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# Air-Quality Impacts and Intake Fraction of $PM_{2.5}$ during the 2013 Rim Megafire

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*Supporting Information*

**ABSTRACT:** The 2013 Rim Fire was the third largest wildfire in California history and burned 257 314 acres in the Sierra Nevada Mountains. We evaluated air-quality impacts of $PM_{2.5}$ from smoke from the Rim Fire on receptor areas in California and Nevada. We employed two approaches to examine the air-quality impacts: (1) an evaluation of $PM_{2.5}$ concentration data collected by temporary and permanent air-monitoring sites and (2) an estimation of intake fraction (iF) of $PM_{2.5}$ from smoke. The Rim Fire impacted locations in the central Sierra nearest to the fire and extended to the northern Sierra Nevada Mountains of California and Nevada monitoring sites. Daily 24-h average $PM_{2.5}$ concentrations measured at 22 air monitors had an average concentration of 20 $\mu g/m^3$ and ranged from 0 to 450 $\mu g/m^3$. The iF for $PM_{2.5}$ from smoke during the active fire period was 7.4 per million, which is slightly higher than representative iF values for $PM_{2.5}$ in rural areas and much lower than for urban areas. This study is a unique application of intake fraction to examine emissions-to-exposure for wildfires and emphasizes that air-quality impacts are not only localized to communities near large fires but can extend long distances and affect larger urban areas.

## INTRODUCTION

Each year thousands of wildland fires burn millions of acres of forested land across the United States, releasing smoke into the environment.[1] A century of fire suppression has changed the structure of forests accustomed to frequent, low-severity fires. This change in forest structure has led to an increase of wildland fires that are burning larger areas and intensify across all forest elevations.[2−4] Additionally, climate change is expected to increase the frequency and intensity of wildfires due to drier fire seasons, warmer temperatures, reduced precipitation, and less snowpack.[4] By the mid-21st century, the wildfire season in the western United States is predicted to become longer, burn a wider area, and produce twice as much smoke.[5]

Wildfires emit large amounts of smoke that contain air pollutants known to cause adverse health effects, such as particulate matter with an aerodynamic diameter ≤2.5 $\mu m$ ($PM_{2.5}$).[6] Smoke from wildland fires has the ability to disperse across thousands of kilometers and potentially expose many people to elevated levels of $PM_{2.5}$.[7,8] Previous studies have suggested that $PM_{2.5}$ from wildland fire smoke causes adverse respiratory health effects and possibly increased mortality and cardiovascular health effects.[9−12] A recent literature review of health outcomes associated with smoke exposure by Liu et al.[13] determined that 70% of all mortality studies and 90% of respiratory health outcome studies found a statistically significant association with smoke from wildfires. The authors concluded that there was insufficient evidence to determine if there is an association between cardiovascular outcomes and smoke exposure, despite there being six studies that have found statistically significant associations with exposure to smoke and cardiovascular outcomes. Rappold et al.[11] reported that there were significant changes in the relative risk of emergency department visits for cardiopulmonary symptoms and heart failure during a peat bog fire in rural North Carolina.

A common method used in health studies to assess exposure to $PM_{2.5}$ from wildland fires is to use ground-based air-monitoring networks.[14] In response to wildland fires and concern about smoke exposure for downwind communities, the California Air Resources Board (CARB) and the United States Department of Agriculture Forest Service (USDA FS) deploy monitors to smaller communities that are experiencing smoke impacts.[15] Additionally, the BlueSky Smoke Modeling Framework[16] produces forecasts of $PM_{2.5}$ concentrations from wildfires across regions of the United States.

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Table 1. Fire Information for Fires during the Active Burning Period of the Rim Fire

| fire name | date (2013) | fire size (ha) | $PM_{2.5}$ emission total (kg) | percentage of total emissions | county |
|---|---|---|---|---|---|
| Rim Fire | Aug 18–Sept 23 | 103 830 | 151 872 000[a] | 85.6 | Tuolumne |
| American Fire | Aug 18–Sept 15 | 11 105 | 24 662 403 | 14 | Placer |
| small fires in study area | Aug 18–Sept 23 | – | 833 464 | 0.5 | all counties |

[a]The Supporting Information gives further information regarding the fuel types, fuel loadings, and PM2.5 emissions.by fuel type for the Rim Fire.

Table 2. Distribution of 24-h Average $PM_{2.5}$ Concentrations and Daily Air-Quality Impacts from August 17 to October 25, 2013, Arranged by Region and Distance to Rim Fire

| | | $PM_{2.5}$ concn ($\mu g/m^3$) | | no. of days at AQI category | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| station name | $N$[a] | mean (SD) | range | good | moderate | USG[b] | unhealthy | very unhealthy | hazardous |
| Central Sierra | | | | | | | | | |
| Rim Fire Camp | 18 | 121 (106) | 24–450 | 0 | 4 | 1 | 8 | 3 | 2 |
| Groveland | 33 | 42 (48) | 3–191 | 10 | 11 | 4 | 6 | 2 | 0 |
| Tuolumne City | 31 | 70 (65) | 5–224 | 6 | 5 | 8 | 8 | 4 | 0 |
| Jamestown | 10 | 8 (3) | 4–14 | 8 | 2 | 0 | 0 | 0 | 0 |
| La Grange | 18 | 16 (14) | 3–44 | 11 | 4 | 3 | 0 | 0 | 0 |
| Yosemite Valley | 39 | 14 (10) | 3–40 | 20 | 18 | 1 | 0 | 0 | 0 |
| Bootjack | 59 | 10 (11) | 3–58 | 50 | 6 | 1 | 2 | 0 | 0 |
| Tuolumne Meadows | 26 | 27 (16) | 7–69 | 4 | 16 | 4 | 2 | 0 | 0 |
| San Joaquin Valley | | | | | | | | | |
| Merced | 70 | 8 (4) | 2–21 | 60 | 10 | 0 | 0 | 0 | 0 |
| Clovis | 47 | 10 (5) | 3–28 | 37 | 10 | 0 | 0 | 0 | 0 |
| Fresno | 67 | 12 (5) | 4–29 | 37 | 30 | 0 | 0 | 0 | 0 |
| Tranquillity | 65 | 6 (3) | 2–12 | 65 | 0 | 0 | 0 | 0 | 0 |
| Eastern Sierra | | | | | | | | | |
| Devils Postpile | 52 | 9 (12) | 1–72 | 43 | 7 | 1 | 1 | 0 | 0 |
| Northern Sierra | | | | | | | | | |
| Pollock Pines | 27 | 31 (39) | 4–157 | 12 | 8 | 3 | 3 | 1 | 0 |
| South Lake Tahoe | 22 | 21 (22) | 4–81 | 12 | 6 | 2 | 2 | 0 | 0 |
| Wentworth | 24 | 15 (12) | 3–44 | 13 | 8 | 3 | 0 | 0 | 0 |
| Cool | 59 | 10 (11) | 3–58 | 50 | 6 | 1 | 2 | 0 | 0 |
| Nevada | | | | | | | | | |
| Gardnerville | 70 | 35 (56) | 2–208 | 47 | 7 | 2 | 8 | 6 | 0 |
| Carson City | 70 | 21 (34) | 3–170 | 49 | 8 | 3 | 9 | 1 | 0 |
| Reno | 66 | 14 (16) | 0–90 | 47 | 13 | 2 | 4 | 0 | 0 |
| Reno Galletti | 66 | 16 (16) | 2–89 | 44 | 15 | 3 | 4 | 0 | 0 |
| Sparks | 66 | 15 (16) | 1–79 | 45 | 15 | 2 | 4 | 0 | 0 |
| total | | | | 670 | 209 | 44 | 63 | 17 | 2 |

[a]$N$ is the number of 24-h average measurements at the location. [b]USG = unhealthy for sensitive groups.

The 2013 Rim Fire ignited from an escaped campfire in the Stanislaus National Forest on August 17, 2013, and burned into Yosemite National Park. The Rim Fire was declared contained on October 24, 2013, and burned a total of 257 314 acres (104 131 ha, 402 square miles). It is the largest wildfire recorded in the Sierra Nevada Mountain range and third largest recorded in California.[17] This fire was notable for its unstable meteorological conditions, which led to extreme fire conditions, resulting in approximately 90 000 acres (36 422 ha) burned just in 2 days (August 21 and 22).[18] Peterson et al. described the general meteorology of the Rim Fire, which is briefly summarized here.[19] During the initial days of the fire, the winds were light and southeasterly; however, by the evening of the August 19 winds shifted to northerly, pushing the fire to the south. From August 20 to 22, 2013, a strong pressure gradient produced strong southwest surface winds, which coincided with the large fire growth of August 21, 2013. A shortwave trough increased southwest winds during the afternoon and evening of August 25, 2013, coinciding with the second period of large fire growth. Rainfall on September 21 and 22, 2013, ended most of the satellite detection of the fire; however, smoldering and brief flare-ups of the fire continued into October.

Our objective was to assess the air-quality impacts of $PM_{2.5}$ from wildland fire smoke during a large megafire, the 2013 Rim Fire, throughout Central and Northern California and Western Nevada. We used previously collected data from permanent and temporary air monitoring sites and data from a smoke-modeling framework to examine concentrations of $PM_{2.5}$ during the fire event. In addition, we estimated the proportion of the mass of $PM_{2.5}$ inhaled by individuals to the mass of the pollutant emitted into the environment $PM_{2.5}$ from smoke across areas that were impacted during the active burning of the Rim Fire.

## METHODS

**Study Location and Time Period.** This study covers 14 counties in the San Joaquin Valley and the central, northern, and eastern Sierra Nevada Mountains in California and western Nevada. These counties were near the Rim Fire or reported air-quality impacts from smoke during the Rim Fire [Figure S1,


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Supporting Information (SI)]. The study period was from August 17 to October 24, 2013, the start and containment dates of the Rim Fire, respectively. In addition to the Rim Fire, there were 11 small fire events (smaller than 300 acres) and 1 other large fire event, the American Fire, that emitted smoke during the active fire behavior period for the Rim Fire (Table 1).[20]

**$PM_{2.5}$ Monitoring Results.** $PM_{2.5}$ concentrations were collected from 22 monitoring sites in California and Nevada (Table S1, SI) and utilized to examine air-quality impacts during the Rim Fire. Monitoring sites included in this analysis were 9 permanent sites operated by CARB, Nevada Bureau of Air Quality Planning (NBAQP) and Washoe County Air Quality Management Division (WAQMD) for National Ambient Air Quality Standard compliance and 10 temporary sites that were operated by the CARB Office of Emergency Response (OER) and USDA FS. Data for permanent sites in California and Nevada were obtained from the US EPA AirData Web page.[21] Data from temporary sites were provided by CARB OER and downloaded from the interagency real-time smoke particulate monitoring Web page.[22] Site locations ranged from 7.3 to 189.4 km from the geographic center of the fire perimeter (origin point) on the origin date of the fire (August 17, 2013). Monitoring sites were located in the following regions: San Joaquin Valley; central, northern, and eastern Sierra Nevada Mountains; and Nevada (Figure S1, SI).

Permanent US EPA regulatory monitoring sites reported hourly $PM_{2.5}$ concentrations with Beta Attenuation Monitors BAM-1020 (BAM) manufactured by Met One Instruments, Inc. Temporary nonregulatory sites deployed by CARB, OER, and USDA FS reported hourly $PM_{2.5}$ concentrations with Environmental Beta Attenuation Monitors (EBAM), monitors that are designed for fast and temporary deployment (Met One Instruments Inc.). Since data collected by EBAMs are not used for regulatory air monitoring, the following parameters were used to exclude any abnormal measurements: (1) if the measurement included an alarm code and (2) the flow rate of the monitor was ±5% of 16.7 L $min^{-3}$. BAM accuracy exceeds US EPA Class III $PM_{2.5}$ Federal Equivalent Methods (FEM) standards for additive and multiplicative bias, and the device has an hourly detection limit of 3.6 $\mu g/m^3$ and a 24-h detection limit of 1.0 $\mu g/m^3$. EBAMs have an accuracy of 10% of the true concentration measured and an hourly detection limit of 6.0 $\mu g/m^3$ and a 24-h detection limit of 1.2 $\mu g/m^3$.[23,24]

Daily 24-h averages were valid if hourly measurements were available for at least 18 h per day (75%). For days without 18 h of available data, a measurement of zero was entered for the missing hours and a 24-h average was calculated as a lower bound. If the calculated lower bound was above or equal to the 24-h standard for $PM_{2.5}$ (35 $\mu g/m^3$), the value was considered valid and used in the analysis as the 24-h average.[25]

For each day, the calculated 24-h average was categorized by the US EPA Air Quality Index (AQI) category, a system used to provide guidance on recommended actions to mitigate exposures to smoke for public health officials, the media, and affected communities (Table 2).[26] The AQI has six categories that correspond with 24-h average concentrations of $PM_{2.5}$: good (0−12 $\mu g/m^3$), moderate (12.1−35.4 $\mu g/m^3$), unhealthy for sensitive groups (USG; 35.5−55.4 $\mu g/m^3$), unhealthy (55.5−150.4 $\mu g/m^3$), very unhealthy (150.5−250.4 $\mu g/m^3$), and hazardous (250.5−500 $\mu g/m^3$).

**Intake Fraction.** One method to examine the relationship between emissions and exposure is to calculate the intake fraction (iF); this metric is useful to compare the impact of a pollutant from specific sources. The iF is used as a measure of the proportion of the mass of a pollutant inhaled by individuals of an exposed population to the mass of the pollutant emitted into the environment from a specific source or event.[27,28] $PM_{2.5}$ from wildland fire smoke is one of multiple sources of $PM_{2.5}$, and iF can be used to examine the impact of $PM_{2.5}$ from smoke compared to other sources of $PM_{2.5}$.

Intake fraction for this study will calculate the proportion of $PM_{2.5}$ mass inhaled in a study area $j$ to $PM_{2.5}$ emissions from wildfires in study area $j$ (eq 1):[27,29]

$$\mathrm{iF} = \frac{\text{population intake}}{\text{total emissions}} = \frac{\sum \mathrm{BR} \times C(i,j)\, P(j)\, D(i)}{\sum E(i,j)} \tag{1}$$

In this equation, BR is the average breathing rate ($m^3$ $person^{-1}$ $day^{-1}$), $C(i,j)$ is the total ambient concentration of $PM_{2.5}$ ($\mu g/m^3$) from wildfires during the active fire period $i$ over the geographic iF study area $j$, $P(j)$ is the population (number of people) in the geographic iF study area $j$, $D(i)$ is the duration (days) of the active fire period $i$, and $E(i,j)$ is the emission of $PM_{2.5}$ (kg) from wildfires during the active fire period $i$ over the geographic study area $j$. We used a breathing rate of 13.9 $m^3$/day and population estimates for the study area from the 2010 US Census.[30,31] The intake fraction was calculated during the active fire period for the Rim Fire (August 18−September 23, 2013; $N$ = 37 days). The intake fraction of $PM_{2.5}$ from wildfires was calculated for the active fire period over 10 counties (iF study area; Figure S1, SI). Parameter values used in this analysis are listed in Table 3 and described below. The iF is calculated as a dimensionless number between 0, representing that no emitted pollutants are inhaled, and 1, representing that all emitted pollutants are inhaled. Generally, iF is expressed in units of per million, meaning that for 1 mg of pollutant inhaled there is 1 kg of pollutant emitted into the environment.[32]

**Table 3. Simplified Intake Fraction Parameters and Analysis**

| parameter | total | daily minimum | daily maximum |
|---|---|---|---|
| breathing rate ($m^3$ $person^{-1}$ $day^{-1}$) | 13.9 | – | – |
| population | 1 211 628 | – | – |
| no. of days | 37 | – | – |
| ambient concn ($\mu g$ $m^{-3}$) | – | 1.2 | 198 |
| intake of $PM_{2.5}$ from wildfires (kg) | 1225 | 0.8 | 123 |
| emissions from wildfires (kg) | $1.8 \times 10^8$ | $2.8 \times 10^5$ | $4.3 \times 10^7$ |
| estimated intake fraction (per million) | 7.4 | 0.07 | 54 |

The BlueSky Smoke Modeling Framework provided daily estimates of $PM_{2.5}$ concentrations and emissions.[16] Briefly, BlueSky is a modeling framework that aggregates independent models of meteorology forecasts, fire activity (e.g., location and size), fuel loads, fuel consumption models, diurnal allocation of fuel consumption and emissions, vertical allocation of emissions (e.g., plume rise), and smoke dispersion models to estimate hourly $PM_{2.5}$ emissions and hourly surface concentrations of $PM_{2.5}$ from wildfires. Fire activity was obtained from the SmartFire2 system, which relies on satellite fire detection by the National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System and ground-based information from the US Forest Service Incident Command System 209 reports (ICS-209). Fuel loadings were obtained from the Fuel Characteristic Classification System (FCCS), and fuel con-


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sumption was calculated using the CONSUME model.[33−35] Fuel consumption was allocated hourly throughout the day using the time profile from the Interagency Western Regional Air Partnership, where wildfire emissions peak at 1600 h local time daily and exhibited an approximately Gaussian profile around the peak.[36] Plume buoyancy was calculated from the heat released from the fire and was then used in the Briggs plume rise algorithm.[37] Some quantity of emissions is always emitted at the surface to account for fire smoldering, and then the remaining emissions are allocated to 20 layers in the atmosphere that extend up to the plume rise value. For this assessment, we used emission and concentration estimates that were produced for daily 72-h smoke forecasts for California and Nevada at a 2-km resolution using Weather Research Forecast38 meteorology from the Desert Research Institute and the NOAA HYSPLIT dispersion model. HYSPLIT was used to simulate primary $PM_{2.5}$ emissions and dispersion and dry deposition from wildfires.[38−40] Secondary $PM_{2.5}$ formation processes, wet deposition, and anthropogenic $PM_{2.5}$ sources were not simulated with BlueSky.

$PM_{2.5}$ concentrations $[C(i,j)]$ for the study area were derived from BlueSky hourly surface $PM_{2.5}$ concentrations. The BlueSky smoke forecasts provided a 2 × 2 km grid for California and Nevada of hourly $PM_{2.5}$ concentrations. For each gridded point contained in the iF study area, a 24-h average was calculated from the hourly concentrations. One day in the active fire period did not have a forecast run (August 20, 2013). For this day, the previous day's forecast that included the day was used to estimate $PM_{2.5}$ concentrations.

Total $PM_{2.5}$ emissions $[E(i,j)]$ from wildfires were estimated from BlueSky $PM_{2.5}$ emission estimates for wildfire events within the iF study area. BlueSky provided daily emission estimates for each fire location in the modeling framework. First, wildfire events that occurred in the iF study area and during the active fire period were selected. Details on the contribution of $PM_{2.5}$ emissions from each fire can be found in Table 1.

We first calculated mass intake, the daily average $PM_{2.5}$ concentration multiplied by breathing rate, for each county in the study area to examine any temporal or spatial differences. To calculate mass intake, the daily $PM_{2.5}$ concentrations from the BlueSky 2-km grids were averaged across each county in the study area for each day in the study period and then multiplied by the breathing rate of the population (13.9 $m^3$/day).

To calculate iF, the daily BlueSky $PM_{2.5}$ concentration values were averaged across the iF study area to create a single daily average concentration of $PM_{2.5}$. Each daily $PM_{2.5}$ average concentration for the iF study area was then summed across the active fire period to get $C(i,j)$. Next, daily $PM_{2.5}$ emissions (kg) were summed across all fire events in the iF study area during the active fire period to derive a total daily emission of PM2.5 from all fire events. Lastly, the summed concentration and emission metrics were input into the intake fraction equation with values for population of the iF study area, breathing rate, and number of days of the active fire period. The daily average concentration and emission values were used to calculate daily iF values. Because we did not have spatially resolved data for $PM_{2.5}$ emissions from wildfires, i.e., specific emission estimates for each county, iF was calculated across the 10 counties and not at a smaller spatial scale.

Ten counties across the entire study area were used (iF study area) to calculate iF of $PM_{2.5}$ from wildfire smoke (Alpine, Amador, Calaveras, Carson, Douglas, El Dorado, Mariposa, Placer, Tuolumne, and Washoe). Counties were included in the iF calculation if the BlueSky $PM_{2.5}$ concentration estimates had good agreement with the $PM_{2.5}$ concentrations measured by monitors in those counties. To test agreement between estimates, each monitor was assigned to the BlueSky grid in which it was located in and a Pearson product−moment correlation coefficient was calculated between the daily concentrations. Counties were selected if the Pearson coefficient ($r$) was greater than 0.4. Although, Mariposa, Calaveras, Amador, and Alpine counties did not have monitors to compare with the BlueSky estimates, they were included in the analysis because satellite images from National Aeronautics and Space Administration's (NASA's) Moderate Resolution Imaging Spectroradiometer (MODIS) show that the smoke plume from the Rim Fire did travel across those counties.[41,19] Counties that did not have a Pearson coefficient ($r$) that was greater than 0.4, Fresno, Madera, Merced, and Mono, were not included in the iF analysis.

We used SAS 9.4 and R v. 3.1.0 for all data cleaning and calculations and ArcGIS 10.2 for spatial data processing and map creation.[42−44]

## ■ RESULTS

Table 1 provides a summary of fire events that occurred during the study period. The Rim Fire was the largest fire event during the study period and accounted for 86.5% of the total $PM_{2.5}$ emissions. The American Fire was an additional large fire (27 440 acres) that occurred during the study period and contributed a total of 14% to the total emissions. When combined, the small fires that occurred during the Rim Fire in the study area accounted for less than 1% of the total $PM_{2.5}$ emissions. Figure S2 (SI) provides information on growth of the fire during the study period. The Rim Fire had extreme fire growth between August 21 and 22, expanding across 36 017 ha over 2 days. The Rim Fire continued to increase in size until September 8, with large area growth on August 26 (12 066 ha) and August 30 (7103 ha); after September 8 the fire growth was minimal.

**$PM_{2.5}$ Monitoring.** Air-quality impacts during the Rim Fire were localized in the central Sierra and extended to the northern Sierra and Nevada monitoring sites during the study period (August 17−October 23, 2013). At the most impacted sites, daily 24-h mean concentrations were elevated from August 23 to September 14, 2013 (Figure S3, SI). This trend follows the trajectory of active fire growth and increasing area burned during the same period. The Rim Fire experienced large growth between August 21 and 30, 2013.

Daily 24-h average $PM_{2.5}$ concentrations measured by the 22 air monitors ranged from 0 to 450 $\mu g/m^3$. Monitoring sites in Rim Fire Camp, Tuolumne City, Groveland, Pollock Pines, and Gardnerville experienced the highest mean 24-h average concentrations of $PM_{2.5}$. The Rim Fire Camp, Tuolumne City, and Groveland sites were located closest to the fire (Table S1, SI). The Rim Fire Camp monitoring site reported the highest mean and maximum 24-h average $PM_{2.5}$ concentration (121 and 450 $\mu g/m^3$). Tuolumne City and Groveland had elevated mean 24-h average $PM_{2.5}$ concentrations, 70 and 42 $\mu g/m^3$, respectively, compared to monitoring locations close to the Rim Fire in Yosemite National Park, Yosemite Valley (14 $\mu g/m^3$), and Tuolumne Meadows (27 $\mu g/m^3$). Locations in the central Sierra foothills, Jamestown, La Grange, and Bootjack, did not have elevated mean 24-h averages (8, 16, and 10 $\mu g/m^3$, respectively) compared to other monitoring locations in the


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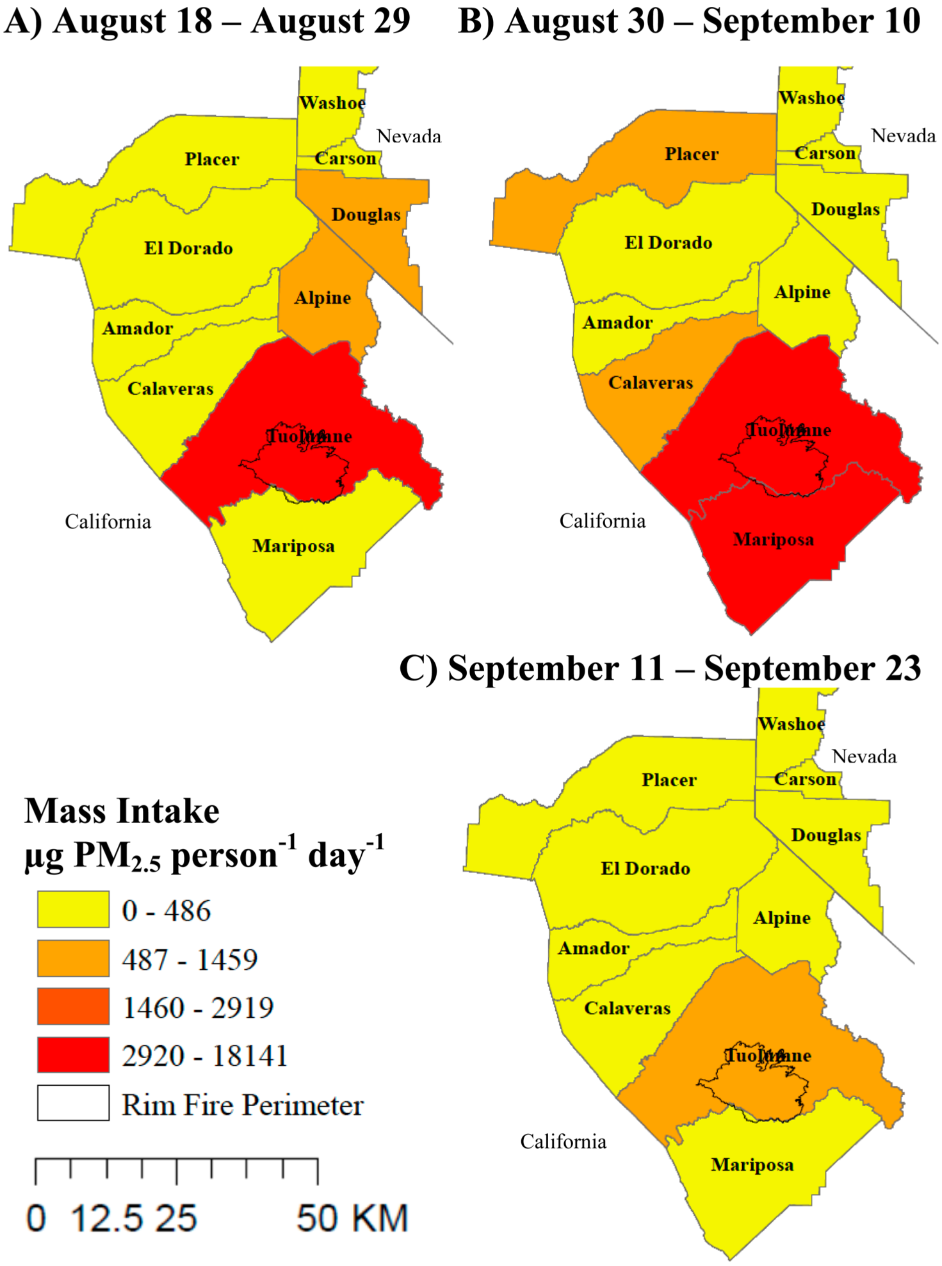


**Figure 1.** Mass Intake ($\mu$g $PM_{2.5}$ person$^{-1}$ day$^{-1}$) for three 12-day periods during the active fire growth period.

study area. $PM_{2.5}$ concentrations measured at Devils Postpile had a wide range of daily 24-h average concentrations, 1−72 $\mu g/m^3$, but did not have a high mean 24-h average $PM_{2.5}$ concentration (9 $\mu g/m^3$), which would indicate that it was heavily impacted by smoke.

Although sites in the northern Sierra and Nevada were not close to the Rim Fire, they reported elevated mean $PM_{2.5}$ concentrations. Pollock Pines and Gardnerville had the highest mean $PM_{2.5}$ concentration in their regions, 31 and 35 $\mu g/m^3$, respectively. San Joaquin Valley monitoring sites in Merced and Tranquility reported two of the lowest 24-h average $PM_{2.5}$ mean concentrations, 6 and 8 $\mu g/m^3$, respectively. Mean 24-h average $PM_{2.5}$ concentrations measured in the San Joaquin Valley did not indicate that those sites were impacted by smoke from any fire.

Impacts on air quality as identified by the AQI were localized to monitors near the fire in the central Sierra and extended to monitoring sites in the eastern Sierra, northern Sierra, and Nevada. The Rim Fire Camp location was the only monitor to measure a hazardous AQI day and had no good AQI days. Very unhealthy and unhealthy AQI days were observed at 10 air monitoring sites in the central Sierra, northern Sierra, and Nevada. Tuolumne City, Polluck Pines, and Gardnerville had the most days that experienced very unhealthy and unhealthy days in each region. Devils Postpile experienced 1 day each of unhealthy and USG AQI. The San Joaquin Valley did not experience any considerable air-quality impacts during the fire period, since all days were in the good or moderate AQI category (Figures S5 and S7, SI).

**Intake Fraction.** Intake fraction (units: per million) of $PM_{2.5}$ from wildfire smoke during the active fire period (August 18−September 23, 2013) across the iF study area in California and Nevada had a daily range of 0.07 and 54 per million with an estimate of 7.4 per million for the entire study period. Table 3


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summarizes the parameters used to calculate iF that were derived from the literature and BlueSky outputs. The sum of the daily average $PM_{2.5}$ concentration $[C(i,j)]$ was 1967 $\mu g/m^3$ across the iF study area and the total $PM_{2.5}$ emission from wildfires was $1.8 \times 10^8$ kg during the active fire period.

The total intake of $PM_{2.5}$ across the study area during the active fire period was 1225 kg. Figure 1 presents the daily mass intake of $PM_{2.5}$ (mass of $PM_{2.5}$ inhaled per person per day) in the study area during the active fire period across three subsequent 12-day periods. Compared to measured concentrations of $PM_{2.5}$, the mass intake of $PM_{2.5}$ followed a similar time pattern, being elevated between August 18 and 29, 2013, and again between August 30 and September 10, 2013. The mass intake of $PM_{2.5}$ was the highest (2920−18141 $\mu g$ $PM_{2.5}$ $person^{-1}$ $day^{-1}$) in Tuolumne County from August 18 to September 10, 2013, and in Mariposa County from August 30 to September 10, 2013. During the active fire period, mass intake was lowest in Washoe, Carson, El Dorado, and Amador counties. Alpine, Douglas, and Placer counties experienced elevated mass intake levels during the active period. By the end of the active fire period, September 11−23, 2013, Tuolumne County was the only location with an elevated mass intake.

BlueSky concentration estimates were compared to measured $PM_{2.5}$ concentrations from air monitors and Pearson product−moment correlation coefficients calculated to examine agreement between modeled and measured data (Figure S4, SI). Results were variable with best correlations at the central Sierra, northern Sierra, and Nevada locations. BlueSky estimates were not well correlated with measured concentrations in the eastern Sierra (Devils Postpile) and the San Joaquin Valley. Daytime southwest winds typically carried the plume to the northeast (Figure S6, SI), with smoke pooling in Sierra mountain valleys overnight.[45] Figure S5 (SI) compares calculated 24-h mean $PM_{2.5}$ concentrations before, during, and after the fire at the four central valley locations. $PM_{2.5}$ concentrations were similar before and during the fire (maximum of 40 and 35 $\mu g/m^3$, respectively), while after the Rim Fire $PM_{2.5}$ concentrations were elevated (up to almost 60 $\mu g/m^3$). Visible daytime satellite images periodically show light smoke over the San Joaquin Valley, and AQI levels were moderate for 10−30 days during the Rim Fire (Table 2).[46] Additionally, the Crane Flat Lookout remote automated weather station (RAWS) located 25 km southwest of the Rim Fire ignition point showed predominantly southwest to southeast wind directions (Figure S7, SI) during the active fire period when the intake fraction was calculated.

## ■ DISCUSSION

Our objectives were to examine and quantify the air-quality impacts of $PM_{2.5}$ from wildland fire smoke during a megafire. We hypothesized that locations nearest the Rim Fire would be most impacted by $PM_{2.5}$ from wildland fire smoke. Although monitoring sites in the San Joaquin Valley were close to the Rim Fire, their mean 24-h averages had no AQI days above moderate, which along with the meteorology and visible satellite imagery indicated that San Joaquin Valley's air quality was not heavily impacted by smoke from the Rim Fire.

A previous study of $PM_{2.5}$ air-quality impacts from the 2011 Lion Fire (20 682 acres), a managed wildfire, demonstrated that wildfire smoke has mostly localized effects. In addition, $PM_{2.5}$ from smoke resulted in days that were very unhealthy and unhealthy according to AQI levels. Compared to the Lion Fire, the Rim Fire burned a much larger area and resulted in fewer days that were categorized as good and moderate. For the 2003 wildfire season in Southern California, Wu et al. estimated population-weighted daily exposures to $PM_{2.5}$ for zip codes in Southern California from filter-based measurements.[47] They estimated daily concentrations of $PM_{2.5}$ on light and heavy smoke days to be 75 and 90 $\mu g/m^3$ throughout Southern California during the fire period. The wildfire event in Southern California had a greater impact on air quality; only the Rim Fire Camp monitoring site had higher mean $PM_{2.5}$ concentrations than Southern California.

During the active fire period, the intake fraction was 7.4, meaning that 7.4 $\mu g$ of $PM_{2.5}$ was inhaled for 1 kg of $PM_{2.5}$ emitted from wildland fires. The highest amount of $PM_{2.5}$ inhaled per person per day was after the large fire growth period on August 27, 2013. Mass intake is a good metric to examine how much $PM_{2.5}$ a population is inhaling per day in a specific area. If the 24-h standard for $PM_{2.5}$ (35 $\mu g/m^3$) concentration was used to calculate the daily mass intake for each county, the daily mass intake would be 486 $\mu g$ $PM_{2.5}$ $person^{-1}$ $day^{-1}$. The mass intake values in Tuolumne and Mariposa counties were between 6 and 31 times the mass intake of the EPA 24-h $PM_{2.5}$ standard. During the active fire growth period, Calaveras, Placer, Alpine, and Douglas counties had mass intake levels that were up to 3 times the mass intake of the EPA 24-h $PM_{2.5}$ standard. The mass intake from August 30 to September 10, 2013, had the most counties that were elevated above 486 $\mu g$ $PM_{2.5}$ $person^{-1}$ $day^{-1}$. The last week of the active fire period had all but Tuolumne County return to a mass intake below the EPA 24-h $PM_{2.5}$ standard.

To our knowledge, this is the only study that has estimated iF of $PM_{2.5}$ from wildfire smoke. When comparing iF values, it should be noted that iF can be influenced by factors such as meteorology, population density, and fate and transport of $PM_{2.5}$.[48] Previously, iF was calculated for $PM_{2.5}$ from wood smoke for census tracts in Vancouver, Canada, during the winter period (162 days).[28] That study used model estimates of $PM_{2.5}$ concentrations and emissions to calculate an iF of 13 per million (range 6.6−24) with daily mass intake values that range from 0 to 120 $\mu g$ $PM_{2.5}$ $person^{-1}$ $day^{-1}$. Although the mass intake range for $PM_{2.5}$ during the Rim Fire was higher than that for wood smoke in Vancouver, the intake fraction was lower during the Rim Fire, which means that the intake of $PM_{2.5}$ from a megafire can be lower than the intake of $PM_{2.5}$ from wood smoke in an urban environment. This difference could be because BlueSky estimates were summed across the iF study area and were not as spatially resolved as the estimates used for the Vancouver wood smoke study. Additionally, our iF study area included some locations that may not have been impacted by smoke and the population of the iF study location is smaller, which could lead to a smaller estimate of iF.

Humbert et al.[48] completed a literature review examining mobile and stationary sources of $PM_{2.5}$ across the United States. All values were adjusted to use a breathing rate of 13 $m^3$/day. The authors determined that representative iF values for urban, rural, and remote locations were 44, 3.8, and 0.1 per million for ground-level $PM_{2.5}$ emissions, respectively. The authors defined urban locations as having a population density of 753 people $km^{-2}$, rural locations having a population density of 100 people $km^{-2}$, and remote locations having a population density of 1 person $km^{-2}$. The population density of the iF study area is 187 people $km^{-2}$ and ranged from 0.6 to 147 for each individual county in the iF study area.[49] Our iF study area population density is best compared to the rural population density. The iF of $PM_{2.5}$ from wildfire smoke is slightly higher than iF of $PM_{2.5}$


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in rural areas and significantly higher when compared to remote areas.

Our results add to the literature quantifying $PM_{2.5}$ concentrations during large wildfire events. We demonstrated the use of estimates of $PM_{2.5}$ concentrations and emissions in a novel approach, calculation of iF, to assess the impact of $PM_{2.5}$ from smoke compared to other sources of $PM_{2.5}$. This approach could be used in a future study, possibly in an urban area that is impacted by smoke to assess the relative impact of $PM_{2.5}$ from wildfires compared to traffic or stationary sources.

We only have $PM_{2.5}$ concentration measurement data for locations where air monitors were deployed or that were part of the regulatory network of monitors. There may be communities or locations that were also highly impacted during the Rim Fire period that did not have a monitoring site nearby, making it harder to evaluate any air-quality impacts. We cannot conclude that $PM_{2.5}$ concentrations and emissions are only attributable to the Rim Fire. Although it was the largest fire actively burning during the study period, there was one other large fire. Since $PM_{2.5}$ concentrations are influenced by weather conditions, smoke dispersion, fuel type, and fire behavior, the results of this study will not be representative of all wildfires.

For the calculation of iF, a limitation is the great uncertainty that exists in estimating emissions from fires. In general, performance of the BlueSky Smoke Modeling Framework was poor at locations south of the fire (with the exception of Yosemite Valley) and improved at locations near and north of the fire (with the exception of Wentworth). Calculating fire emissions and modeling near-surface $PM_{2.5}$ concentrations for the Rim Fire was a process with many sources of uncertainty and variability. The uncertainty can range from approximately 10% to over 100% depending on variations in the fuels, consumption model, emission factors, and fire size. Calculating downwind $PM_{2.5}$ concentrations from fire emissions is further complicated by uncertainties in the wind field, choice of dispersion or chemical transport model, and allocation of emissions diurnally and vertically in the atmosphere.[50,51]

Daily fire size was estimated from satellite hot spot detections and fire perimeter reports. Figure S2 (SI) compares the fire area used in the BlueSky model simulations with the actual fire perimeter growth and shows how the simulated fire growth tended to underestimate cumulative acres burned from August 21 to September 8, 2013, eventually agreeing well with actual observed total fire perimeter data by September 9, 2013. Within the Rim Fire perimeter, there were six major classes of FCCS fuel loadings with a factor of 5 variability, ranging from 45 tonnes/ha for live oak−blue oak woodland to 207 tonnes/ha for red fir forest. These fuel loading estimates are slightly higher than those recently used by other researchers, who estimated a maximum fuel loading of 165 tonnes/ha.[52,53]

Much of the Rim Fire burned during plume-dominated conditions, resulting in high severity fire impacts.[54] Kane[55] estimated 23% of the area burned in high-severity (patches with >75% overstory mortality) and 31% of the area burned in moderate severity (patches with 25−75% overstory tree mortality). For this work, 50% of the canopy fuels were assumed to burn and be consumed. Emission factors were multiplied by the fuel consumed to estimate grams of $PM_{2.5}$ emitted per kg of fuel consumed. Emission factors varied by type of combustion phase and ranged from 7 to 17 g/kg. Urbanski reported $PM_{2.5}$ emission factors for western forest fuels between 14 and 23 g/kg with an uncertainty range of 4−10 g/kg. Combining these factors into the final emission calculation yielded an order of magnitude variation in emission estimates of 0.24 to 2.7 tonnes/ha (Table S2, SI), within the range of other studies.[49,51,52,57] Total emissions were allocated diurnally and vertically in the atmosphere, along with a 3-d meteorology that was input into the HYSPLIT dispersion model. Additional studies have discussed the underlying uncertainty in the fire emission calculation stream, the importance of accurately representing the wind field for smoke modeling, and overall smoke model performance.[50,51,56−62]

Our study demonstrates methods to assess air-quality impacts of $PM_{2.5}$ from wildfires. This study revealed that air-quality impacts are not only localized to communities near large fires but can extend long distances and affect distant urban areas. The BlueSky Smoke Modeling Framework provided a unique opportunity to calculate iF and assess the impact of $PM_{2.5}$ from smoke compared to other sources of $PM_{2.5}$. With the predicted increase of the fire season in the western United States due to climate change resulting in more acres burned and smoke produced, it is important to quantify the air-quality impacts from wildfires to develop effective strategies to protect the public health.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b02252.

Tables S1 and S2 and Figures S1−S7 (PDF)

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### Notes

The authors declare no competing financial interest.


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