UC Merced
Public Health Capstone Projects

Title
Analyzing the effects of the 2015 Rough Fire in the San Joaquin Valley and in Sierra Nevada, California

Permalink
https://escholarship.org/uc/item/23m55565

Author
Veloz, David

Publication Date
2018-04-01

eScholarship.org Powered by the California Digital Library
University of California

Analyzing the effects of the 2015 Rough Fire in the San Joaquin Valley and in Sierra Nevada, California

David Veloz*

University of California, Merced

dveloz@ucmerced.edu

April 26, 2017

Abstract

Objective: Evaluate the effects of the Rough Fire on air quality specifically particles <2.5μm in diameter ($PM_{2.5}$) concentrations in communities of San Joaquin Valley and Sierra Nevada.

Background: Smoke from severe wildfires exposes populations to increased levels of air contaminants such as, particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$). The Rough Fire was the third biggest fire in the California Sierra Nevada it burned in parts of the Sierra National Forest and Sequoia National Forest. Between July 31 and November 5 2015, the Rough Fire burned over 150,000 acres.

Methods: We examined the air-quality impacts by conducting a statistical and spatial analysis of $PM_{2.5}$ concentration data collected by temporary and permanent air-monitoring sites in the San Joaquin Valley and nearby communities in the Sierra Nevada. The equipment used to measure air quality consisted of BAMs and EBAMs. Beta attenuation monitoring (BAM) is a widely used air monitoring technique employing the absorption of beta radiation by solid particles extracted from air flow. This technique allows for the detection of PM_{10} and $PM_{2.5}$ which are monitored as standards by most air pollution regulatory agencies. Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) was used to produce forward trajectories and to confirm questionable days.

Results: From the data collected $PM_{2.5}$ concentrations increased at Porterville and Visalia during the fire when compared with pre-fire concentrations for the Central Valley. The Sierra Nevada was most impacted the fire compared to pre-fire periods having an increased amount of Unhealthy and Very Unhealthy days at all locations.

Conclusion: Our results indicated the Rough Fire impacted air quality in most of Sierra Nevada sites. The Central Valley was not as impacted as the Sierra Nevada sites and foothill communities.

---

*

1. Introduction

California is one of the most biologically and climatically diverse locations in the world. The highest air pollutant emissions from forest fires in the United States, including prescribed fire, occur in the Pacific coastal states which includes California (Liu, 2004). The magnitudes of these wildfires will continue to increase in the western part of the United States (Liu, 2004) and there exist a need to analyze their smoke impacts. There are not many studies and analyzing wildfire smoke impacts especially studies that conduct an exposure assessments. This case study of the Rough Fire will contribute to current literature providing a new case study available to public health departments who evaluate smoke exposure in California. Research shows that emissions from large wildfires analyzed using satellite data document air quality impacts (Langmann et al., 2009) with smoke toxicity (Wegesser et al.,2009). Previous studies demonstrate the negative impacts of large wildfires on human health creating concern for exposure and public health (Tham et al., 2009). This study will evaluate the effects of the Rough Fire on air quality specifically particles <2.5µm in diameter ($PM_{2.5}$) in communities of San Joaquin Valley and Sierra Nevada Mountains.

2. Forest Fires impacts on health

Although there are known health impacts caused by wildfires there are very few health studies conducted in the United States. It is important to recognize that air pollutants emitted by wildfires have impacts on human health since it might impact vulnerable populations, including the old and the young and people with compromised immune systems. This was proven in a study conducted in Southern California where the strongest effect on asthma hospitalizations related to particulate matter less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$) during a wildfire was found for people ages 65-99 and the second strongest association was found for children ages 0-4 years of age (Delfino et al., 2009).

Other studies in the United States have found significant associations between exposure to wildfire smoke and increased self-reported respiratory symptoms (Kunzli et al., 2006; Mirabelli et al., 2009), increased respiratory physician visits (Lee et al., 2009), respiratory Emergency Department (ED) visits (Rappold et al., 2011), and respiratory hospitalizations (Delfino et al., 2009). Lee et al. (2009) and Mirabelli et al., (2009) reported that adults with pre-existing respiratory conditions or weakness (i.e. small air way size) were more likely to seek care or have additional symptoms after wildfire exposure than individuals without respiratory conditions.

Studies have documented significantly increased ED visits (Duclos et al., 1990; Rappold et al., 2011) and hospitalizations (Delfino et al., 2009) for asthma in association with wildfire smoke exposure. Vora et al. (2011) demonstrated no significant changes in acute lung function related to $PM_{2.5}$ from wildfires among asthmatics. This may be because people with an established diagnosis of asthma are better at self-management of symptoms such as exposure avoidance and increased use of rescue medication in response to elevated levels of smoke (Vora et al., 2011). People with asthma reported elevated levels of rescue medication usage during a wildfire in Southern California (Vora et al., 2011; Kunzli et al., 2006). Kunzli et al., (2006) reported that children without pre-existing asthmatic conditions had a greater increase in respiratory symptoms under exposure than did other children with pre-existing asthmatic conditions. The authors suggested that children with pre-existing asthmatic conditions tended to be on medication and have better access to care and as a result there was a smaller increase in symptoms when exposed to wildfire smoke.

Two studies, one conducted in California and the other in North Carolina, found association in ED visits for COPD related to wildfire smoke (Duclos et al., 1990; Rappold et al., 2011). Rappold et al. (2011) found an association with elevated risk of pneumonia and acute bronchitis in counties exposed to smoke from peat fires. Duclos et al. (1990) found a higher number of hospitalizations for bronchitis and pneumonia to be associated with PM_{10} from wildfire. A study in southern California found that $PM_{2.5}$ during a wildfire was associated with increased hospital admissions for exacerbations of COPD (Delfino et al., 2009).

The evidence for impacts of wildfire smoke exposure to respiratory infections in general is inconsistent. Duclos et al. (1990) found an association of ED visits for respiratory infections during major wildfires in California. This is contrary to Rappold et al. (2011) who found no association between ED visits for upper respiratory infections in smoke-affected counties during a peat fire in North Carolina.

Few studies have documented evidence of adverse effects for some specific cardiovascular diseases associated with exposure to wildfire smoke. One study in North Carolina have shown significant increases for ED visits for congestive heart failure associated with wildfire smoke exposure (measured using satellite Atmospheric Optical Depth measurements) during a peat fire (Rappold et al., 2011). However, when diseases were grouped together by age and sex, the association between cardiovascular disease and smoke exposure was not found (Rappold et al., 2011). Another study in Southern California found no association between hospitalizations for congestive heart failure and $PM_{2.5}$ during a wildfire (Delfino et al., 2009). Delfino et al. (2009) also found no association between $PM_{2.5}$ from wildfire and hospital admissions for cardiac dysrhythmias; and no association to hospital admissions for ischaemic heart disease (Delfino et al., 2009). In a study conducted in Northern California near the Hoopa Valley Indian Reservation, particulate matter less than 10 microns in aerodynamic diameter (PM_{10}) was a significant predictor of clinic visits for coronary artery disease (also known as heart disease) in a Native American reservation during a wildfire event (Lee et al., 2009). More work needs to be conducted in this area, hence existent studies are inconsistent and few. Thus, the association between cardiovascular outcomes and exposure to wildfire smoke is unclear at this point.

A study of a population seeking emergency relief services after a wildfire found that having difficulty breathing because of smoke or ashes was significantly associated with the probability of Post-Traumatic Stress Disorder (PTSD) or major depression three months after the fire occurred (Marshall et al., 2007). Duclos et al. (1990) found no increase in mental health hospitalizations during the 1987 California fires.

Very few studies have investigated an association for exposure to smoke from wildfires and poor birth outcomes, which prevents any conclusive associations. Holstius et al. (2012) found a small but significant decline in birth weight for babies that gestated during the 2003 southern California wildfires in comparison to babies from the same region who were born before or more than nine months after the fires. The effects were significant for wildfire exposure during the second and third trimester of pregnancy however not during the first trimester. Since this study did not quantify air pollution exposures for the pregnant women in the study, it cannot be determined if the observed effect was due to smoke exposure to smoke from wildfires or the stress of living in an area that was experiencing a wildfire.

More epidemiological research that examines the health effects of Forest Fires is needed. Typical studies have only looked at short term fire incidents, thus lack statistical power. Studies conducted for longer periods of time are required to confirm the inconsistencies and determine groups that are most affected by smoke. Additionally, the health impacts and relative risk from prescribed, managed, and wildfire (mega-fire) smoke must be understood for forest management to effectively produce the best health outcomes.

3. Air quality impacts of Forest Fires

Air pollutants from a wildland fire are dependent on fuels, can be complex near the flame front, and interact with anthropogenic sources (Alves et al., 2010; Hosseini et al., 2013; Statheropoulos and Karma, 2007). Smoke emissions can be more toxic than urban emission during large high intensity fires (Wegesser et al., 2009) however, there is limited understanding of the causal factors of smoke composition including fuels, fire size and intensity, and chemicals introduced when agricultural areas and houses burn. The same fire can produce large variability in smoke composition even at the same monitoring site (Wigder et al., 2013). The variability of plume chemistry during transport along with varying dispersal conditions makes understanding individual plume toxicity challenging. This is a reason why it is difficult to determine the net effects of forest fires on human health (Fowler, 2003). Wildfire smoke contains many air pollutants of concern for public health, such as carbon monoxide (CO), nitrogen dioxide (NO2), ozone (O3), particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), other hydrocarbons, volatile organic compounds (VOCs), and free radicals (Naeher et al., 2007). The PM emitted from fires is most elevated compared to background levels (Naeher et al., 2007), and is one of the best ways to assess smoke exposure (Naeher et al., 2007; Vedal and Dutton, 2006). Therefore, this section will focus on $PM_{2.5}$ to consider wildland fire smoke exposure.

Particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) is a large portion of emissions from wildland fire (Clinton et al., 2006) and is easily transported over long distance (Bein et al., 2008; Dokas et al., 2007) having a large impact on air quality

(Fowler, 2003; Langmann et al., 2009). Particulate matter is the most frequently studied pollutants when studying wildland fire smoke impacts in part because it can be 10 times higher than non-fire background concentrations (Liu et al., 2015) and it is also a great tracer for smoke. Smoke transport can easily be detected by remote sensing (Hoff and Christopher, 2009). Quantifying ground level concentrations of $PM_{2.5}$ using remote sensing is difficult (Toth et al., 2014; Yao and Henderson, 2013). Remote sensing and modeling can increase remote sensing estimates of ground level $PM_{2.5}$ (Li et al., 2015; Reid et al., 2015; Yao et al., 2013). Remote sensing can be used to indicate exceedances from the normal of ground level $PM_{2.5}$ concentrations due to smoke in the Sierra Nevada but ground based monitors are necessary for accurate quantification (Preisler et al., 2015).

4. Rough Fire

Large areas of land in the Sierra Nevada have been set aside for environmental conservation and most of this land is adjacent to the San Joaquin Valley. The occurrence of large wildfires (megafires) has been increasing in California. Thirteen of the 20 largest California wildfires in recorded history (2015 as the last year) have occurred since 2002 (Table 1). The combination of fire prone ecosystems and large amounts of anthropogenic emissions in the valley create a setting where there exists a need to understand the implications of climate change, and human health impacts from forest fires in an already polluted environment.

Smoke from these wildfires often cause the largest air quality impacts of the year in the towns and cities closer and downwind of the fire. This is particularly true for the more rural areas further away from the major anthropogenic emission sources and typically better air quality. Wildfires such as the Rough Fire that occurred near the San Joaquin Valley emit air pollutants many of which are a concern for public health. Between July 31 and November 5 2015 the Rough Fire burned over 150,000 acres. The Rough Fire is the third biggest fire in the California Sierra Nevada it burned in parts of the Sierra National Forest and Sequoia National Forest. It is hypothesized that the Rough Fire affected air quality in locations surrounding the fire. The focus of this study is to evaluate the effects of the Rough Fire on $PM_{2.5}$. Below is a satellite image of the Rough Fire location that played a role in the hypothesis in regards to the impact it had on air quality(Figure 1).

Table 1. Twenty largest California suppression fires since 1932.

Fire name (cause)	Date	County	Acres	Structures	Deaths
1. Cedar (human)	Oct-03	San Diego	273,246	2820	15
2. Rush (lightning)	Aug-12	Lassen	271,911	0	0
3. Rim (human)	Aug-13	Tuolumne	257,314	112	0
4. Zaca (human)	Jul-07	Santa Barbara	240,207	1	0
5. Matilija (undetermined)	Sep-32	Ventura	220,000	0	0
6. Witch (powerlines)	Oct-07	San Diego	197,990	1650	2
7. Kamath theater complex (lightning)	Jun-08	Siskiyou	192,038	0	2
8. Marble cone (lightning)	Jul-77	Monterey	177,866	0	0
9. Laguna (powerlines)	Sep-70	San Diego	175,425	382	5
10. Basin complex (lightning)	Jun-08	Monterey	162,818	58	0
11. Day fire (human)	Sep-06	Ventura	162,702	11	0
12. Station fire (human)	Aug-09	Los Angeles	160,557	209	2
13. Rough (lighting)	Jul-15	Fresno	151,623	4	0
14. McNally (human)	Jul-02	Tulare	150,696	17	0
15. Stanislaus complex (lightning)	Aug-87	Tuolumne	145,980	28	1
16. Big bar complex (lightning)	Aug-99	Trinity	140,948	0	0
17. Happy Camp complex (lightning)	Aug-14	Siskiyou	134,056	6	0
18. Campbell complex	Aug-90	Tehama	125,892	27	0
19. Wheeler (Arson)	Jul-85	Ventura	118,000	26	0
20. Simi (under investigation)	Oct-03	Ventura	108,204	300	0

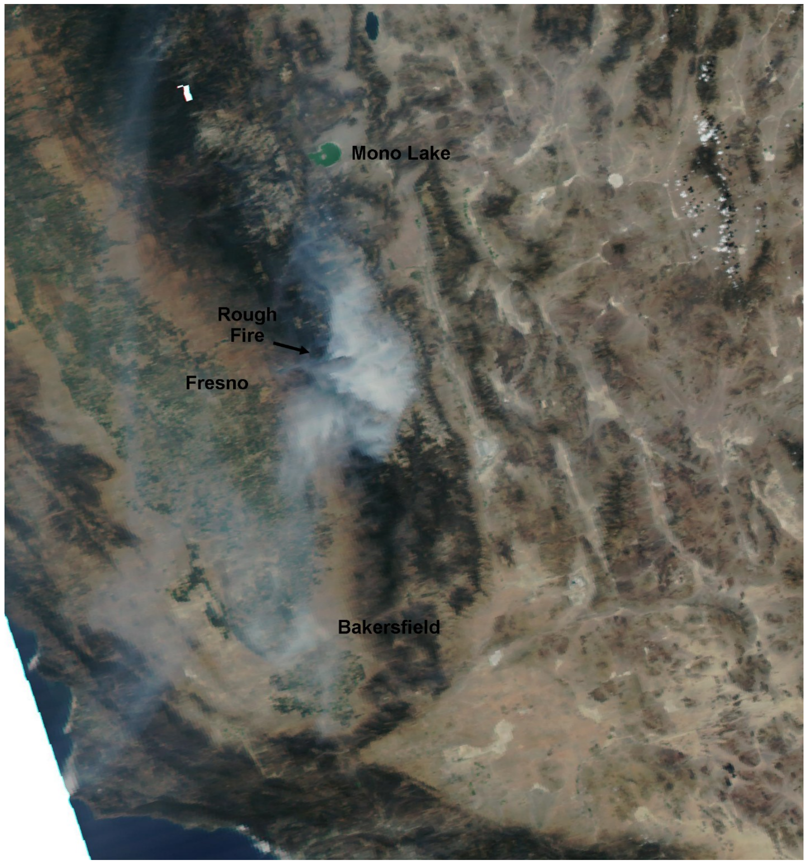

Figure 1.Modis satellite image of the Rough fire August 31, 2015.

5. Methods

5.1 Data collection

Particulate matter ($PM_{2.5}$) data was compiled from sites in the San Joaquin Valley and in the Sierra Nevada during the Rough Fire to assess smoke exposure to human health. The site locations used in this assessment consisted of Pinehurst, Sequoia Kings Canyon, Cedar Grove, Dunlap, Grant Grove, Hume Lake, Lodgepole, Monocito, Wishon (Central Sierra), Springville, Kernville, Camp Nelson (South Sierra), Bishop, Devils Postpile, Lone Pine (East), Fresno, Clovis, Madera, Merced(Central Valley North), Bakersfield, Hanford, Lebec, Porterville, Visalia (Central Valley South). Air quality data available was obtained from the California Air Resource Board (CARB) network (see https://www.arb.ca.gov/aqmis2/aqdselect.php, accessed 3 January 2017), Sequoia National Park (SNP) and the US Forest Service (USFS). Sites were selected based on air quality data availability and likelihood of site being impacted by the fire.

The CARB network consists of 9 sites mostly located in urban locations in Fresno, Kern, and Tulare Counties except for Kernville which is located in a smaller rural location in Kern County. Data from the Great Basin Unified Air Pollution Control District (GBUAPCD) was collected from three sites located east of the southern Sierra Nevada. The data from the USFS came from a monitoring station set up at the Kernville Work Center. The Kernville Work Center is located in the Kern River drainage south of the fire and was the closest site to the fire. Particulate matter mass concentrations in the CARB was collected by EBAMs. The EBAMs use a vacuum pump to draw a sample of ambient air and deposits particles onto the filter paper. A carbon-14 source emits b particles that pass through the tape and are counted by a detector. To determine the particulate mass, a b count is taken before and after the sample is taken. The air flow measured is used to calculate the concentration. $PM_{2.5}$ in the USFS network was collected as a 1-h average every day.

Location is an important variable in this exposure assessment since it is essential to know what areas were most affected by the increased levels of particulate matter caused by the Rough Fire. Some sites are temporary sites that do not collect data year round due to equipment being installed during the wildfire. Temporary sites used were Camp Nelson, Devil's Post Pile, Dunlap, Hume Lake, Kernville, Lodgepole, Monocito, Pinhurt, Prather, Springville, and Wishon.

5.2 Data measures

Using the Air Quality Index (AQI) the air quality was categorized for every day before the fire and after the fire day for $PM_{2.5}$. Daily averages of particulate matter with aerodynamic diameter ≤ 2.5 µm ($PM_{2.5}$) concentration data were collected by temporary and permanent air-monitoring sites in the San Joaquin Valley and nearby communities in the Sierra Nevada. These concentrations were categorized into good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous. These measurement categories are set by the EPA and listed in the Air Quality Index (AQI).

Good- 0-50 It is a great day to be active outside. The air quality is considered satisfactory and air pollution possess little or no risk (Environmental Protection Agency, 2014).

Moderate- 51-100 Unusually sensitive people: Consider reducing prolonged or heavy exertion and watch for symptoms such as coughing or shortness of breath since these are signs to take it easier. Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution (EPA, 2014).

Unhealthy for sensitive- 101-150 Sensitive groups: Reduce prolonged or heavy exertion. It's okay to be active outside, but take more breaks and do less intense activities. Watch for symptoms such as coughing or shortness of breath. People with asthma should follow their asthma action plans and keep quick relief medicine handy. This is because members of sensitive groups may experience health effects however, general public is not likely to be affected (EPA, 2014).

Unhealthy 151-200 -Sensitive groups: Avoid prolonged or heavy exertion. Move activities indoors or reschedule to a time when the air quality is better. Everyone else: Reduce prolonged or heavy exertion. Take more breaks during all outdoor activities. Everyone may begin to experience health effect however members of sensitive groups may experience more serious health effects (EPA, 2014).

Very Unhealthy-201-300 Sensitive groups: Avoid all physical activity outdoors. Move activities indoors or reschedule to a time when air quality is better. Everyone else: Avoid prolonged or heavy exertion. Consider moving activities indoors or rescheduling to a time when air quality is better. This is because everyone may experience more serious health effects (EPA, 2014).

Hazardous- 301-500 Everyone: Avoid all physical activity outdoors. Sensitive groups: Remain indoors and keep activity levels low. Follow tips for keeping particle levels low indoors. This is because the entire population is more likely to be affected (EPA, 2014).

5.3 Data calculations

This current ongoing project is ultimately an exposure assessment that will contribute to current literature available to local public health departments. Public health departments utilize these exposure assessments when making decisions on informing surrounding communities on how and when the public should avoid exposure depending the effects of the fire. As the size and intensity of the fire increase the pollution is also expected to increase however, we cannot compare to previous fires since there exists other effects that influence the size and intensity of the fire such as wind patterns and terrain. Therefore we utilized available data to obtain descriptive statistics such as how many air quality violations of federal and state standards occurred prior to and after the Rough Fire. Also how many good, moderate, unhealthy for sensitive people, unhealthy, very unhealthy, and hazardous air quality days occurred during the pre and post fire and do a comparison. With descriptive statistics from the data we determined counties or foothill communities were most impacted with the fire. The methods implemented followed those that previous exposure assessments have done in the past to contribute to current research on the impacts that wildfires have on air quality. The counties selected were not selected randomly. By Looking at satellite images of smoke plumes and likelihood of impact sites in this case study were selected.

Running a linear regression for this project would not be appropriate. This is due to the issues that arise when analyzing particulate matter concentrations as the duration of the fire increases without having data on other sources of particulate matter pollution such as $PM_{2.5}$ from agriculture and vehicle emissions. Without data on other pollution contribution sources, adding other variables to the equation would essentially be impossible.

Upper winds during the time of year of the study were typically from the west and generally moved smoke that was upward to the east. Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) forward trajectories (NOAA Air Resources Laboratory, http://ready.arl.noaa.gov/HYSPLIT.php) was used to confirm questionable days. Questionable days were days that demonstrated a slight increase in $PM_{2.5}$ but were not confirmed to have been caused the fire. Therefore HYPSPLIT was used to verify or deny when air parcel was heading towards the impacted location (Figure 2)

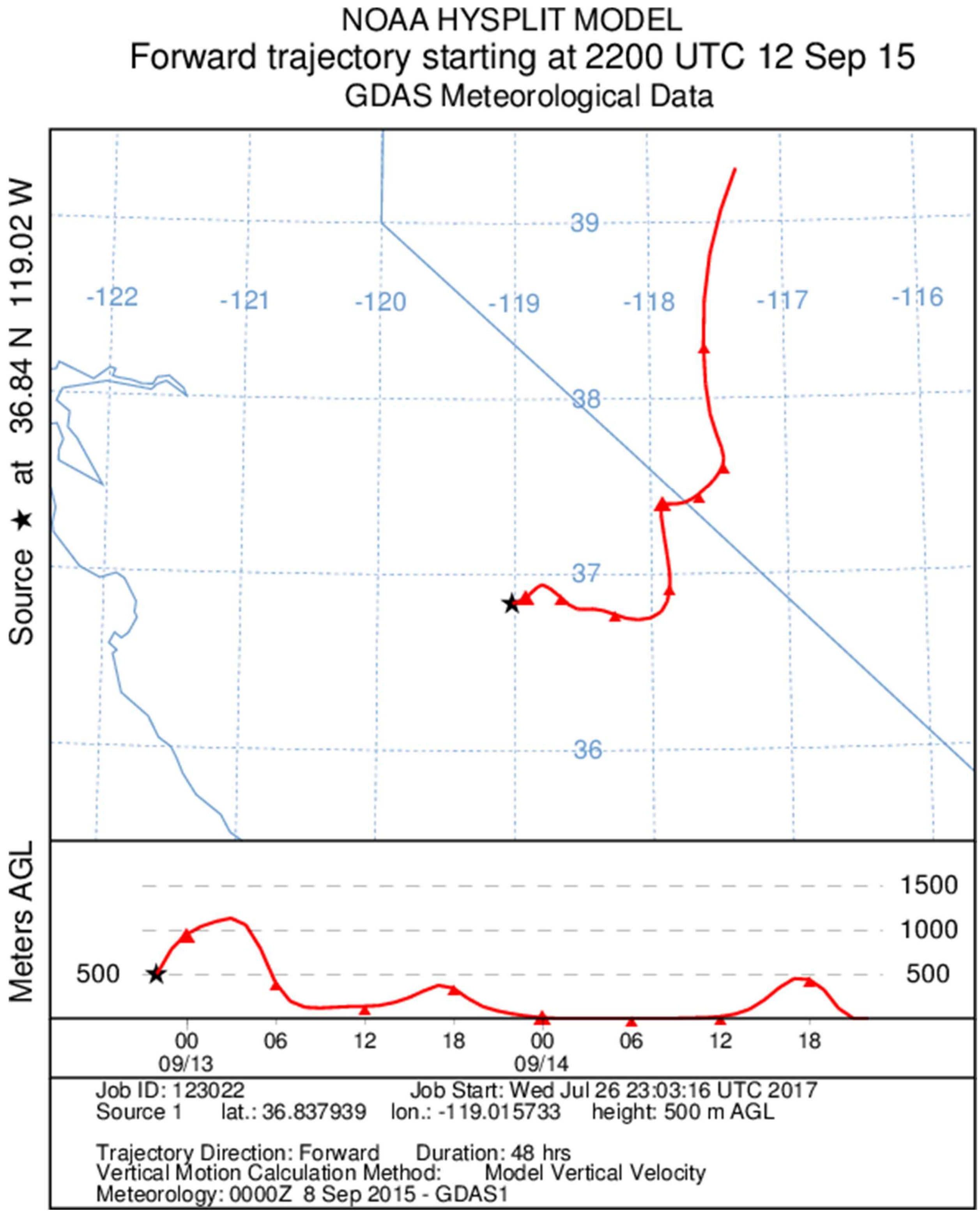

Figure 2.Forward Trajectory image of the Rough fire September 15, 2015.

6. Findings

6.1 Summary of $PM_{2.5}$ Air Quality

The Summary of mean, range, and standard deviation of $PM_{2.5}$ (Particulate Matter smaller than 2.5 µm) 24 hour average concentrations before and during the fire are explained below for Table 2. Without the fire emissions, $PM_{2.5}$ 24-hour mean concentrations of all sites were approximately 6 µm to 13 µm. When evaluating The Northern Sites of the Sierra Nevada Prior to the fire $PM_{2.5}$ 24-hour averages were 7-13μgm^{-3} . However, when the fire started the PM2.5 24-hour averages were 15-22 μgm^{-3} showing a slight increase.

For the Central Sierra Nevada sites the only locations that were monitoring air quality prior to the fire were Pinehurst and Sequoia Kings Canyon. For the remaining Central Sierra Nevada sites there is no previous air quality data since monitoring equipment was installed upon the onset of the fire. Comparing the data available prior to the fire in the Central Sierra Nevada sites, the $PM_{2.5}$ 24-hour average was 8 μgm^{-3} in both Pinehurst and Sequoia Kings Canyon. After the fire started the 24-hour mean increased to 18 μgm^{-3} in Pinehurst and 14 μgm^{-3} in Sequoia Kings Canyon.

When evaluating the southern sites of the Sierra Nevada there was air quality data available for 2 out of the 3 sites prior to the fire. This is due to equipment being installed on the third site at the start of the fire. Prior to the fire in the Southern Sierra Nevada sites the $PM_{2.5}$ 24-hour average was 10 μgm^{-3} in both Springville and Kernville. During the fire the 24-hour mean was 10 μgm^{-3} in Springville and 11 μgm^{-3} in Kernville. Camp Nelson the third site which is north of the Kernville had a $PM_{2.5}$ 24-hour average of 13 μgm^{-3}. Comparing to the Previous PM2.5 24-hour averages in the southern Sierra Nevada little to no impact was observed.

When Analyzing the Eastern Sierra Nevada sites prior to the fire Bishop had a $PM_{2.5}$ 24-hour average of 2 μgm^{-3}, Devils Postpile had a $PM_{2.5}$ 24-hour average of 12 μgm^{-3}, and Lone Pine had a $PM_{2.5}$ 24-hour average of 8 $\mu g m^{-3}$. Bishop's $PM_{2.5}$ concentration was the only site in the Eastern Sierra Nevada sites that indicated statistically significant differences between pre-fire and during-fire concentrations.

When evaluating the sites in the Central Valley the Northern sites consisted of Fresno, Clovis, Madera and Merced. Prior to the fire Fresno had a $PM_{2.5}$ 24-hour concentration of 8 $\mu g m^{-3}$, Clovis a $PM_{2.5}$ 24-hour average of 13 $\mu g m^{-3}$, Madera a $PM_{2.5}$ 24-hour average of 11 $\mu g m^{-3}$, and Merced had a $PM_{2.5}$ 24-hour average of 9 $\mu g m^{-3}$. During the fire Fresno had a $PM_{2.5}$ 24-hour concentration of 11 $\mu g m^{-3}$, Clovis a $PM_{2.5}$ 24-hour average of 15 $\mu g m^{-3}$, Madera a $PM_{2.5}$ 24-hour average of 11 $\mu g m^{-3}$, and Merced had a $PM_{2.5}$ 24-hour average of 11 $\mu g m^{-3}$. All the Northern Central Valley sites indicated statistically significant differences between pre-fire and during-fire, concentrations except Madera. The Southern Central Valley sites consisted of Bakersfield, Hanford, Lebec, Porterville, and Visalia. Prior to the fire Bakersfield had a $PM_{2.5}$ 24-hour concentration of 10 $\mu g m^{-3}$, Hanford a $PM_{2.5}$ 24-hour average of 9 $\mu g m^{-3}$, Lebec a $PM_{2.5}$ 24-hour average of 7 $\mu g m^{-3}$, Porterville had a $PM_{2.5}$ 24-hour average of 7 $\mu g m^{-3}$, and Visalia had a $PM_{2.5}$ 24-hour average of 9 $\mu g m^{-3}$. During the fire Bakersfield had a $PM_{2.5}$ 24-hour concentration of 10 $\mu g m^{-3}$, Hanford a $PM_{2.5}$ 24-hour average of 9 $\mu g m^{-3}$, Lebec a $PM_{2.5}$ 24-hour average of 7 $\mu g m^{-3}$, Porterville had a $PM_{2.5}$ 24-hour average of 7 $\mu g m^{-3}$, and Visalia had a $PM_{2.5}$ 24-hour average of 9 $\mu g m^{-3}$.

Table 2. Summary of mean, range and standard deviation of $PM_{2.5}$ (particulate matter smaller than 2.5 µm in diameter) 24-h average concentrations before and during the fire

Station	Before Rough Fire					During Rough Fire				
	Days	$PM_{2.5}$ Concentration				Days	$PM_{2.5}$ Concentration			
		Mean	SD	Min	Max		Mean	SD	Min	Max
Sierra Nevada (North)										
Prather	1	9	.	9	9	94	15	14	4	98
North Fork	42	13	11	6	51	92	16	13	4	65
Yosemite	61	**7**	3	3	16	76	**15**	24	2	165
Trimmer	-	-	-	-	-	62	22	18	4	89
Sierra Nevada (Central)										
Pinehurst	61	**8**	2	4	15	81	**18**	16	1	64
Sequoia Kings Canyon	59	**8**	3	3	16	66	**14**	12	1	62
Cedar Grove	-	-	-	-	-	47	99	93	12	390
Dunlap	-	-	-	-	-	19	13	5	6	21
Grant Grove	-	-	-	-	-	38	119	190	11	809
Hume Lake	-	-	-	-	-	53	122	127	7	545
Lodgepole	-	-	-	-	-	48	27	21	10	127
Monocito	-	-	-	-	-	38	59	75	4	279
Wishon	-	-	-	-	-	70	61	53	4	204
Sierra Nevada (South)										
Springville	61	10	3	4	25	93	10	5	2	33
Kernville	40	10	2	7	18	94	11	5	4	37
Camp Nelson	-	-	-	-	-	23	13	8	6	40
Sierra Nevada (East)										
Bishop	61	**2**	3	0	15	95	**8**	12	0	80
Devils Postpile	43	12	9	4	57	92	17	27	2	207
Lone Pine	61	6	2	0	14	95	8	8	0	52
Central Valley (North)										
Fresno	61	**8**	3	4	15	91	**11**	5	3	25
Clovis	61	**13**	4	6	21	95	**15**	6	4	34
Madera	61	11	3	6	18	95	11	5	3	27
Merced	50	**9**	3	4	16	95	**11**	6	2	40
Central Valley (South)										
Bakersfield	57	**10**	4	3	21	95	**14**	8	4	53
Hanford	61	**9**	3	4	21	95	**14**	7	3	34
Lebec	61	7	2	2	11	94	8	4	2	20
Porterville	61	**7**	3	3	16	76	**15**	24	2	165
Visalia	52	**9**	3	4	16	91	**14**	8	4	58

Bolded mean PM2.5 Concentrations indicate statistically significant differences between pre-fire and during-fire concentrations at the 0.05 significance level using the Mann–Whitney Test

6.2 Air day Categories using the Air Quality Index

Air quality findings presented below use the current health standards for $PM_{2.5}$. Table 3 shows the count of days in each of the categories of the air quality index for $PM_{2.5}$ on pre-fire and during-fire periods. Prior to the fire there were no Unhealthy air quality days in the Central Valley and Sierra Nevada except for one day at the Devils Postpile site.

During the fire the Northern Sierra Nevada Sites had a couple unhealthy air quality days. Prather had a count of 2 unhealthy days, North Fork 1 unhealthy day, Yosemite had 4 unhealthy days and Trimmer had 3 unhealthy days. When evaluating count of Unhealthy days for the Central Sierra Nevada Pinehurst had 3, Sequoia Kings Canyon 1, Cedar Grove 9, Dunlap 0, Grant Grove 6, Hume Lake 10, Lodgepole 5, Monocito 4, and Wishon 28. When evaluating count of Unhealthy days for the Southern Sierra Nevada sites Springville, Kernville, and Camp Nelson had zero Unhealthy days. When observing count of Unhealthy days for the Easter Sierra Nevada sites Bishop had 2, Devils Postpile 3, and Lone Pine 0.

When evaluating count of Unhealthy days for the Central Valley sites Porterville and Visalia were most affected. Porterville had 4 Unhealthy days and Visalia had 1 Unhealthy day. The Northern Central Valley sites did not have any Unhealthy days it did however have an increased amount of Moderate air quality days during the fire compared to before the fire. Prior to the fire the Fresno had 7 Moderate days and during fire the count of Moderate increased to 36 Moderate days. Clovis had a count of 34 Moderate air quality before the fire and a count of 64 Moderate air quality days during the fire period. Madera had 19 Moderate air quality days prior to the fire and 38 Moderate days during the fire nearly doubling in Moderate air quality days. Merced had 10 Moderate air quality days before the fire and 34 Moderate air quality days during the fire.

When analyzing the count of Hazardous days some of the Central Sierra Nevada sites Monocito had 1 Hazardous air quality day, Hume Lake had 8 Hazardous days, Cedar Grove had 3 Hazardous days, and Grant Grove had 4 Hazardous days throughout the duration of the fire. The Northern Sierra Nevada sites as well as the Southern and Eastern Sierra Nevada Sites did not have any Hazardous air quality days. The Norther Central Valley sites did not have any Hazardous air quality days prior to the fire or during the fire period.

Table 3. Count of days using the Air Quality Index Categories for PM2.5 (particulate matter smaller than 2.5 μm in diameter)

	Before Rough Fire						**During Rough Fire**					
Station	**Good**	**Moderate**	**USG**	**Unhealthy**	**Very Unhealthy**	**Hazardous**	**Good**	**Moderate**	**USG**	**Unhealthy**	**Very Unhealthy**	**Hazardous**
Prather	1	0	0	0	0	0	64	22	6	2	0	0
North Fork	34	4	4	0	0	0	54	28	9	1	0	0
Yosemite	55	6	0	0	0	0	57	14	0	4	1	0
Trimmer							26	26	7	3	0	0
Pinehurst	56	5	0	0	0	0	45	22	11	3	0	0
Sequoia Kings Canyon	53	6	0	0	0	0	40	21	4	1	0	0
Cedar Grove	-	-	-	-	-	-	11	19	3	9	11	3
Dunlap	-	-	-	-	-	-	11	8	0	0	0	0
Grant Grove	-	-	-	-	-	-	1	17	6	6	4	4
Hume Lake	-	-	-	-	-	-	7	11	6	10	11	8
Lodgepole	-	-	-	-	-	-	2	37	4	5	0	0
Monocito	-	-	-	-	-	-	17	6	4	4	6	1
Wishon	-	-	-	-	-	-	13	18	7	28	4	0
Springville	53	8	0	0	0	0	71	22	0	0	0	0
Kernville	36	4	0	0	0	0	67	26	1	0	0	0
Camp Nelson	-	-	-	-	-	-	14	8	1	0	0	0
Bishop	60	1	0	0	0	0	75	17	1	2	0	0
Devils Postpile	34	8	0	1	0	0	54	31	3	3	1	0
Lone Pine	60	1	0	0	0	0	83	10	2	0	0	0
Fresno	54	7	0	0	0	0	55	36	0	0	0	0
Clovis	27	34	0	0	0	0	31	64	0	0	0	0
Madera	42	19	0	0	0	0	57	38	0	0	0	0
Merced	40	10	0	0	0	0	60	34	1	0	0	0
Bakersfield	41	16	0	0	0	0	49	43	3	0	0	0
Hanford	53	8	0	0	0	0	39	56	0	0	0	0
Lebec	61	0	0	0	0	0	84	10	0	0	0	0
Porterville	55	6	0	0	0	0	57	14	0	4	1	0
Visalia	46	6	0	0	0	0	50	39	1	1	0	0

6.3 Description of air quality during the Fire

Higher peaks in air quality of $PM_{2.5}$ 24-hour mean concentration are observed for Clovis, Fresno, Madera, and Merced from 09/07/15 to 09/14/15. These peaks are probably not due to the Rough Fire according to HYSPLIT back trajectories.

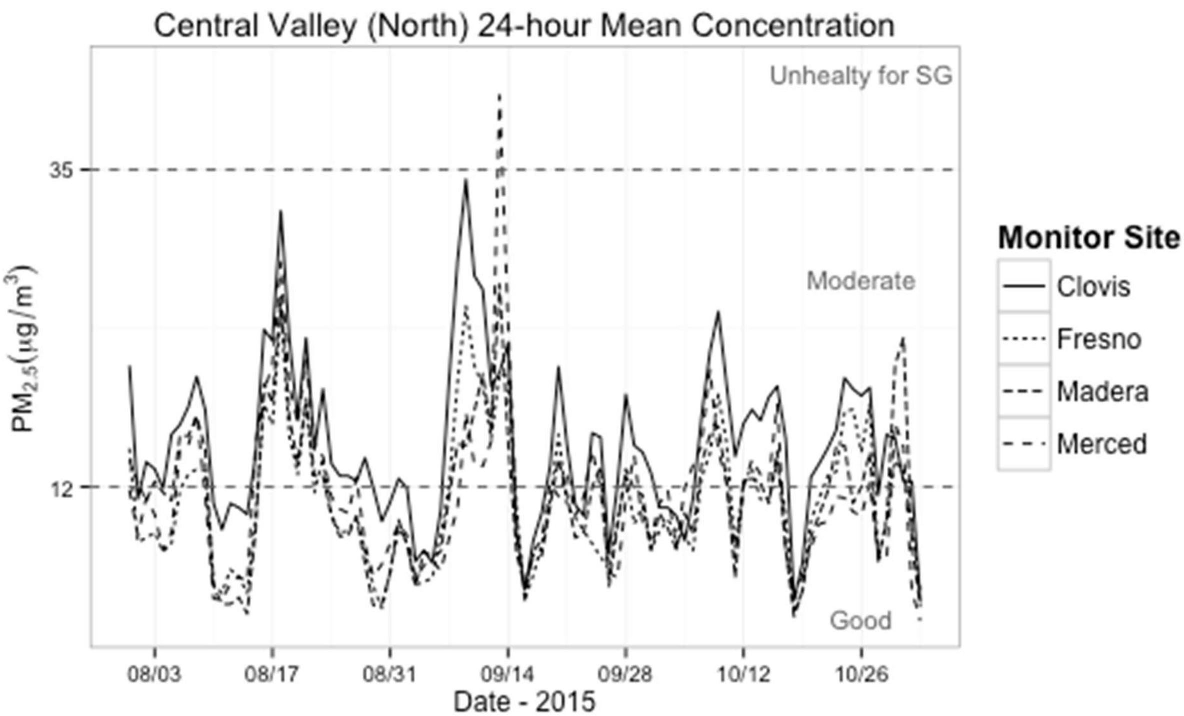

Figure 3. 24-Hour Particulate matter less than 2.5 microns (PM2.5) with Air Quality Index (AQI) breakpoints of the Rough Fire for Central Valley (North).

Higher peaks in air quality of $PM_{2.5}$ 24-hour mean concentration are observed for Porterville and Visalia from 09/07/15 to 09/14/15. Comparing previous full year $PM_{2.5}$ 24-hour mean concentration for Visalia during this period shows that the $PM_{2.5}$ 24-hour mean concentration increased at this site.

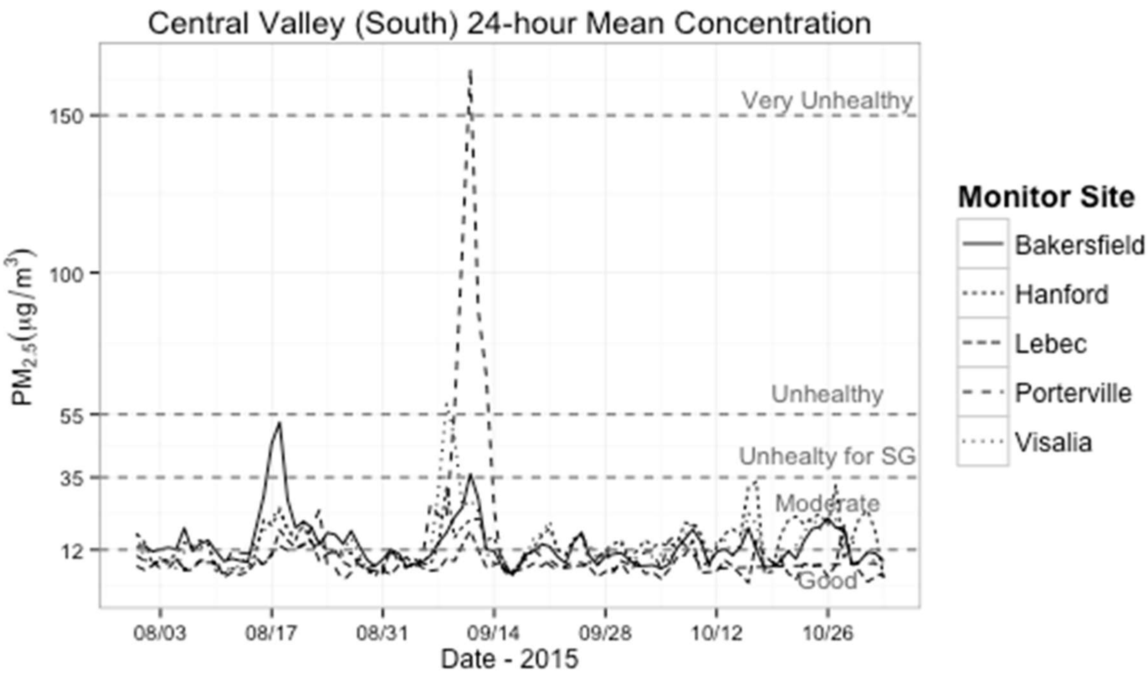

Figure 4. 24-Hour Particulate matter less than 2.5 microns (PM2.5) with Air Quality Index (AQI) breakpoints of the Rough Fire for Central Valley (South).

Multiple high peaks in air quality of $PM_{2.5}$ 24-hour mean concentration are observed for Cedar Grove, Grant Grove, and Hume Lake during the fire from 08/17/15 to 08/24/15 and 09/07/15 to 09/14/15. Grant Grove reached a $PM_{2.5}$ maximum concentration of $809\ \mu g m^{-3}$. Hume Lake experienced a $PM_{2.5}$ maximum concentration of $545\ \mu g m^{-3}$. Cedar Grove reached a $PM_{2.5}$ maximum concentration of $390\ \mu g m^{-3}$.

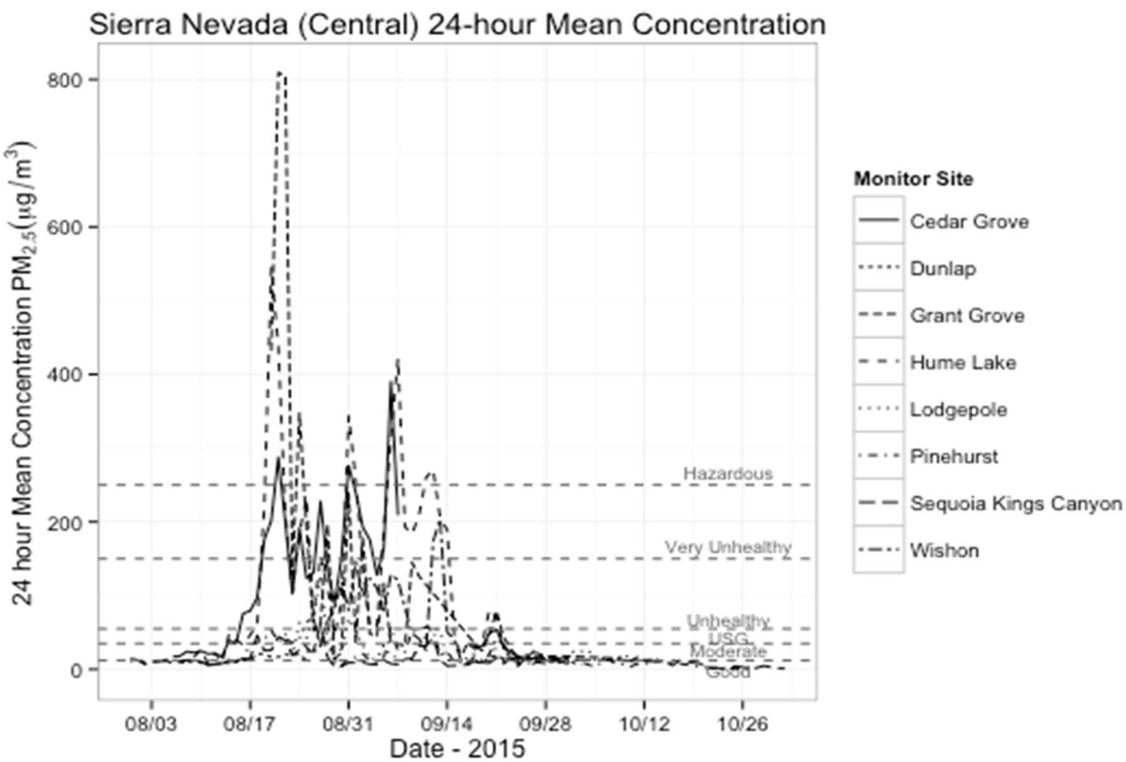

Figure 5. 24-Hour Particulate matter less than 2.5 microns (PM2.5) with Air Quality Index (AQI) breakpoints of the Rough Fire for Sierra Nevada (Central).

Higher peaks in air quality of $PM_{2.5}$ 24-hour mean concentration are observed for Yosemite, Trimmer, and Hume Prather during the fire from 08/17/15 to 08/24/15 and 09/07/15 to 09/14/15. Yosemite reached a $PM_{2.5}$ maximum concentration of 165 $\mu g m^{-3}$. Trimmer experienced a $PM_{2.5}$ maximum concentration of 89 $\mu g m^{-3}$. Prather reached a $PM_{2.5}$ maximum concentration of 98 $\mu g m^{-3}$. Comparing to a previous full years $PM_{2.5}$ 24-hour mean concentrations for Yosemite during this period show that the $PM_{2.5}$ 24-hour mean concentration at this site ranges from 7 to 10 $\mu g m^{-3}$ in Septembers. During the Rough Fire the $PM_{2.5}$ 24-hour mean concentration at Yosemite was 15 $\mu g m^{-3}$ in mid-September.

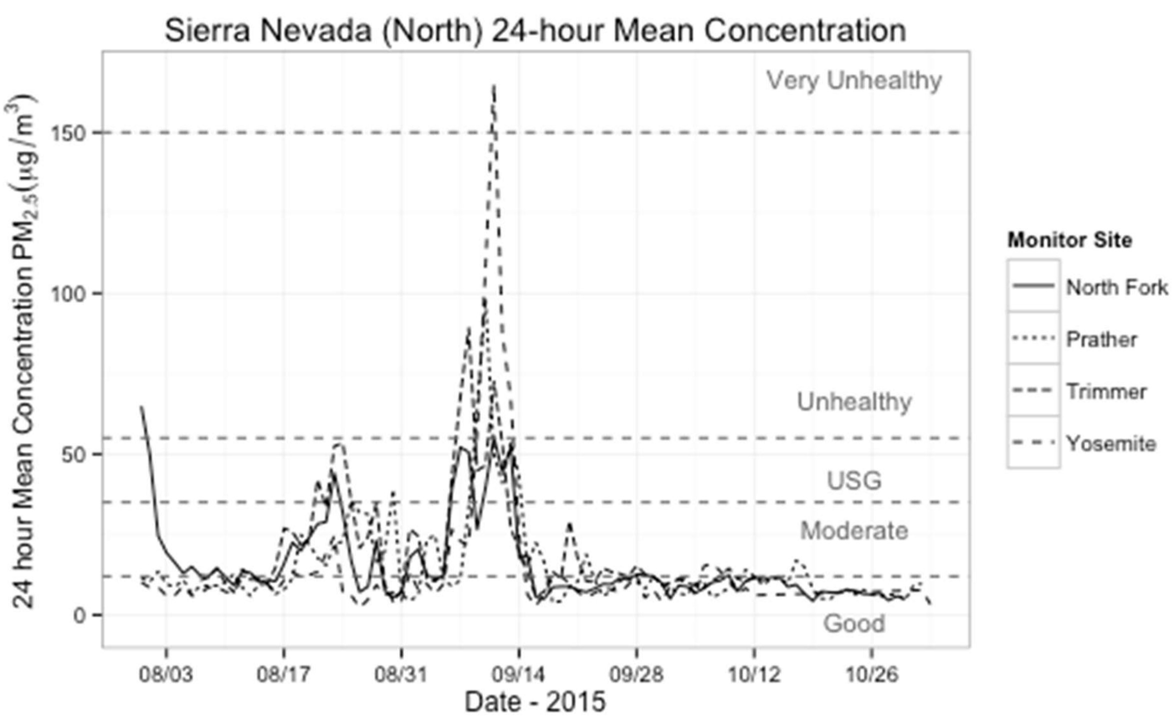

Figure 6. 24-Hour Particulate matter less than 2.5 microns (PM2.5) with Air Quality Index (AQI) breakpoints of the Rough Fire for Sierra Nevada (North).

Multiple peaks in the Moderate category of $PM_{2.5}$ 24-hour mean concentration were observed for Springville, Kernville, and Camp Nelson during the fire from 07/31/15 to 08/31/15. For Springville there is a noticeable peak on 10/26/15. Springville reached a $PM_{2.5}$ maximum concentration of 33 $\mu g m^{-3}$. Kernville experienced a $PM_{2.5}$ maximum concentration of 37 $\mu g m^{-3}$. Camp Nelson reached a $PM_{2.5}$ maximum concentration of 40 $\mu g m^{-3}$. Comparing to previous seasonal $PM_{2.5}$ 24-hour mean concentrations for Yosemite in October the $PM_{2.5}$ 24-hour mean concentration at this site ranges from 10to 12 $\mu g m^{-3}$ at the location and elevation.

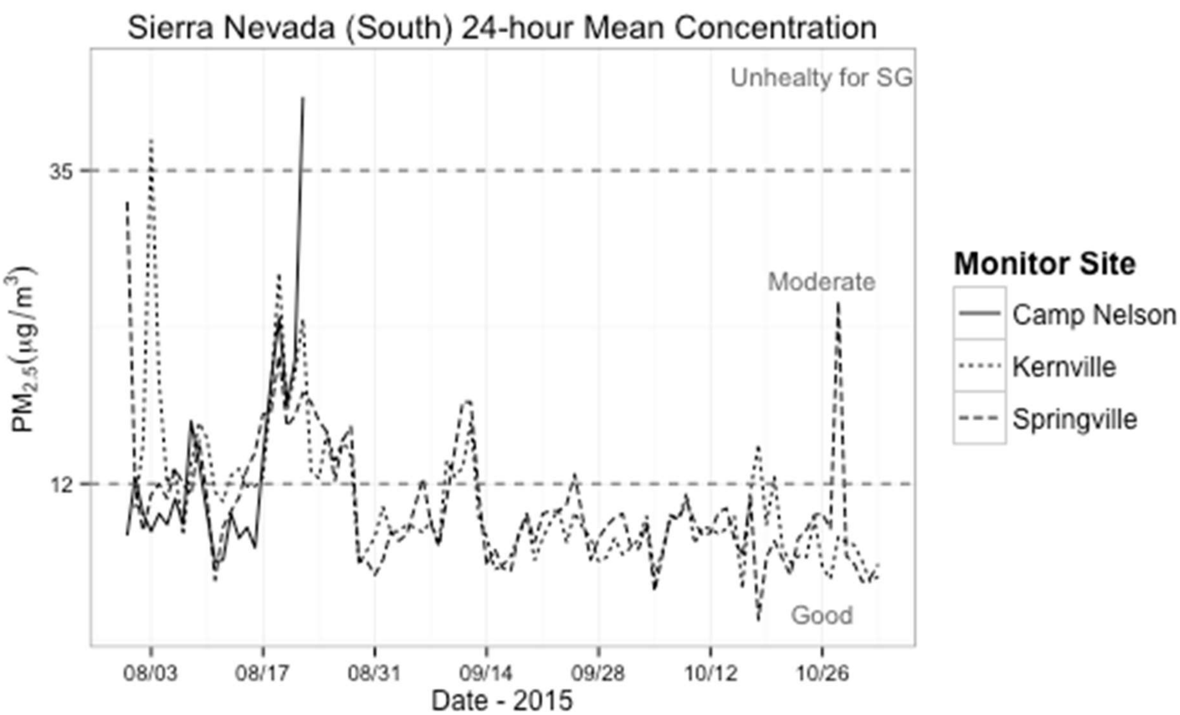

Figure 7. 24-Hour Particulate matter less than 2.5 microns (PM2.5) with Air Quality Index (AQI) breakpoints of the Rough Fire for Sierra Nevada (South).

Multiple high peaks in air quality of $PM_{2.5}$ 24-hour mean concentration are observed for Bishop, Devils Postpile, and Lone Pine during the fire from 08/17/15 to 09/14/15. For Devils Postpile there is a noticeable peak on 10/26/15 which reached the Very Unhealthy category. Bishop reached a $PM_{2.5}$ maximum concentration of 80 $\mu g m^{-3}$. Devils Postpile experienced a $PM_{2.5}$ maximum concentration of 207 $\mu g m^{-3}$. Lone Pine reached a $PM_{2.5}$ maximum concentration of 52 $\mu g m^{-3}$.

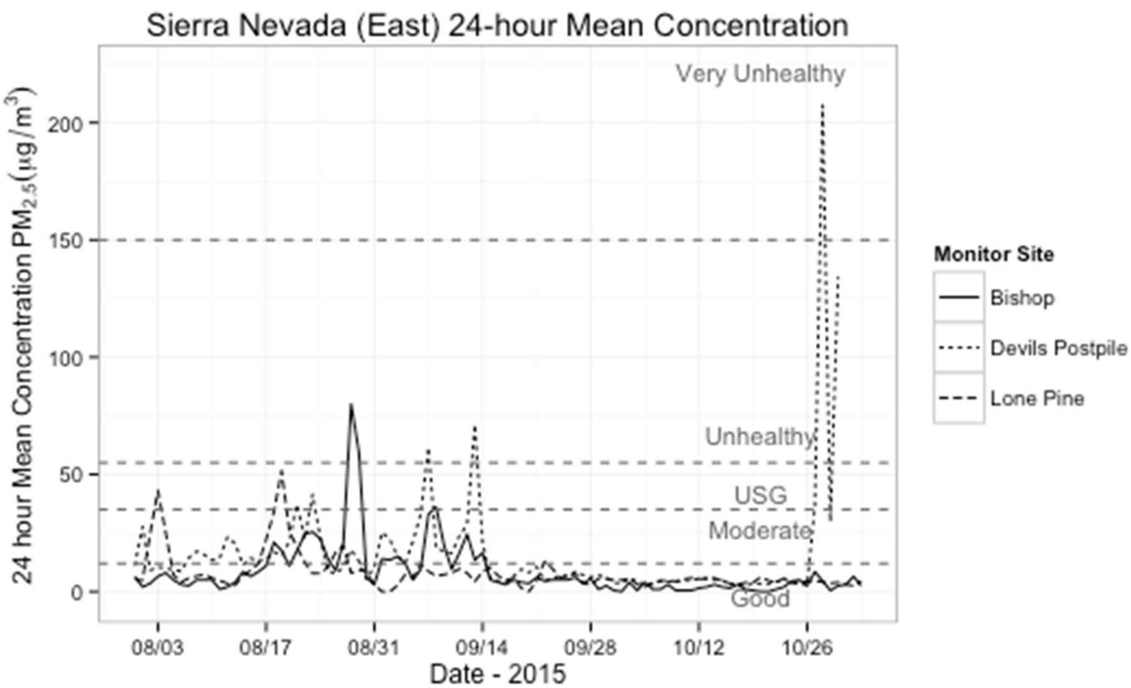

Figure 8. 24-Hour Particulate matter less than 2.5 microns (PM2.5) with Air Quality Index (AQI) breakpoints of the Rough Fire for Sierra Nevada (East).

7. Limitations

Local forest fire size and behavior during this study was assumed to be typical of the Sierra Nevada Mountains and Central Valley. Specific impacts of the other fires, agricultural pollution and pollution from Asia or Bay area were not quantified, therefore included in the descriptive statistics calculations.

8. Conclusion

Mean 24-h average concentrations of $PM_{2.5}$ increased at most mountain locations and only at two valley monitoring sites in the study, with the highest $PM_{2.5}$ 24-h concentrations occurring on the central side of the Sierra Nevada. During the fire, 24-h concentrations of $PM_{2.5}$ nearly doubled at sites (Pinehurst and Sequoia Kings Canyon) on the central side of the Sierra Nevada. The sites Kernville, Springville and Camp Nelson, which were the south sites of Sierra Nevada were not impacted in comparison to all other sites in this study. The results presented here show that the Rough Fire increased the Mean $PM_{2.5}$ concentration of Yosemite in the Sierra Nevada (North), Pinehurst and Sequoia Kings Canyon in the Sierra Nevada (Central)and Bishop in the Sierra Nevada (South). As for the Central Valley sites Fresno, Clovis, Merced, Bakersfield, Hanford, Porterville, and Visalia were impacted the most.

Continuous monitoring by state and federal agencies proved to be valuable in determining the effects of the Rough Fire. However, there is a need for an expansion of current monitoring networks in mountain areas since those were the most affected by this high-intensity wildfire. For that reason, a network of real time portable PM monitors is essential for evaluating air quality impacts caused by wildfires. Large size fires and high intensity fires in combination with anthropogenic pollutants from the Central Valley may be the leading cause of increased concentrations of Particulate Matter (PM) in rural mountain communities of the Sierra Nevada.

References

[1] CA Alves, C Goncalves, CA Pio, F Mirante, A Caseiro, L. Tarelho, MC Freitas, DX Viegas, (2010), Smoke emissions from biomass burning in a Mediterranean shrubland, Atmospheric Environment, 44, 3024-3033.

[2] KJ Bein, Y Zhao, MV Johnston, AS Wexler, (2008), Interactions between boreal wildfire and urban emissions, Journal of Geophysical Research Atmospheres, 113, 1-17.

[3] NE Clinton, P Gong, K Scott, (2006), Quantification of pollutants emitted from very large wildland fires in Southern California, USA, Atmospheric Environment, 40, 3686-3695.

[4] P Duclos, LM Sanderson, M Lipsett (1990), The 1987 forest fire disaster in California: Assessment of emergency room visits, Archives of Environmental Health 45:53-58.

[5] RJ Delfino, S Brummel, J Wu, H Stern, B Ostro, M Lipsett, A Winer, DH Street, L Zhang, T Tjoa, DL Gillen, (2009), The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. Occupational Environmental Medicine, 66,189-197.

[6] I Dokas, M Statheropoulos, S Karma, (2007), Integration of field chemical data in initial risk assessment of forest fire smoke, Science of the Total Environment, 376, 72-85.

[7] CT Fowler, (2003), Human Health Impacts of Forest Fires in the Southern

United States: A Literature Review, Journal of Ecological Anthropology, 7, 39-63.

[8] RM Hoff, SA Christopher, (2009), Remote sensing of particulate pollution from space: have we reached the promised land?, Journal of the Air and Waste Management Association, 59, 645-675.

[9] DM Holstius, CE Reid, BM Jesdale, R Morello-Frosch (2012) Birth weight following pregnancy during the 2003 southern California wildfires, Environmental Health Perspectives, 120, 1340-1345.

[10] S Hosseini, SP Urbanski, P Dixit, L Qi, IR Burling, RJ Yokelson, TJ Johnson, M Shrivastava, HS Jung, DR Weise, JW Miller, DR Cocker III, (2013), Laboratory characterization of PM emissions from combustion of wildland biomass fuels, Journal of Geophysical Research Atmospheres, 118, 9914-9929.

[11] N Kunzli, E Avol, J Wu, WJ Gauderman, E Rappaport, J Millstein, J Bennion, R McConnell, FD Gilliland, K Berhane, F Luhrmann, A Winer, JM Peters, (2006), Health Effects of the 2003 Southern California Wildfires on Children, American Journal of Respiratory and Critical Care Medicine, 174, 1221-1228.

[12] B Langmann, B Duncan, C Textor, J Trentmann, G van der Werf (2009), Vegetation fire emissions and their impact on air pollution, Atmospheric Environment, 43, 107-116.

[13] TS Lee, K Falter, P Meyer, J Mott, C Gwynn (2009), Risk factors associated with clinic visits during the 1999 forest fires near the Hoopa Valley Indian

Reservation, California, USA. International Journal of Environmental Health Research, 19:5, 315-327.

[14] X Li, W Song, L Lian, X Wei, (2015), Forest Fire Smoke Detection Using Back-Propagation Neural Network Based on MODIS Data, Remote Sensing, 7, 4473-4498.

[15] YQ Liu (2004), Variability of wildland fire emissions across the contiguous United States, Atmospheric Environment, 38, 3489-3499

[16] GN Marshall, TL Schell, MN Elliott, NR Rayburn, LH Jaycox (2007), Psychiatric disorders among adults seeking emergency disaster assistance after a wildland-urban interface fire, Psychiatric Services, 58, 509-514

[17] MC Mirabelli, N Kunli, E Avol, FD Gilliland, JW Gauderman, R McConnel, JM Peters (2009), Respiratory symptoms following wildfire smoke exposure: airway size as a susceptibility factor, Epidemiology,20, 451-459.

[18] LP Naeher, M Brauer, M Lipsett, JT Zelikoff, CD Simpson, JQ Koenig, KR Smith, (2007), Woodsmoke Health Effects: A Review, Inhalation Toxicology, 19, 67-106.

[19] HK Preisler, D Schweizer, R Cisneros, T Procter, M Ruminski, L Tarnay, (2015), A statistical model for determining impact of wildland fires on Particulate Matter ($PM_{2.5}$) in Central California aided by satellite imagery of smoke, Environmental Pollution, 205, 340-349.

[20] AG Rappold, SL Stone, WE Cascio, LM Neas, VJ Kilaru, MS Carraway, JJ Szykman, A Isling, WE Cleve, JT Meredith, H Vaughan-Batten, L Deyneka, RB Devlin (2011), Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance, Environmental Health Perspectives, 119, 1415-1420.

[21] CE Reid, M Jerrett, ML Petersen, GG Pfister, PE Morefield, IB Tager, SM Raffuse, JR Balmes, (2015), Spatiotemporal Prediction of Fine Particulate Matter During the 2008 Northern California Wildfires Using Machine Learning, Environmental Science and Technology, 49, 3887-3896.

[22] M Statheropoulos, S Karma, (2007), Complexity and origin of the smoke components as measured near the flame-front of a real forest fire incident: A case study, Journal of Analytical and Applied Pyrolysis, 78, 430-437.

[23] R Tham, B Erbas, M Akram, M Dennekamp, MJ Abramson, (2009), The impact of smoke on respiratory hospital outcomes during the 2002-2003 bushfire season, Victoria, Australia, Respirology, 14, 69-75.

[24] TD Toth, J Zhang, JR Campbell, EJ Hyer, JS Reid, Y Shi, DL Westphal, (2014), Impact of data quality and surface-to-column representativeness on the $PM_{2.5}$/satellite AOD relationship for the contiguous United States, Atmospheric Chemistry and Physics, 14, 6049-6062.

[25] S Vedal, SJ Dutton, (2006), Wildfire air pollution and daily mortality in a large urban area, Environmental Research, 102, 29-35.

[26] C Vora, MJ Renvall, P Chao, P Ferguson, JW Ramsdell (2011) 2007 San Diego wildfires and asthmatics, Journal of Asthma, 48, 75-78.

[27] TC Wegesser, KE Pinkerton, JA Last, (2009), California Wildfires of 2008: Coarse and Fine Particulate Matter Toxicity, Environmental Health Perspectives, 117, 893-897.

[28] NL Wigder, DA Jaffe, FA Saketa, (2013), Ozone and particulate matter enhancements from regional wildfires observed at Mount Bachelor during 2004-2011, Atmospheric Environment, 75, 24-31.

[29] J Yao, SB Henderson, (2013), An empirical model to estimate daily forest fire smoke exposure over a large geographic area using air quality, meteorological, and remote sensing data, Journal of Exposure Science and Environmental Epidemiology, 24, 328-335.

[30] "Environmental Protection Agency. (2014). *A Guide to Air Quality and Your Health* (EPA Publication No. EPA-456/F-14-002). Research Triangle Park, NC: U.S. Environmental Protection Agency."