*Atmospheric Pollution Research 5 (2014) 581-590*

Atmospheric Pollution Research

www.atmospolres.com

# Spatial and seasonal patterns of particulate matter less than 2.5 microns in the Sierra Nevada Mountains, California

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## ABSTRACT

This paper presents particulate matter data collected in the California southern Sierra Nevada Mountains (SNM) during 2002 to 2009 from the Central Valley (elevation 91 m) into the SNM (elevation 2 598 m). Annual average concentrations of particles smaller than 2.5 µm in diameter ($PM_{2.5}$) for all sites during this study ranged from 3.1 to 22.2 µg m$^{-3}$. The highest elevation site experienced annual $PM_{2.5}$ concentrations ranging from 3.1 to 4.6 µg m$^{-3}$, while the lowest elevation site concentrations ranged from 18 to 22.2 µg m$^{-3}$. $PM_{2.5}$ generated from natural source emissions (background particulate matter) in the southern SNM was estimated to be 4.7±1.3 µg m$^{-3}$. Higher elevation sites in the southern SNM exhibit a pattern of high $PM_{2.5}$ in the summer as compared to the winter. For regulatory purposes, air quality throughout the southern Sierra Nevada is assumed to be similar to the Central Valley, which is currently in nonattainment. However, we determined that locations used in this study of elevations above 500 m in the southern SNM are actually in compliance with federal standards for $PM_{2.5}$. Elevation and day of year appear to account for most of the variation in $PM_{2.5}$ concentrations. Fires occurring during this study were typical of the size and intensity historically documented in this area of the SNM. We determined that while these fires impact air quality they do not appear to be a major driver in exceeding the United States Federal $PM_{2.5}$ standard in the southern SNM.

***Keywords:*** *$PM_{2.5}$, Sierra Nevada Mountains, background particulate matter, nonattainment, forest fires*

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***Article History:***
*Received: 14 January 2014*
*Revised: 15 April 2014*
*Accepted: 18 April 2014*

**doi:** 10.5094/APR.2014.067

## 1. Introduction

The U.S. Environmental Protection Agency (EPA) has established particulate matter as one of six criteria pollutants. Short term exposure to $PM_{2.5}$ concentrations are associated with adverse health effects on the general population; including increased mortality and morbidity, reduced lung function, increased respiratory symptoms (such as chronic cough or bronchitis), aggravated respiratory and cardiovascular disease, eye and throat irritation, coughing, breathlessness, blocked and runny noses, and skin rashes (U.S. EPA, 2004; Boogaard et al., 2013; Li et al., 2013). Long term exposure to particulate matter (PM) is believed to have a significant impact on human health (Kloog et al., 2013), and may lead to a reduction of life expectancy (WHO, 2003).

The SNM range is located in the western United States and runs north–south in the state of California. Mountain peaks in the SNM reach over 4 400 m. Concentrations of $PM_{2.5}$ are affected by global, regional, and local sources of air pollutants. Pollution transport is a complex phenomenon, taking place at the surface and aloft as well as moving vertically. Prevailing winds in this area are northwesterly (Fujioka et al., 1999), transporting anthropogenic pollution from urban centers to the SNM. The complex terrain of the SNM is a primary driver and determinant of local transport of polluted air (Vanooy and Caroll, 1995). The heating of the land during the day creates local anabatic winds from the west and southwest on the western side of the SNM (Hayes et al., 1984) which results in the predominant transport moving the air eastwards to the crest of the SNM. Also adding to the transport complexity, the SNM has multiple deep river drainages that are major transport corridors with predominantly up canyon winds transporting pollution to the east side of the SNM (Cisneros et al., 2010). The mountains of the southern Sierra Nevada rise directly to the east of the heavily populated Central Valley of California where urban and agricultural emissions contribute to the high $PM_{2.5}$ concentrations in this area.

Exposure to air pollutants, including $PM_{2.5}$, for the SNM residents and visitors is not well understood. Although monitoring has been conducted in urban areas, it has been limited in the SNM locations. Since 1988, PM has been monitored in the SNM by the IMPROVE (Interagency Monitoring of Protective Visual Environments) program at some locations. The IMPROVE network provides 24–hour $PM_{2.5}$ concentrations seven times per month and was established to monitor visibility and air quality trends in National Parks and Wilderness in the United States. Prior to 2006, no real time $PM_{2.5}$ information was available in the Sierra Nevada. Thus, to gain better understanding on $PM_{2.5}$, in 2006, the United States Forest Service (USFS) began near real time monitoring of $PM_{2.5}$. This campaign is the first to intensely monitor forest areas and provides hourly measurements for $PM_{2.5}$.

The SNM has a long history of naturally occurring fires necessary for ecosystem health (SNEP, 1996). It is estimated that before 1800, 1.8 million hectares in California burned annually (Stephens et al., 2007). High severity stand replacing fires have been increasing in frequency since that time (Miller et al., 2009). Keeping the frequent, low intensity fire regime in the SNM can reduce emissions and fire severity (Collins et al., 2007; Hurteau et al., 2008). Previous studies have found a relatively weak association between fires and $PM_{2.5}$ levels at IMPROVE sites in California even though there is significant wild land fire activity and high summer (relative to winter) mean $PM_{2.5}$ concentration (Jaffe et al., 2008).

Air quality in California's Central Valley is consistently in nonattainment of the federal standard for $PM_{2.5}$. Currently, measurements of $PM_{2.5}$ made at urban sites in the Central Valley are used to determine the compliance with ambient air quality standards in the SNM. The spatial and seasonal variability of $PM_{2.5}$ from the Valley to the SNM crest is not well understood. As population in the Central Valley has increased, populations of the mountain communities and recreational visits to the southern SNM have also increased. Unless changes to population and anthropogenic emissions change drastically from historic trends, $PM_{2.5}$ emissions from internal combustion motor vehicles and stationary sources, including industrial and agricultural sites, will likely dominate air pollution in the SNM.

Understanding background $PM_{2.5}$ (the portion of particulates that would be present without anthropogenic source contributions) and the patterns and amount of contribution from the primary sources of emission in the Sierra Nevada are fundamental to adequately understanding impacts to public health for both rural and urban residents and assessing whether regulatory actions currently in place are effectively mitigating both short and long term $PM_{2.5}$ exposure. In the United States, not much is known about background $PM_{2.5}$ concentrations and regional variation because most of the $PM_{2.5}$ monitoring network in the United States did not start routine operation until 1999 (Parkhurst et al., 1999). Monitoring sites are typically in urban areas where primary source contributors are anthropogenic. The prevalence of fire as a part of the Sierra Nevada ecosystem makes this understanding even more problematic since fire has contributed historically to background $PM_{2.5}$. Assumptions may be made that emissions from fire are part of a regional air quality problem when, in fact, they might be much more localized depending on size, location and weather patterns.

$PM_{2.5}$ concentrations throughout the Sierra Nevada are regulatory considered to be similar to those in urban areas of the Central Valley of California. The validity of this regulatory assumption has not been evaluated. Data from this study provides information on spatial and seasonal variability of $PM_{2.5}$ from urban Central Valley sites to higher elevations in the SNM to help public health officials, air regulatory agencies, and land managers make informed policy decisions on air quality particularly as they relate to natural ignition wild land fire. Analysis in this paper uses available $PM_{2.5}$ data (both hourly and 24–hour) from 2002 through 2009.

The main objectives of this paper are: (1) The assessment of the levels of $PM_{2.5}$ concentrations occurring in different locations in the southern SNM using both hourly and 24–hour concentrations data collected from 2002 to 2009, (2) the establishment of $PM_{2.5}$ background concentrations specific to the southern SNM, where background is an estimate of $PM_{2.5}$ values in the absence of anthropogenic inputs, (3) the investigation of compliance of $PM_{2.5}$ concentrations with federal air quality standards in the southern SNM that is needed in order to identify future potential compliance challenges caused by the projected increase in wildfire activity, as well as the potential increase in anthropogenic inputs, and (4) the investigation of the spatial–temporal distribution of $PM_{2.5}$ and the factors contributing to the observed $PM_{2.5}$ concentrations in the southern SNM, in particular, elevation, location, weather, and day of the year.

## 2. Methods

### 2.1. Data collection

Data presented here is from the USFS network, the IMPROVE network, and two sites from the California Air Resources Board (CARB) network (Figure 1 and Table 1). The sites used in this study are located from the Central Valley into the southern SNM. Included in Table 1 are distances to the closest urban center (population greater than 50 000). CARB sites at Fresno and Visalia are used as representative for $PM_{2.5}$ in the Central Valley and categorized in this paper as urban sites. The IMPROVE site at Kaiser is the most remote site, and is considered a natural or undeveloped site. All other sites are categorized as rural.

Hourly $PM_{2.5}$ data was obtained from Met One Instruments, Inc. Beta Attenuation Monitors BAM–1020 (BAM), or Met One Instruments, Inc. Environmental Beta Attenuation Monitors (EBAM) operated at USFS and CARB sites. The BAM and EBAM use a vacuum pump to draw a measured sample volume of ambient air that deposits particulates on to filter paper. A Carbon 14 source emits beta particles that pass through the tape and are counted on a scintillation detector. A beta count is taken prior to the sample, and after the sample to determine the particulate mass. The measured air flow through the filter tape is used to calculate the concentration (MOI, 2008a). The BAM is a Federal Equivalent Method (FEM) for measuring $PM_{2.5}$. BAM hourly measurements have a resolution of ±0.1 μg $m^{-3}$. The BAM hourly lower detection limit, set by twice the standard deviation of the hourly zero noise, is less than 4.8 μg $m^{-3}$. The BAM 24–hour average lower detection limit is less than 1.0 μg $m^{-3}$ (MOI, 2008a). The EBAM is designed for temporary and quick deployment. The EBAM has not been designated by the EPA as an FEM. When compared to an FEM in laboratory conditions, an EBAM was found to overestimate smoke particulate concentration by 1% (USFS, 2006). EBAM hourly readings have an accuracy of ±10%; hourly lower detection limit, set by twice the standard deviation of the hourly zero noise, is less than 6.0 μg $m^{-3}$; 24–hour average lower detection limit is less than 1.2 μg $m^{-3}$ (MOI, 2008b). Any hourly data with data logger documented errors was invalidated. Downloaded flow rate was required to be within ±5% (0.83 Lpm) of the 16.7 Lpm design value. All negative $PM_{2.5}$ values were invalidated. $PM_{2.5}$ data for the BAMs in the Central Valley cities of Fresno and Visalia was obtained from the CARB Air Quality and Meteorological Information System (AQMIS) website at http://www.arb.ca.gov/aqmis2/aqmis2.php. Data for the BAM located at Ash Mountain in Sequoia National Park was downloaded from the Interagency Real Time Smoke Monitoring website at http://www.airsis.com/usfs/.

$PM_{2.5}$ data for the IMPROVE sites was obtained from the IMPROVE database (http://vista.cira.colostate.edu/improve/). IMPROVE uses differences in pre– and post–weights of a Teflon filter (gravimetric) to determine $PM_{2.5}$ concentration with measurements conducted once every three days (IMPROVE, 2008).

### 2.2. Statistical model

The statistical model described below was used to estimate the distributions of $PM_{2.5}$ as a function of elevation, time of year, and meteorology. The model would be used to further our understanding of the effects of weather and elevation, and distance of urban centers on the average $PM_{2.5}$ values.

The following generalized additive model (GAM) was fitted to study the contribution of selected topographic, seasonal, and weather variables on the variability of $PM_{2.5}$ values in the southern Sierra Nevada:

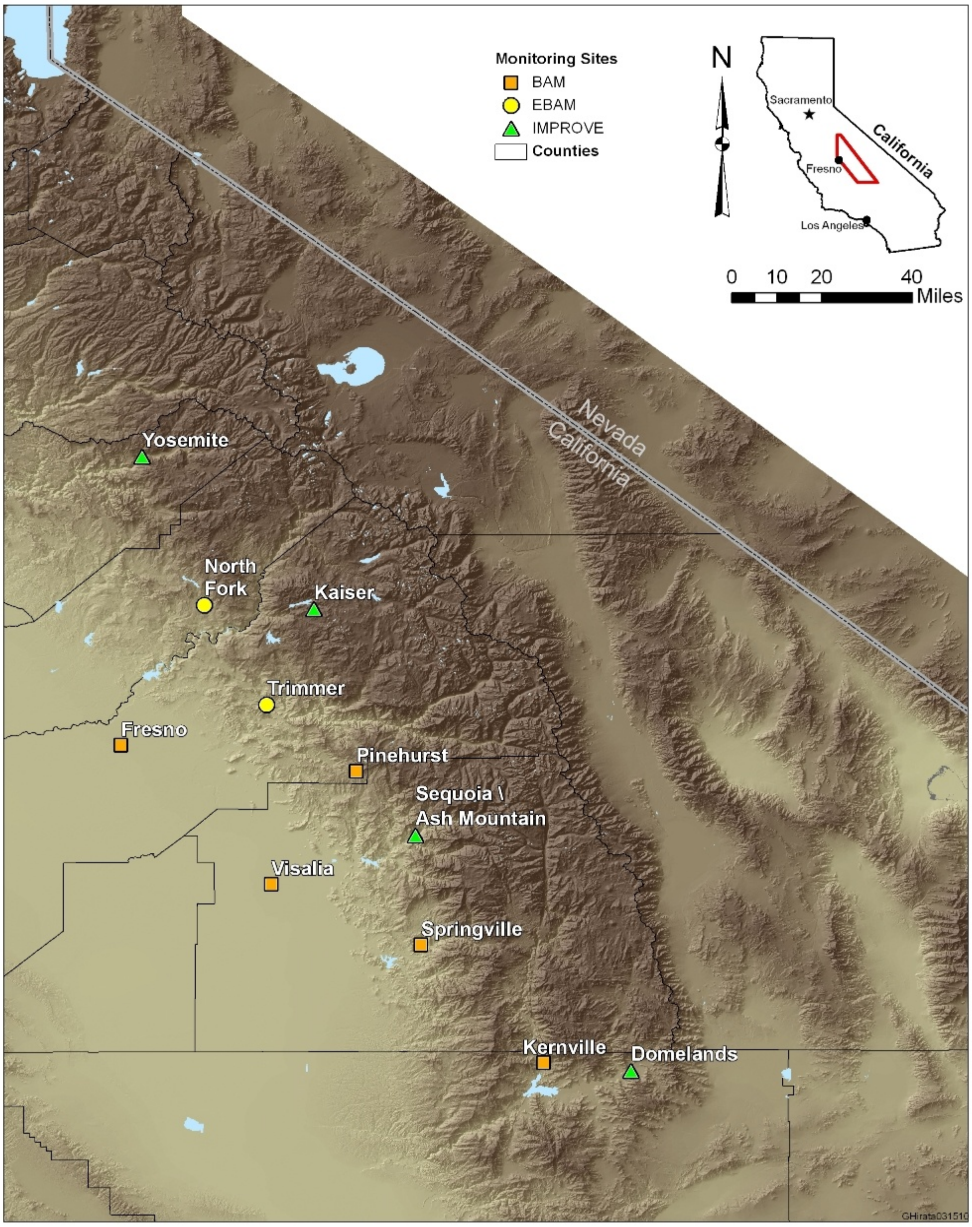


***Figure 1.*** *Locations of monitoring sites.*

***Table 1.*** *Site descriptions*

| Site | Latitude | Longitude | Elevation (m) | Equipment Network | Equipment Type | Km. to Urban | Years of Data |
|---|---|---|---|---|---|---|---|
| Fresno | 36.7819 | –119.7731 | 91 | CARB (urban) | BAM | 0 | 2005–2009 |
| Visalia | 36.3325 | –119.291 | 102 | CARB (urban) | BAM | 0 | 2005–2009 |
| Springville | 36.1363 | –118.8107 | 321 | USFS (rural) | BAM | 21 | 2006–2009 |
| Trimmer | 36.9112 | –119.306 | 450 | USFS (rural) | EBAM | 47 | 2006–2009 |
| Ash Mt. | 36.4894 | –118.8292 | 519 | NPS (rural) | BAM | 45 | 2007–2009 |
| Sequoia | 36.4894 | –118.8291 | 519 | IMPROVE (rural) | Gravimetric | 45 | 2002–2009 |
| North Fork | 37.233 | –119.506 | 841 | USFS (rural) | EBAM | 60 | 2006–2009 |
| Kernville | 35.7551 | –118.4174 | 842 | USFS (rural) | BAM | 41 | 2006–2009 |
| Domelands | 35.7278 | –118.1377 | 927 | IMPROVE (rural) | Gravimetric | 86 | 2002–2009 |
| Pinehurst | 36.6973 | –119.0188 | 1 246 | USFS (rural) | BAM | 47 | 2006–2009 |
| Yosemite | 37.7133 | –119.7061 | 1 603 | IMPROVE (rural) | Gravimetric | 83 | 2002–2009 |
| Kaiser | 37.2207 | –119.1546 | 2 598 | IMPROVE (undeveloped) | Gravimetric | 74 | 2002–2009 |

*Y=year+IMP+s(elev, dyear)+s(WS)+s(RH)+s(ATC)+ε* (1)

where, *Y* is the logarithm of the 24–hour mean $PM_{2.5}$ concentration at a given site and date; *year* is the categorical year effect, 2006–2009; *IMP* is the effect from the monitor type (IMPROVE or BAM/EBAM); *s(elev, dyear)* is a smooth 2–dimensional function describing the interactive effect of elevation on different days of the year; *s(X)* is a non parametric smooth function used to estimate the potentially non linear relationships between $PM_{2.5}$ and the explanatory variables, wind speed (*WS*), relative humidity (*RH*) and average temperature (*ATC*); *ε* is an autoregressive error to account for the serial correlation in the time series. The GAM module in the R statistical package (R, 2009) was used to estimate the parameters and the 2–dimensional function in Equation (1).

The overall adjusted $R^2$ for the model was 60%. A similar model with elevation (elev) in Equation (1) replaced by distance of site to nearest urban area was also fitted. The model with elevation gave a marginally better fit than that with distance to urban location when Akaiki Information Criteria (AIC) was used as goodness of fit metric. We did not include both elevation and distance to urban in the same model because the correlation between the two variables was high ($r$=0.81).

Note that the statistical model is not a predictive model and only used for the purpose of explaining the $PM_{2.5}$ spatial and temporal phenomenon of observed data and it was not used for correction purposes or in any other calculation in this paper.

### 2.3. Data calculations

USFS site annual and 24–hour calculations were made using the Guideline on Data Handling Conventions for the PM NAAQS (U.S. EPA, 1999) Calculations for USFS BAM $PM_{2.5}$ concentrations are for the calendar years 2006–2009. To attain the annual $PM_{2.5}$ federal standard, the 3–year mean of the annual $PM_{2.5}$ concentration must be less than or equal to 15 µg $m^{-3}$. The 24–hour $PM_{2.5}$ federal standard is attained when the 3 year mean of the annual $98^{th}$ percentile of 24–hour concentrations is less than or equal to 35 µg $m^{-3}$. All of our analysis was done using 24–hour mean concentrations. Differences in data collection methods (gravimetric IMPROVE, beta attenuation BAM and EBAM) likely are having an effect on comparative analysis. Loss of ammonium nitrate using Teflon membrane filter sampling has been estimated at 8–16% of 14 month average (Ashbaugh and Eldred, 2004; Chow et al., 2005).

Data collected at the USFS BAM sites at Pinehurst and Springville are used to compare annual mean and 24–hour calculations with data for the Central Valley CARB BAM sites at Fresno and Visalia. Site data is used to determine background $PM_{2.5}$ in the SNM and to examine the effect of elevation and day of year on $PM_{2.5}$. Because of significant data gaps throughout the calendar years, data from the USFS site at Kernville and the National Park Service site at Ash Mountain are not used to estimate the relevant statistics, such as background levels, or attainment of air quality standards, but their data is used in the statistical model.

**$PM_{2.5}$ background calculation.** A method proposed for calculating background $PM_{2.5}$ concentrations by Van Dingenen et al. (2004) has been applied in Europe. Continental background $PM_{2.5}$ concentration was derived from the average of the annual $5^{th}$ percentile of sites within 50 km of a large pollution source ($5^{th}$ percentile is used as an estimate of background $PM_{2.5}$ concentration at sites dominated by anthropogenic sources) and the annual mean of the natural background sites (sites located greater than 50 km from a large pollution source) (Van Dingenen et al., 2004). In this paper, background $PM_{2.5}$ in the SNM was estimated as the mean of the yearly concentrations at the IMPROVE sites greater than 50 km from and urban center [Kaiser, Yosemite and Domelands (2002–2009)] and $5^{th}$ percentile concentrations at the urban sites of Fresno and Visalia (2005–2009) plus or minus 1 standard deviation. The Northfork site (60 km from an urban center) was not included in the background calculation because data at this site was seasonal and did not capture winter concentrations. To calculate background $PM_{2.5}$, IMPROVE filter sample loss is assumed to be zero even though it is known that $PM_{2.5}$ mass loss occurs due to volatilization of $NH_4NO_3$ (Ashbaugh and Eldred, 2004). No correction factor was included for IMPROVE data in the background calculation because the IMPROVE sites selected are remote sites which are expected to have $PM_{2.5}$ mass loss of less than 5% in summer and less than 10% in winter (Ashbaugh and Eldred, 2004). No correction was included for Asian aerosols inputs. Asian aerosols contribute to $PM_{2.5}$ concentrations at IMPROVE sites in the range of 0.2 to 1 µg $m^{-3}$ roughly equating to 4% to 20% respectively of the observed $PM_{2.5}$ concentrations (VanCuren and Cahill, 2002). Both filter loss and Asian aerosol contributions are within 1 standard deviation of the mean background calculated and thus no corrections to IMPROVE data were introduced into the calculation.

## 3. Results and Discussion

### 3.1. Particulate matter concentrations

Characteristics of the distribution of daily $PM_{2.5}$ concentrations by year and location are presented in Table 2. Annual mean $PM_{2.5}$ concentrations during the study for all the sites ranged from 3.1 to 22.2 µg $m^{-3}$. The monitoring sites in the IMPROVE network are the highest elevation sites and recorded the lowest concentrations (Table 1). IMPROVE sites in this study appear to be underestimating annual $PM_{2.5}$ relative to the BAM and EBAM sites (Figure 2). This observation is consistent with previous research. $PM_{2.5}$ mass loss of IMPROVE site filters from volatilization of $NH_4NO_3$ have been found to be less than 10% during the summer and ranges up to 30% during the winter with lower mass losses occurring at more remote sites (Ashbaugh and Eldred, 2004). The underestimation of $PM_{2.5}$ was also confirmed by our statistical model where the estimated factor for the IMPROVE site (IMP) was –0.248 (SE=0.034). Namely, the IMPROVE sites were estimated to be 22% (95% CL 16–27%) lower on average than the non–IMPROVE sites.

The lowest concentrations for this study were found at the Kaiser site where the yearly mean concentration ranged from 3.1 to 4.6 µg $m^{-3}$ from 2002 to 2009. The Kaiser monitor is located at an elevation of 2 598 m, and is the highest elevation monitoring site in the southern SNM. The highest $PM_{2.5}$ concentrations in the IMPROVE network were experienced at the Sequoia monitoring site where the yearly mean concentration ranged from 7.5 to 9.7 µg $m^{-3}$ during the years 2002–2009. The Sequoia monitoring site is the lowest IMPROVE site in this study. The highest 24–hour maximum $PM_{2.5}$ concentration in the IMPROVE network occurred during 2007 at the Domelands monitoring site where a concentration of 69.3 µg $m^{-3}$ was documented. This was likely due to the relatively active 2007 fire season in the Southern California mountains which are upwind of the Domelands monitor location (Keeley et al., 2009). During the summer of 2007, smoke was visible in satellite images and observed to be transported towards the Domelands monitor from fires such the Zaca Fire. Measured concentrations of $PM_{2.5}$ at this location were higher during 2007 than in other years. All other sites in the IMPROVE network experienced the highest 24–hour $PM_{2.5}$ concentrations in 2008. The year 2008 was a high fire year in California where hundreds of fires in Northern California were naturally ignited by lightning creating a heavy smoke episode during the months of June and July (Gyawali et al., 2009).

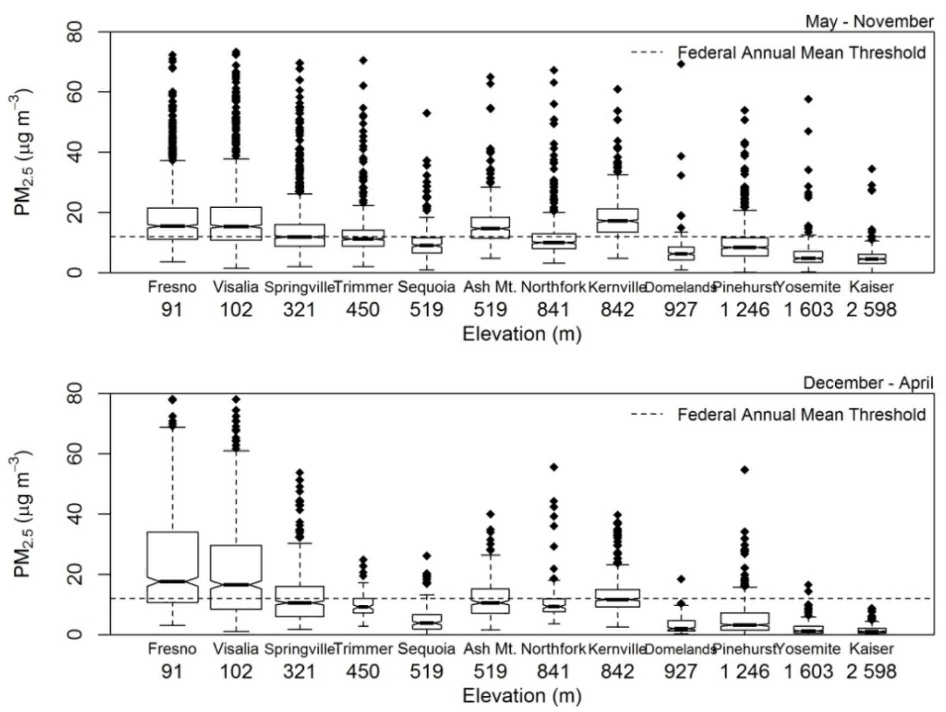


***Figure 2.*** *Daily mean $PM_{2.5}$ concentrations during fire season (May–November) and winter/spring (December–April). The dotted line represents the federal annual mean $PM_{2.5}$ threshold of 15 µg $m^{-3}$.*

The highest annual mean $PM_{2.5}$ concentrations during the study occurred at the Fresno and Visalia urban sites located in the Central Valley at elevations of 91 and 102 m respectively. At the Fresno monitoring site, annual mean $PM_{2.5}$ concentrations ranged from 18 to 22.2 µg $m^{-3}$. Annual mean ranged from 16.3 to 22.5 µg $m^{-3}$ for the Visalia monitoring site. The lowest $PM_{2.5}$ concentrations at the urban sites occurred in 2009.

USFS site elevations ranged from 321 to 1 246 m. During the study, Trimmer experienced the highest 24–hour maximum $PM_{2.5}$ concentration of 162 µg $m^{-3}$ in 2007. The second highest 24–hour maximum $PM_{2.5}$ concentration occurred in 2008 at the North Fork site with a concentration of 108.3 µg $m^{-3}$. For mid–elevation sites, the years 2007 and 2008 had the highest 24–hour maximum $PM_{2.5}$ concentrations during times of high forest fire activity.

### 3.2. $PM_{2.5}$ background in the Sierra Nevada

Our estimate of the current background $PM_{2.5}$ in the southern SNM using the method proposed by Van Dingenen et al. (2004) was 4.7±1.3 µg $m^{-3}$. This background estimate is less than half the mean $PM_{2.5}$ concentration in the western United States of approximately 11±1 µg $m^{-3}$ during the summers of 2000–2002 and the mean for the entire U.S. of approximately 13±3 µg $m^{-3}$ calculated by Tagaris et al. (2007) and similar to the European continental estimate of 4.8±2.4 µg $m^{-3}$ (Van Dingenen et al., 2004).

Differences in seasonal profiles (Figures 3 and 4) between low elevation sites (closer to large pollution sources) and high elevation sites (further from large pollution sources) along with lower annual mean and 98th percentile (Table 2 and Figures 2 and 5) at higher elevation sites further from large pollution sources support the assumption that $PM_{2.5}$ monitored at higher elevations in the SNM are less impacted by large anthropogenic pollution sources.

Local forest fire size and behavior during this study was assumed to be typical of the SNM. Specific impacts of fires and aerosols from Asia were not quantified, thus were included in the background calculation. Long–range transport of aerosols from Asia contributes to PM in the SNM. Asian aerosol deposition in the SNM primarily occurs above 500 m in elevation (VanCuren and Cahill, 2002). Deposition of Asian aerosols occur primarily from March to October and have been shown to contribute significantly to background $PM_{2.5}$ at higher elevation sites in California and Oregon (VanCuren, 2003), with Asian sources contribution peaking during the month of July (Vicars and Sickman, 2011).

### 3.3. Attainment of $PM_{2.5}$ U.S. Federal Standard

All monitoring sites above the elevation of 321 m were below the annual federal standard (Figure 2, Table 2). Whereas sites above 500 m were below the 24–hour federal standard (Figure 5, Table 2). Springville located at 321 m of elevation was above the 24–hour federal standard in 2008 and 2009 (Figure 5, Table 2). The Central Valley urban sites were above both the 24–hour and annual federal standards from 2007 to 2009. Annual and 24–hour mean $PM_{2.5}$ decreased with elevation.

The monitors at Trimmer and North Fork did not collect data during the entire year. Annual mean $PM_{2.5}$ concentrations at Trimmer and North Fork would likely be lower than what is presented in this paper if data was collected during November to April and captured the lower concentration days. The annual mean, at Trimmer and North Fork were below the annual federal standard (Table 2, Figure 2).

Most of the highest concentration days in non–urban sites were during the months of May through November (Figure 2), which is typical fire season in the SNM. Three year mean 98th percentile for $PM_{2.5}$ was below the federal standard (35 µg $m^{-3}$) for all sites above 500 m elevation (Figure 5). Overall, 98th percentile for $PM_{2.5}$ is lower at higher elevation sites (Table 2).

Fire events during these years have limited impact on meeting annual or 24–hour federal standards for concentration of $PM_{2.5}$ in the rural areas. The rural sites, closest geographically to the largest wild land fires, were consistently below the federal standards for both annual mean and 24–hour 98th percentile; even though effects from fire are expected to have the most significant impacts on $PM_{2.5}$ closer to the fire (emission source).

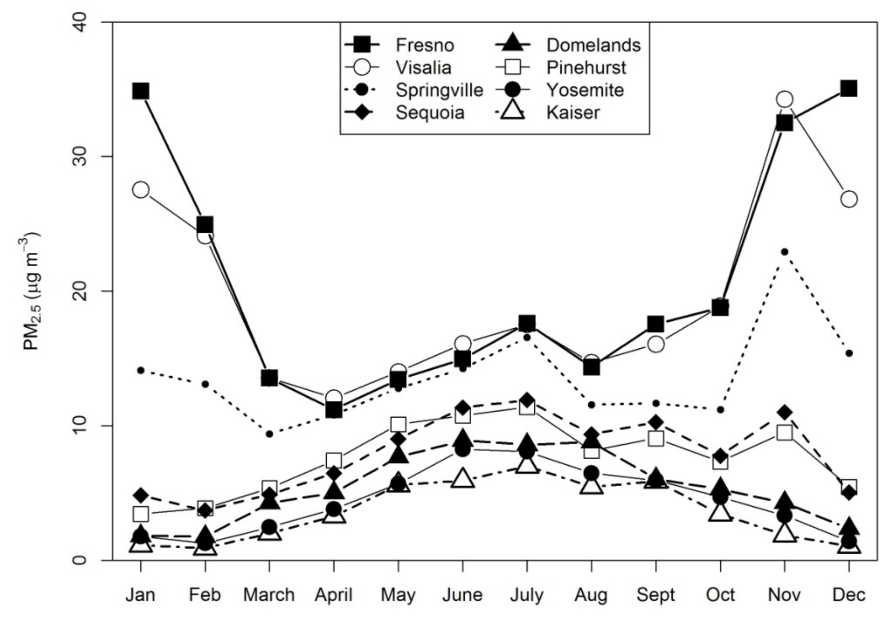


***Figure 3.*** *Monthly mean $PM_{2.5}$ concentrations at sites with full year data contrasting seasonality differences between higher and lower elevation sites.*

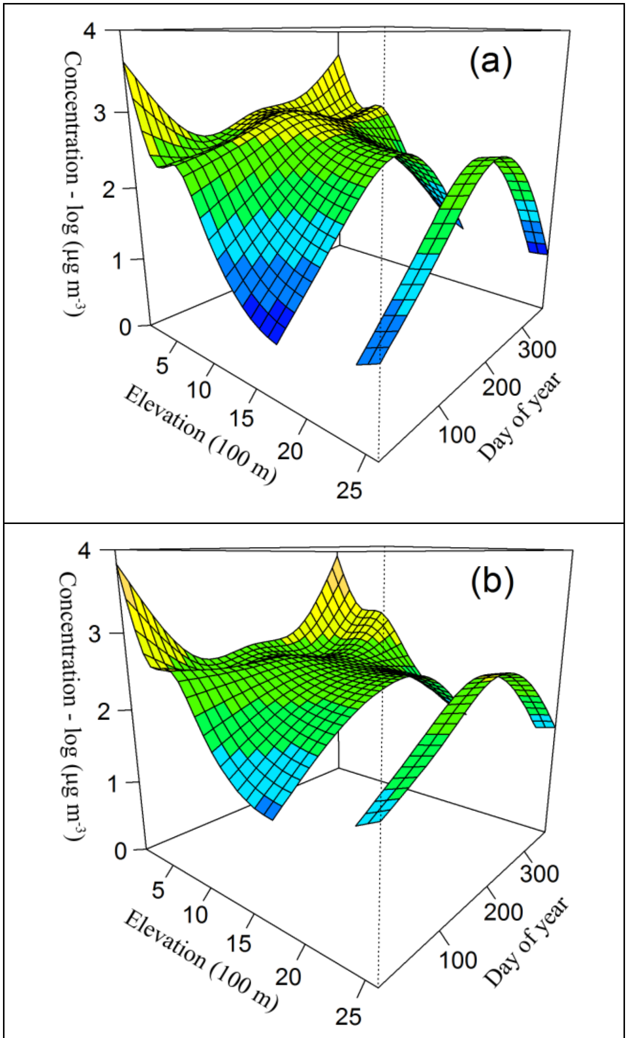


***Figure 4. (a)*** *Estimated interactive effect of elevation and day in year on the logarithm of $PM_{2.5}$.* ***(b)*** *Estimated effect after removing effects of weather (temperature, relative humidity and wind speed).*

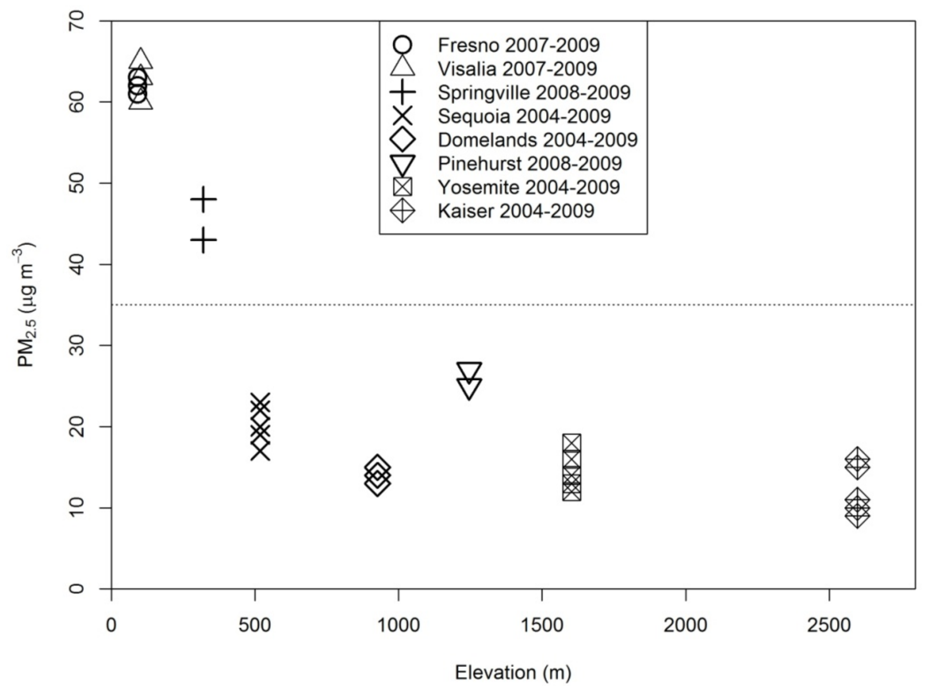


***Figure 5.*** *Three year mean 98th Percentile. Days with the highest $PM_{2.5}$ concentrations decreases as elevations increases. The dotted line represents the federal 24 hour mean $PM_{2.5}$ threshold of 35 µg $m^{-3}$.*

### 3.4. Spatial and temporal distribution of $PM_{2.5}$

Monthly mean $PM_{2.5}$ for the IMPROVE and BAM sites (Figure 3), and the results of the statistical regression (Figures 4a and 4b), show distinct seasonal differences for high elevation rural sites versus low elevation urban sites. An increase in summer $PM_{2.5}$ concentration is seen in all but the lowest elevation sites, with the relative increase in summer to winter $PM_{2.5}$ concentration increasing with elevation.

The lower elevation urban sites (Fresno and Visalia) show increased $PM_{2.5}$ during the months November to February consistent with previous studies (Chow et al., 2005; Chu and Paisie, 2006). This phenomenon is not seen at higher elevations near federally protected wilderness areas where the $PM_{2.5}$ concentrations for the winter are mostly lower than the summer (Figure 3).

The highest elevation site (Kaiser) reaches its highest $PM_{2.5}$ concentrations April through October. While at the lowest elevation sites (Fresno and Visalia) in the Central Valley a spring low (~April–May) is followed by a slight increase in $PM_{2.5}$ throughout the summer. This Central Valley low in $PM_{2.5}$ coincides with an increase in $PM_{2.5}$ above ~1 000 m elevation (Figures 3, 4a, and 4b). At higher elevation sites, winter lows in $PM_{2.5}$ increase relatively quickly in spring (~April–May), peak around mid–year, and slowly return to winter lows (Figures 3, 4a, and 4b)

Weather variables (temperature, relative humidity, and wind speed) seem to account for some of the $PM_{2.5}$ concentrations in the summer months at sites less than ~1 000 m elevation (Figure 4b). The same is not observed for the higher elevation sites. The three weather variables explain the variation of about 20% in Fresno and Visalia to 5% in the highest elevation site of Kaiser of the $PM_{2.5}$ concentrations.

Different seasonal patterns seen between higher and lower elevation sites are potentially reliant on winter inversions that set up over the Central Valley. The lower mixing height typical of the winter may slow the transport of $PM_{2.5}$ from the urban area by inhibiting mixing and venting of air masses from the Central Valley creating stagnation and an increased residence time for $PM_{2.5}$ and other pollutants (Ying and Kleeman, 2009). As the mixing height increases in the spring, $PM_{2.5}$ concentrations may lower as circulation and venting of this airshed increases. Seasonal patterns suggest that anthropogenic activities in the Central Valley dominate winter high $PM_{2.5}$ events that are primarily limited to lower elevations.

### 3.5. Policy implications of the effects of fire on $PM_{2.5}$

Fire is an integral part of SNM forest health. The past policy of fire suppression and resulting buildup of fuel, along with increasing ambient temperatures are likely contributing to increased fire size and intensity. Studies have shown that California, with significant wild land fire and a relatively high summer $PM_{2.5}$ mean, has a weak association between fires and $PM_{2.5}$ likely caused by regional anthropogenic sources obscuring the relationship with fire (Jaffe et al., 2008).

Background $PM_{2.5}$ in the SNM is confounded by local and global emissions and atmospheric transport. Daily mean $PM_{2.5}$ concentrations approximately double during June and July 2008, and coincide with satellite imagery of smoke plumes from large fires in northern California observed over the sampling sites. Urban sites at Fresno and Visalia also experienced higher $PM_{2.5}$ concentrations during this time when compared to previous years (estimated fire season effects were 3.1±1.4 µg $m^{-3}$ for Fresno and 2.0±1.4 µg $m^{-3}$ for Visalia). This suggests that large fires in Northern California in June and July 2008 affected all sites (Table 2). Considering the total area burned in California in 2008, the increase in $PM_{2.5}$ could be assumed as the historic levels of non–anthropogenic $PM_{2.5}$ from fire during a normal fire year.

To explore the relationship between fire activity and $PM_{2.5}$ concentration in the southern SNM during 2006 to 2008, total fire hectares burned are categorized into the most appropriate month of emission (Figure 6). Fire start dates, daily hectares of fire growth, and fire out and containment dates were used to determine the emission month or months for Sequoia National Forest, Sierra National Forest, Sequoia and Kings Canyon National Parks, and Yosemite National Park. The largest fires typically had daily to weekly estimates of fire size. Fire hectares burned during the years 2006 to 2008 primarily occurred between the months of June and September. The largest fire in these areas was the 15 000 ha Piute Fire (latitude 35.4192, longitude –118.4003) during July 2008. This fire was in the southern most portion of the monitoring area. The overall fire activity, using the total hectares burned in a given year as the metric, was highest in 2008 followed by 2006 and 2007 (Figure 6).

***Table 2.** Summary of data*

| Site | Yearly Mean | SD | Yearly 98th Percentile | Max | Min | 3 Year Mean | 3 Year 98th Percentile |
|---|---|---|---|---|---|---|---|
| 2009 | | | | | | | |
| Fresno | 18.0 | 12.6 | 56.0 | 78.1 | 3.1 | 20.5 [a] | 61 [a] |
| Visalia | 16.3 | 11.1 | 48.7 | 59.7 | 1.3 | 19.5 [a] | 60 [a] |
| Springville | 10.0 | 5.3 | 28.6 | | 1.5 | 13.7 | 43 [a] |
| Trimmer | 9.9 | 2.7 | 15.6 | 15.8 | 4.6 | – | – |
| Sequoia | 6.7 | 4.7 | 15.5 | 37.3 | 0.1 | 8.1 | 22 |
| North Fork | 11.4 | 3.5 | 19.8 | 29.3 | 3.9 | – | – |
| Domelands | 4.7 | 3.0 | 9.9 | 18.5 | 0.3 | 5.5 | 13 |
| Pinehurst | 6.2 | 4.5 | 17.3 | 29.8 | 0.0 | 7.5 | 25 |
| Yosemite | 4.0 | 4.1 | 14.9 | 26.6 | 0.1 | 4.5 | 18 |
| Kaiser | 3.4 | 2.5 | 9.4 | 12.2 | 0.2 | 3.9 | 16 |
| 2008 | | | | | | | |
| Fresno | 21.3 | 13.7 | 59.5 | 93.0 | 4.8 | 21.6 [a] | 62 [a] |
| Visalia | 19.6 | 14.8 | 65.4 | 88.5 | 1.1 | 20.6 [a] | 63 [a] |
| Springville | 16.2 | 11.0 | 54.9 | 67.7 | 2.0 | 14.6 | 48 [a] |
| Trimmer | 13.4 | 8.2 | 46.3 | 54.7 | 2.8 | – | – |
| Sequoia | 9.4 | 7.5 | 27.9 | 53.0 | 0.3 | 8.6 | 23 |
| North Fork | 12.2 | 10.4 | 43.3 | 108.3 | 3.2 | – | – |
| Domelands | 5.5 | 4.7 | 11.7 | 38.7 | 0.5 | 5.5 | 14 |
| Pinehurst | 9.1 | 8.1 | 34.6 | 54.7 | 0.1 | 8.0 | 27 |
| Yosemite | 5.1 | 7.8 | 27.9 | 57.6 | 0.1 | 4.6 | 18 |
| Kaiser | 4.6 | 5.3 | 24.4 | 34.5 | 0.1 | 3.8 | 15 |
| 2007 | | | | | | | |
| Fresno | 22.2 | 17.5 | 68.2 | 81.5 | 4.4 | 21.0 [a] | 63 [a] |
| Visalia | 22.5 | 15.6 | 65.0 | 73.3 | 1.3 | 20.7 [a] | 65 [a] |
| Springville | 14.8 | 9.7 | 44 | 53.8 | 1.9 | | |
| Trimmer | 14.7 | 15.9 | 47.9 | 162 | 2 | | |
| Sequoia | 8.2 | 5.2 | 21.6 | 27.1 | 0.6 | 7.9 | 19 |
| North Fork | 12.0 | 9.8 | 44.1 | 97 | 4.2 | | |
| Domelands | 6.3 | 7.7 | 18.9 | 69.3 | 0.7 | 4.5 | 15 |
| Pinehurst | 7.2 | 5.3 | 22.1 | 43.3 | 0.3 | – | – |
| Yosemite | 4.4 | 4.1 | 14.9 | 34.3 | 0.2 | 4.1 | 12 |
| Kaiser | 3.7 | 3.7 | 13.6 | 27.6 | 0.3 | 3.3 | 10 |
| 2006 | | | | | | | |
| Fresno | 21.3 | 12.9 | 57.3 | 88.1 | 3.6 | | |
| Visalia | 19.8 | 12.1 | 58.1 | 78.1 | 2.0 | | |
| Springville | 12.8 | 8.7 | 44.1 | 69.6 | 2 | | |
| Trimmer | 12.1 | 6.1 | 31.1 | 32.1 | 3.7 | | |
| Sequoia | 8.1 | 5.6 | 18.1 | 32.4 | 0.4 | 7.9 | 17 |
| North Fork | 11.4 | 4 | 20.5 | 30.8 | 5.9 | – | – |
| Domelands | 4.8 | 3.3 | 11.8 | 15 | 0.4 | 4 | 13 |
| Pinehurst | 7.8 | 5.7 | 24.4 | 34.2 | 0 | | |
| Yosemite | 4.2 | 3 | 10.1 | 12.2 | 0.2 | 4.1 | 13 |
| Kaiser | 3.1 | 2.3 | 7.6 | 8.5 | 0.2 | 3.2 | 9 |
| 2005 | | | | | | | |
| Fresno | 19.7 | 15.0 | 64.6 | 82.2 | 2.1 | | |
| Visalia | 19.9 | 15.3 | 73.3 | 95.6 | 1.5 | | |
| Sequoia | 7.5 | 4.7 | 17.3 | 25.7 | 0.3 | 8.4 | 20 |
| Domelands | 2.6 | 3.7 | 14.9 | 17.7 | 0.5 | 4.2 | 13 |
| Yosemite | 3.8 | 2.8 | 10.3 | 11.4 | 0.1 | 4.1 | 14 |
| Kaiser | 3.1 | 2.7 | 10.1 | 11.2 | 0 | 3.2 | 9 |
| 2004 | | | | | | | |
| Sequoia | 8.1 | 5.4 | 16.5 | 39.7 | 0.7 | 9.1 | 23 |
| Domelands | 4.8 | 3.1 | 11.2 | 12.4 | 0.2 | 5.3 | 14 |
| Yosemite | 4.2 | 4.1 | 17.2 | 26.5 | 0 | 4.5 | 16 |
| Kaiser | 3.4 | 2.8 | 8.6 | 18.6 | 0.1 | 3.6 | 11 |
| 2003 | | | | | | | |
| Sequoia | 9.5 | 6.6 | 25.8 | 29.8 | 0.4 | | |
| Domelands | 5.3 | 3.5 | 13.8 | 15.2 | 0.3 | | |
| Yosemite | 4.3 | 4.4 | 14 | 35.8 | 0.3 | | |
| Kaiser | 3.2 | 2.5 | 8.6 | 9.2 | 0.1 | | |
| 2002 | | | | | | | |
| Sequoia | 9.7 | 6.9 | 27 | 29.2 | 0.6 | | |
| Domelands | 5.9 | 4.7 | 17.1 | 25.6 | 0.6 | | |
| Yosemite | 5.1 | 4.3 | 16.4 | 19.5 | 0.3 | | |
| Kaiser | 4.4 | 4 | 16.1 | 18.2 | 0.2 | | |

*[a] Values in exceedance of federal standards*
*Sites are arranged yearly in order of increasing elevation*

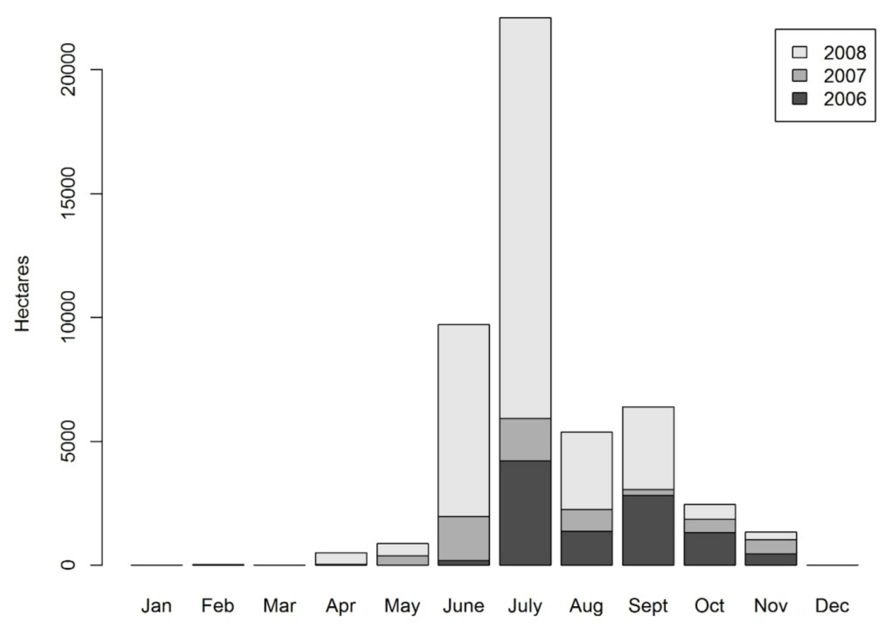


***Figure 6.*** *Monthly hectares burned on federal lands in the southern Sierra Nevada (2006 to 2008) with wild land fire activity primarily occurring May through November.*

Localized impacts to $PM_{2.5}$ from fire can be extreme especially for short duration events, but fire activity as seen during this study (2002–2009) did not caused rural and undeveloped sites to exceed mean annual and 98$^{th}$ percentile federal standards. More remote monitoring sites, typically closer to the larger fires, had the lowest $PM_{2.5}$ mean annual and mean 98$^{th}$ percentile. This implies that $PM_{2.5}$ impacts from natural ignition fires burning at historic intensities and areas do not significantly contribute to the violation of the current federal standards in many instances.

It is likely that anthropogenic emissions are the primary driver of exceedances of federal standards for $PM_{2.5}$ in the Central Valley because the vast majority of high $PM_{2.5}$ concentration days occur in winter and not in the typical fire season of the SNM (Figure 3). Although $PM_{2.5}$ is contributed from fire and adds to an area already exceeding federal standards, it is likely that fires are not the major driver of exceedances of federal standards during the years of this study.

Sites located closer to the largest burn areas did not typically have the highest concentrations of $PM_{2.5}$. This suggests that $PM_{2.5}$ from fire is being confounded by other sources. The gradual increasing trend in $PM_{2.5}$ concentration starting in the month of May at the highest elevation sites (see Figure 3) when fire is the least active (see Figure 6) suggest a non–fire source of $PM_{2.5}$. $PM_{2.5}$ transported from the Central Valley and Asia is likely contributor at this time. A subsequent peak in $PM_{2.5}$ during the high fire activity months of June through September is not seen at the highest elevation sites where concentrations remain close to pre–fire May $PM_{2.5}$ concentrations. This also suggests that overall impacts from fire are significant in a more localized setting near the fire. Over the years of this study, local fires did not cause annual or 24–hour $PM_{2.5}$ federal standard violations at these sites in the SNM. Contributions from fire can be assumed to become more significant as fire size increases, and distance to the fire decreases.

It is unknown what effect fire suppression has had on current background concentrations of $PM_{2.5}$ in the SNM. Summer enhancement in mean $PM_{2.5}$ in California by fire is estimated to be 1.21 $\mu g\ m^{-3}$ by correlating IMPROVE $PM_{2.5}$ and organic carbon concentrations to estimations of area burned and fire emissions (Jaffe et al., 2008). $PM_{2.5}$ at rural sites in this study shows a low summer enhancement of $PM_{2.5}$ that is currently below annual federal standards. Current and historic fire management practices in the Sierra Nevada should be considered when attempting to understand $PM_{2.5}$ fluxes at the interface between developed and natural areas. Background $PM_{2.5}$ is likely lowest over multiple years when wild land fire is allowed a role in the SNM ecosystem. A better understanding of urban transport, and continued yearly monitoring in rural locations are needed to understand the implications.

## 4. Conclusions

Information on $PM_{2.5}$ background concentrations in the southern SNM presented in this paper help defines the regional distribution of $PM_{2.5}$. The calculated current background $PM_{2.5}$ concentration in the southern SNM is 4.7±1.3 $\mu g\ m^{-3}$. At higher elevation undeveloped areas of the southern SNM, daily $PM_{2.5}$ concentrations were typically less than 15 $\mu g\ m^{-3}$ in the summer and less than 5 $\mu g\ m^{-3}$ in the winter. At elevations above ~500 m in the southern SNM, $PM_{2.5}$ concentrations were under the federal standards for annual mean (15 $\mu g\ m^{-3}$) and 98$^{th}$ percentile (35 $\mu g\ m^{-3}$). At elevations below ~500 m in the southern SNM, concentrations frequently exceed the 24–hour 98$^{th}$ percentile standard. At foothill sites (~250–500 m), the highest recorded $PM_{2.5}$ concentrations of the year are occurring in November.

Over the years of this study, local fires did not cause annual federal standard violations in the southern SNM sites due to the low $PM_{2.5}$ levels found in this area. Late summer to early fall $PM_{2.5}$ concentrations at higher elevation sites located in natural areas are lower than what would be expected if $PM_{2.5}$ concentrations were being driven primarily by fire. Violation of federal standards does not correspond well with high hectare fire months, suggesting that current regulation of fire emissions is not the most effective use of regulatory authority. Regional impacts to $PM_{2.5}$ from fire are within current federal standards.

Localized impacts from fire can have significant detrimental effects to public health. Further research is needed to understand variation in $PM_{2.5}$ caused by fire. Local condition of the vegetation, fire size and intensity, location, topography, wind speed, and wind direction are likely the primary determinants of smoke impact on public health. Quantifying $PM_{2.5}$ as the plume ages and understanding regional air flow will likely better define fire contributions to $PM_{2.5}$. Specific case studies are needed to understand fire impacts in the rural and undeveloped western slope of the SNM.

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