEM) (Lutes 2014) or the BlueSky Playground.¹ Emissions from fires may vary by an order of magnitude, depending on the type of vegetation, the fuel loading associated with that vegetation type (Leenhouts 1998), and the intensity and the severity of the fire activity. For example, a forest where fuels have accumulated unchecked for decades will have much heavier fuel loads and expected emissions than otherwise similar areas subjected to frequent fires. Consequently, area burned, while easy to measure, may not correlate well with smoke production.

The second step in the framework is to evaluate population exposure to pollutants within observed or modeled smoke plumes. Because standards to protect public health are often based on 24-hour average PM_{2.5} values and available dispersion varies substantially from day to day, daily emissions

are particularly important for evaluating smoke impacts. The National Oceanic and Atmospheric Administration (NOAA) began providing maps of smoke plume density based on satellite observations through their Hazard Mapping System (HMS) in November 2006 (Ruminski et al. 2007). Predictions of surface $PM_{2.5}$ levels are limited by difficulty in determining how much smoke has reached the surface, but these data provide an objective means of defining a potential area of influence for a particular fire.

Our framework can also be applied prospectively to fires by using BlueSky, HYSPLIT,² CALPUFF,³ or other modeling tools to spatially and temporally forecast smoke concentrations downstream from fires using daily emission and dispersion estimates (Goodrick et al. 2013). Research has supported this approach, as Fusina et al. (2007) found that plume trajectories generated in BlueSky agree well with satellite observations and ground-level $PM_{2.5}$ concentrations. Furthermore, Yao et al. (2013) found significant associations between BlueSky-forecasted and HMS smoke plumes and respiratory health outcomes such as asthma-related physician visits.

The third step in the framework is to quantify the size and vulnerability of the affected populations within the areas of smoke influence for the duration of the fire. One approach is to use census data to estimate populations underlying mapped smoke plumes weighted by smoke density and the expected likelihood and intensity of impact. Finer analyses of such data can consider demographic variables that often indicate vulnerability, such as age, income, race, education, and health, although fine-scale data on the incidence of respiratory disease are usually lacking (Gaither et al. 2015).

The framework can be extended to include monetary metrics by multiplying the estimates of person-days of exposure by estimated health costs or other valuations. The US EPA has developed a tool, BenMAP-CE,⁴ for estimating economic impacts of air pollution based on population data, modeled or monitored air quality data, concentration-response functions, and valuation measures (Jones et al. 2016). Another extension of the framework would be to iteratively model regional airshed conditions to project the benefits of using fire at large scales over long periods. Such efforts would be com-

plex, but they would help decisionmakers and the public evaluate potential tradeoffs.

Method for Applying the Framework to Selected Fires

We applied the framework retrospectively to compare differences in smoke impacts between resource objective wildfires and full-suppression wildfires within the San Joaquin River watershed in California's Sierra Nevada, the Sierras that burned between 2002 and 2013, including 10 resource objective wildfires (totaling 20,494 acres), 17 prescribed fires (totaling 6,636 acres), 4 small wildfires (totaling 12,025 acres), and the exceptionally large Rim Fire (257,314 acres). This comparison requires several caveats: (1) the use of resource objective wildfires has varied historically, reflecting continuing evolution in policy and practice; (2) some resource objective fires are categorized as suppression wildfires when they no longer meet desired objectives; (3) the Rim Fire burned through and into several of the previous fires; and (4) the limited availability of smoke monitoring data, particularly before 2007, requires a focus on modeled emissions.

We evaluated the smoke impacts of two relatively large resource objective wildfires: the Grouse Fire (3,042 acres) and the Harden Fire (1,653 acres), which were ignited by lightning on May 31, 2009, and June 8, 2009, respectively, and then allowed to burn for multiple objectives. The Grouse Fire is significant as the first instance in which fire managers in Yosemite National Park explicitly designed the fire contingency plan to incorporate thresholds for $PM_{2.5}$ monitored at sensitive sites. The same incident team simultaneously managed the Harden Fire for resource objectives within an area bounded by containment lines and rock, while focusing active resources on the Grouse Fire. These two fires illustrate the potential for managing multiple fires to achieve resource objectives for an extended period. Furthermore, when combined, these resource objective fires were the largest in the study area for which the HMS smoke density maps were available.

To estimate emissions in the first step in the framework, we developed maps of daily fire spread for fires of all types in the Tuolumne watershed since 2002 using records of fire progression from the Yosemite fire his-

tory database (Yosemite National Park 2012), operational notes, and smoke management plans for prescribed fires on the Stanislaus National Forest and Yosemite National Park (Kent van Wagendonk, Taro Pusina, and Mike Beasley, National Park Service, pers. comm., July 19, 2015). In this analysis, we assumed that daily emissions are based only on areas of new fire growth for a given day because there is no established method for allocating emissions across multiple days. We used FOFEM within a geographic information system (GIS) to calculate emissions for each daily fire progression polygon based on inputs of fuel loads and fuel moisture for each vegetation type, following the approach by Clinton et al. (2003). This spatially explicit method accounts for area of the different vegetation types within the polygons for each days spread, for each fire, then incorporating crosswalks assigned from the California Gap Analysis Project (GAP) land cover map (Davis et al. 1998), to estimate total daily emissions from the FOFEM output. Because we lack systematic and detailed fuel plots, we assigned "light" fuel loads for areas that had experienced fires in the previous 12 years, while assigning "typical" loads otherwise (see Supplemental Table S1⁵). Lydersen et al. (2014) found that this approach yielded reasonably accurate consumption estimates when applied to large areas within the Sierra Nevada. We modeled prescribed burns as surface fires but allowed wildfires and resource objective wildfires to burn into tree crowns. We estimated fuel moistures using operational notes from individual fires and representative values from remote automatic weather stations used in Yosemite's fire management program.

For the second step in the framework, we adapted the methodology used by Preisler et al. (2015), who related HMS smoke maps to monitored surface $PM_{2.5}$ values for a range of fires in the Central Sierra Nevada. They determined that plumes of HMS smoke within 6.2 miles of a monitoring site were associated with significant increases in daily average values of $PM_{2.5}$, with a likelihood of 36.5% (95% confidence limit [CL] was 27–47%) of exceeding the "norm" on days with dense smoke and 17% (95% CL was 12–23.5%) on days with medium-density smoke. The norm was the expected level on each day for each site when smoke

⁵ Supplementary data are available with this article at <http://dx.doi.org/10.5849/JOF-2016-042R2>.

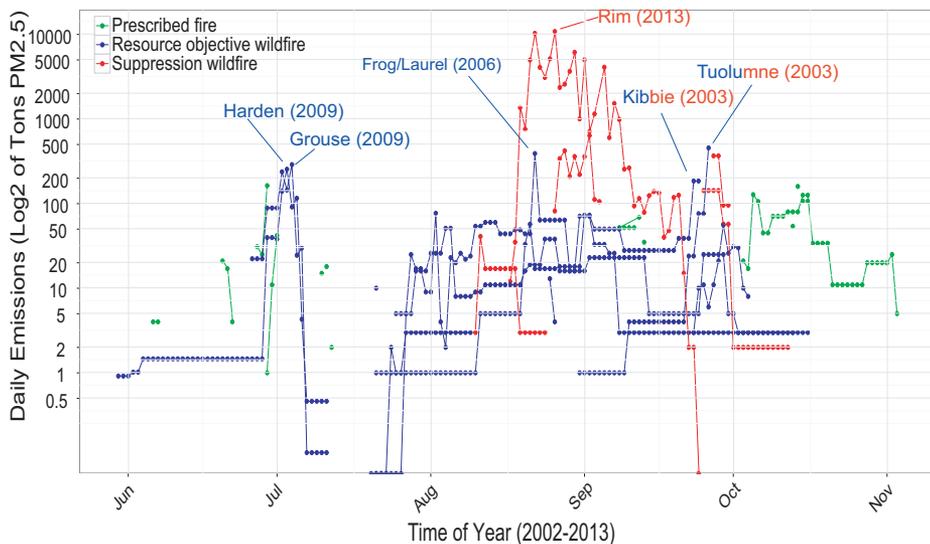


Figure 2. Estimated daily emissions of $PM_{2.5}$, as generated by the FOFEM for different types of fire within the Tuolumne River watershed, California, between 2002 and 2013. Points on each line represent one day of estimated emissions for a specific fire. Note the log base 2 y-axis; see Figures 4A and 4B for the nonlogarithmic version.

plumes were excluded. In particular, they estimated that the daily 96th percentile value of $PM_{2.5}$ increased by $14 \mu\text{g}/\text{m}^3$ (95% CL was $9\text{--}19 \mu\text{g}/\text{m}^3$) where there was heavy smoke and by $5 \mu\text{g}/\text{m}^3$ (95% CL was $3.6\text{--}6.1 \mu\text{g}/\text{m}^3$) where there was medium-density smoke. At many of the higher elevation sites, the normal values were far below the $35 \mu\text{g}/\text{m}^3$, so only heavy smoke plumes were likely to cause an exceedance. However, in some urban sites, the norm during the fire season was already close to the $35 \mu\text{g}/\text{m}^3$ threshold for “unhealthy for sensitive groups.” In such locations, even the modest $5 \mu\text{g}/\text{m}^3$ increase due to medium density smoke could cause or worsen exceedances (Cisneros et al. 2014).

We mapped the HMS medium- and high-density smoke plumes that appeared to be connected with the Rim, Grouse, and Harden Fires. In particular, we had to demarcate some of the smoke plumes during the early days of the Rim Fire that overlapped with the American Fire, which was fully contained by Aug. 29, 2013. To represent ground-level impacts over time, we examined the values for particulate matter for the Rim and Grouse Fires at monitoring sites in Yosemite Village in both 2009 and 2013 and in Reno for 2013 (data were not available for 2009) (US EPA 2016).

For the third step of the analysis, we used ArcMap (version 10.1; ESRI, Redlands, CA) to sum the populations (based on 2010 census data) for each census block whose centroid was within areas of high- and

medium-density smoke plumes. We confined our analysis to California and Nevada, because archived reports⁵ and AirNow maps⁶ did not indicate air quality impacts in other states despite evidence that Rim Fire smoke traveled as far as central Canada (Peterson et al. 2015).

Results of the Case Study

This comparison cannot prove that managing fire for resource objectives has reduced smoke impacts in a particular landscape compared with those for a suppression-centered strategy, but it illustrates how managing fires for resource objectives could reduce smoke impacts relative to those for more extreme fires. An actual experiment to compare the effects of managing fire for resource objectives at a scale large enough to evaluate major smoke impacts seems impractical given the enormous consequences, and modeling approaches face numerous challenges in representing the effectiveness of the suppression response and the impacts of low-probability or uncertain extreme events (Hasan and Foliente 2015).

Within the study area, daily emissions from both prescribed burns and resource objective wildfires remained well below 500 tons $PM_{2.5}$, whereas the Rim Fire had 20 days exceeding that threshold (nearly half of its entire period of active fire growth) and peaked at nearly 11,000 tons $PM_{2.5}$ /day on Aug. 26, 2013 (Figure 2). During the late summer, air quality is already problematic in downwind areas such as the Lake Tahoe Ba-

sin and San Joaquin Valley. In contrast, most of the fires managed for resource objectives had peak emissions either in the early summer or in the fall, when airshed conditions are often more favorable.

Modeled emissions from the Rim Fire within each vegetation polygon varied by an order of magnitude because of the different types of vegetation and amount of accumulated fuels (Figure 3A). However, daily emissions from the Rim Fire (Figure 3B) were quite high even in areas that had relatively light fuels (e.g., in the center of the fire, as shown in Figure 3A), because the fire burned through those areas so quickly.

The Rim Fire generated a surge in emissions that began on August 19 and continued through September 8, after which estimated daily emissions dropped below 265 tons (Figure 4B). That rapid growth resulted in high- and medium-density smoke plumes over large populations in California and Nevada between August 22 and September 10 (Figure 4D). We weighted the population estimates by the weights reported by Preisler et al. (2015) (36.5 and 17% for high- and medium-density smoke plumes, respectively), to estimate 2.9 million person-days associated with high smoke and 4.1 million person-days associated with medium density smoke or 7 million total person-days of exposure to higher than normal levels of $PM_{2.5}$ (Figure 4D). Ground-level monitoring indicated that these large smoke plumes coincided with highly polluted days in Reno, which occurred on August 23–25 and again on August 28–29, when $PM_{2.5}$ values exceeded the “unhealthy for all populations” standard ($55.5 \mu\text{g}/\text{m}^3$) (Figure 4F). Such high levels are such a serious health concern that people are advised to avoid going outdoors. Navarro et al. (2016) reported that very unhealthy and unhealthy days occurred at 10 air monitoring sites in the central Sierras, northern Sierras, and Nevada during the Rim Fire. They used BlueSky modeling calibrated with ground-level monitoring to estimate that the Rim Fire exposed 1.2 million people to smoke across 10 counties in California and Nevada during 37 days of active growth. Multiplying our estimate of person-days of exposure by the willingness to pay to avoid days of smoke impact found by Richardson et al. (2012) suggests that the cost of smoke impact may have been nearly \$600 million. That sum is comparable to the entire estimate of non-air quality losses in environmental benefits resulting from the Rim Fire (Batker et al. 2013).

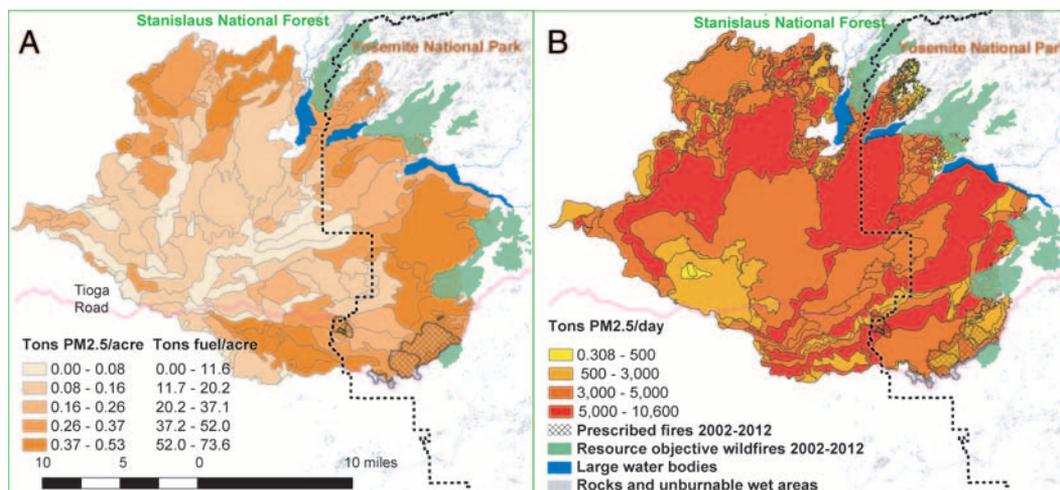


Figure 3. Fuel loading and estimated emissions of PM_{2.5} per unit area within different vegetation polygons (A) and estimated emissions of PM_{2.5} per day within daily progression polygons (B), within the Rim Fire.

The enormous spatial impact of the Rim Fire is illustrated by a map on August 31 (Figure 5), showing how plumes extended north from the Rim Fire over large urban populations in the Lake Tahoe Basin (55,607), Carson City (55,212), Sparks (90,264), and Reno (225,221), before shifting southward over Fresno (494,665), Madera (61,416), Visalia (124,442), and other cities in the Central Valley. Altogether, medium- and high-density HMS smoke from the Rim Fire on that day covered a large area (251,691 mi²) with a population of 2.8 million people, more than 2 million of whom resided below high-density smoke. Within Yosemite Village, which had few of its typical visitors, levels exceeded the “very unhealthy” standard of 150 μg/m³ (Figure 5B) on that day.

In contrast, the Grouse and Harden Fires burned slowly over the early summer of 2009, with very modest emissions until the last week of June (Figure 4A). Both fires were managed for resource objectives using different tactics. For the Grouse Fire, managers used an intensive “push-pull” approach of checking the fire’s spread during periods of limited dispersion and speeding up the fire through aerial ignition during periods of favorable dispersion (Figure 6), particularly during its last week, while slowing the fire in wet drainages and when dispersion conditions were less favorable. Meanwhile, the Harden Fire was contained on its western flank and allowed to spread eastward toward natural barriers so that resources could be focused on managing the more complex Grouse Fire (van Wagten-donk 2012). Our analysis of HMS maps indicated that there were only 2 days when

medium-density plumes overlaid substantial populations in California and Nevada, amounting to 25,000 person-days (Figure 4C). Ground-level monitoring at Yosemite Village showed relatively modest impacts, where PM_{2.5} levels remained between 30 and 55 μg/m³ from July 1 through July 6 (Figure 4E). Although these levels are considered “unhealthy for sensitive groups,” concentrations in Yosemite Valley due to local sources combined with regional wildfire impacts often reach or exceed such levels (Preisler et al. 2015).

By specifically evaluating smoke dispersal, our analysis shows that extremely large and intense fires like the Rim Fire presented a disproportionately greater public health hazard than did previous fires managed for resource objectives. Specifically, the Rim Fire burned 55 times more area (257,213 acres) than the combined footprint of the Grouse and Harden Fires (4,695 acres), but our analysis suggests that it had at least 275 times greater impact in terms of person-days, or 5.5 times greater impact relative to area burned. Impacts from the Rim Fire are even greater than suggested by those figures because of the increased hazard associated with unhealthy levels for the general population and high-density smoke plumes, neither of which was reported during the Grouse and Harden resource objective wildfires.

Potential Benefits of Resource Objective Wildfires

The framework can also be useful for comparing the public health impacts of fire management strategies across broader tem-

poral and spatial scales. Our analyses help to illustrate and begin to quantify many of the potential benefits of resource objective wildfires compared with those of extreme fires:

1. *Reduced fuels and reduced consumption.*

Where fires burn over the footprints of relatively recent fires, emissions estimates should typically reflect lighter fuels and reduced crown consumption (Wiedinmyer and Hurteau 2010). We accounted for this effect within the 10,385 acres of the Rim Fire’s footprint that had experienced prescribed fires or resource objective wildfires since 2002 by changing “typical” fuel loads to “light,” which reduced estimated emissions in those areas by 53% and was consistent with the approach used by Stephens et al. (2007) (see Supplemental Table S1 for all the parameters used). Because recent reburns constituted only 4.0% of the entire Rim Fire area, accounting for those reduced emissions lowered the estimated emissions for the entire fire by only 3.2% (also see Supplemental Table S1). Had the entire area of the Rim Fire been treated with recent fire, its estimated emissions would have been reduced by 48% (see Supplemental Table S2), with most of the reduction due to the change of dead fuels from “typical” to “light.” Similarly, Wiedinmyer and Hurteau (2010) found that replacing infrequent wildfires with lighter prescribed burns would roughly halve fire emissions in dry forests in the Western United States, although they also noted that emissions would be more frequent under a prescribed burning scenario.

2. *More favorable dispersion and potential for*

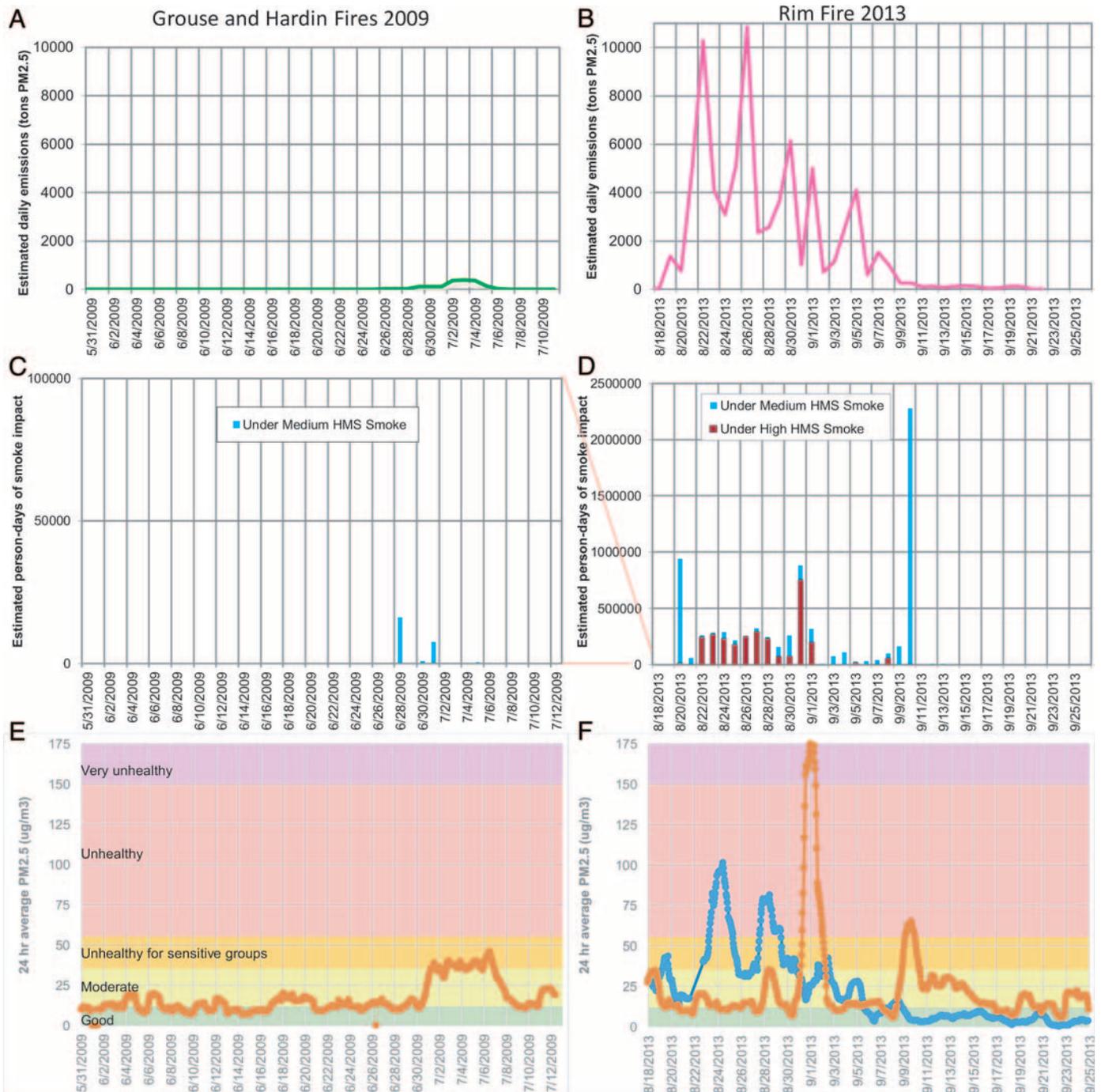


Figure 4. Comparisons between three measures of potential smoke impact during the Grouse and Harden fires of 2009 (left) and the Rim wildfire of 2013 (right), including estimated daily emissions (top); estimated person-days of smoke impact associated with medium- and high-density smoke plumes (middle, note that the y-axis scale on the chart of impacts during the Grouse and Harden fires [C] is 250 times smaller than the one for the Rim Fire [D]); and 24-hour rolling average PM_{2.5} values (bottom, shown in relation to associated levels of health concern) for Yosemite Village, California, and Reno, Nevada (data were not available for Reno in 2009).

less ozone. As maintenance burns reduce fuel levels over time, managers may be able to burn more safely earlier in the summer and or later in the fall, when dispersion is often more favorable and ozone concentrations are lower (Jaffe et al. 2013). Fires managed for resource objectives are less likely to result in the

greater lofting and concentrations of smoke reported from extreme fires, which often deliver pollution to distant, large urban populations in lower-elevation valleys (Colarco et al. 2004, Peterson et al. 2015).

3. *Greater ability to regulate fire spread.* Because wildfires would be managed for re-

source objectives when weather and fire behavior conditions are more moderate than under extreme wildfires, their slower fire spread can curb daily emissions. In addition, managers can employ the push-pull tactics burn described for the Grouse Fire to regulate daily emissions based on monitored concentrations

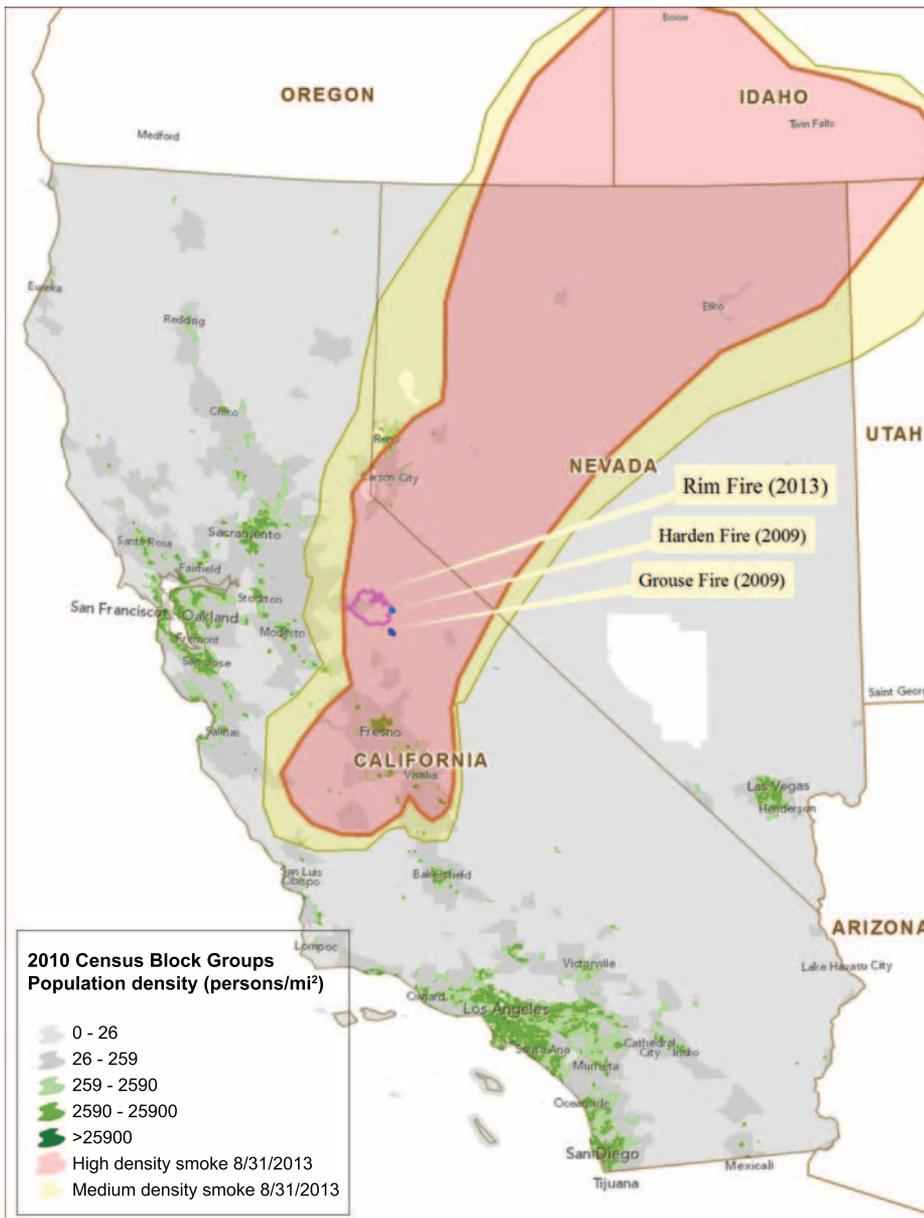


Figure 5. HMS smoke plumes from the Rim Fire on Aug. 31, 2013, a day of extensive heavy smoke impact, overlying population density of census tracts in California and Nevada.

fire will become increasingly important for reducing the likelihood and extent of large-scale, extreme fires like the Rim Fire (Westerling et al. 2015).

A comprehensive comparison of smoke impacts under different management strategies is challenging to model because of complex processes (such as capacity to suppress or safely manage fires), feedbacks (such as changes in fuels, fire behavior, and emissions after fires), sensitivity to extreme events, and uncertainty of climate. Despite such challenges, smoke monitoring and smoke modeling are essential for guiding future management strategies, given changing climate and fire regimes (McKenzie et al. 2014).

Strategies to Support Greater Use of Fire

The framework and results of the case study suggest several management approaches to align ecological restoration with reduction in public health impacts through greater use of fire to achieve resource objectives.

Managing Fires Based on Direct Smoke Impacts

Although large-resource objective fires are challenging to implement and do not entirely avoid smoke impacts, the Grouse Fire and other resource objective fires (Schweizer and Cisneros 2014) have demonstrated that large areas can burn with relatively minor smoke impacts. An important strategy is to manage fires at least in part based on monitored smoke concentrations at key monitoring sites, rather than applying predetermined area limits or assuming a direct correlation with smoke impacts. This approach is directly responsive to human health impacts while providing greater flexibility to take advantage of favorable dispersion and treat more area during a given fire.

Public Communication to Reduce Smoke Impact and Support Use of Fire

Smoke exposure can be reduced by distilling monitoring and modeling tools into information that people can use to their modify behavior (Olsen et al. 2014, Rappold et al. 2014). The combination of advance warning and education can also increase public support for managing fire for resource objectives over time (Sneeuwjagt et al. 2013, Blades et al. 2014). It is important for outreach efforts to explain how for-

or concentrations projected using tools such as the BlueSky framework. When dispersion is limited, firefighters can slow progression by herding the fire into barriers, roads, and areas of previous fuel reduction. Conversely, they can encourage fire growth during periods of favorable dispersion to dilute emissions. They can burn perimeters (“black-lining”) under marginal dispersion conditions, just before a mild front arrives and then ignite larger interior areas aerially once more favorable dispersion arrives. Using such techniques requires resources and coordination among fire operations, air quality, and meteorology specialists.

4. *Creating anchors that facilitate future fire management.* In addition, strategic placement of relatively large resource objective fires within fire-prone landscapes can create anchors for limiting the spread of hazardous wildfires and increasing opportunities to use future wildfires for resource benefit (North et al. 2015). For example, the cumulative effect of decades of managing wildland fires for resource objectives in Yosemite National Park created opportunities to suppress the Rim Fire on its northern and eastern edge (Figure 3A). As fuels continue to accumulate and climate conditions increase the likelihood of large fires, such strategic use of



Figure 6. Fire managers pushed the Grouse Fire to spread during periods of favorable smoke dispersion, including times at night.

est management can mitigate smoke impacts from extreme fires not only in rural forest communities but also in downwind urban populations.

Engaging Air Resource Advisors

Air resource advisors, who are commonly assigned to large wildfire incident teams, can also help managers mitigate the negative health effects of prescribed fires and resource objective wildfires. Such trained specialists can facilitate public communication and prepare documents used by air quality regulators in permitting burns and considering exemptions for exceedances of air quality standards that might be caused by such fires.

Incentivizing Reduction of Smoke Impacts Rather than Area Burned

Rather than using area burned, public health objectives can be better met by measuring exceedances of health thresholds at monitoring sites or person-days of expected harm. Replacing unit-area fees on restorative burning with flat annual fees, as employed by some air districts, would reduce one of the disincentives for intentionally using large fires to restore landscapes (Sneeuwjagt et al. 2013).

Conclusion

The combination of a warming climate and accumulation of forest fuels ensures a future with more large fires and smoke in dry western US forests. We have outlined a

framework to more directly account for regional-scale smoke impacts from these events using surface monitoring and satellite observations of smoke. Managing large fires for resource objectives can shift the release of inevitable emissions to conditions that minimize large-scale smoke impacts, by controlling fire spread based on available dispersion and monitored impacts and creating anchors for containing future hazardous fires. When well supported by firefighting, air quality monitoring and modeling, and public communications resources, this approach can overcome existing disincentives for achieving ecological and public health goals.

Endnotes

1. For more information, see <http://playground.airfire.org>.
2. For more information, see www.arl.noaa.gov/HYSPLIT_info.php.
3. For more information, see src.com/calpuff/calpuff1.htm.
4. For more information, see www.epa.gov/benmap.
5. For more information, see inciweb.nwcg.gov/.
6. For more information, see airnow.gov/.

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