Where there's fire, there's smoke

The impact of the extraordinary 2007 fire season on Santa Barbara County air quality

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Introduction

2007 was an unusually intense year for Southern California wildfires. The California fire season is usually confined to the late summer and autumn months when hot, dry 'Santa Ana' winds race from the desert to the ocean. But in 2007, the season began early in July when the Zaca Fire was ignited in the Sierra Madre mountains north of Santa Barbara, raging for four months in what became the state's second largest fire in recorded history. Although the fire burned in remote National Forest land and did not cause much loss of property, the firefighting effort was costly – over $100 million (Table 1).

The season intensified on October 20—22 when a string of fires erupted all along the coast from Santa Barbara to San Diego, in what became known collectively as the October Fires (Figure 1). Strong Santa Ana winds with gusts up to 70 mph in some places caused the fires to grow rapidly[1]. Unlike the Zaca Fire, these fires burned close to the urban—wildland interface, killing 9 people, injuring 61 firefighters, and burning 1,500 homes. The damage was the worst in San Diego County, where authorities evacuated 500,000 people from communities threatened by the Witch Creek and Harris fires. The last fire was finally contained on November 9, after the damages had risen to $1 billion.

Figure 1. In this satellite image from October 24, 2007, plumes of smoke from multiple fires along the Southern California coast can be seen blowing westward into the Pacific. Source: NASA.

Table 1. A comparison of the relative impacts of the Zaca Fire and the October 2007 Fires.

	Zaca Fire	October 2007 Fires
Date started – Date extinguished	July 4 – November 14, 2007	October 20 – November 9, 2007
Area burned	240,207 acres	500,300 acres (total all fires)
Regions affected	Los Padres Nat'l Forest Santa Barbara County	Multiple, but greatest impacts in San Diego County
Cost	$118 million in firefighting costs	Est. $1 billion in damages
Impact	43 injuries / minor property damage	9 fatalities / >100 injuries / 1,500 homes destroyed

Data from the California Department of Forestry and Fire Protection[2]

[1] California Fire Siege 2007: An Overview. California Department of Forestry and Fire Protection. Accessed online (11/24/13) at: http://www.fire.ca.gov/fire_protection/downloads/siege/2007/Overview_CompleteFinal.pdf

[2] Zaca Fire Incident Information. California Department of Forestry and Fire Protection. Accessed online (11/24/13) at: http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=190

Cover photo of Zaca Fire by John Newman, U.S. Forest Service. http://en.wikipedia.org/wiki/File:Zaca3.jpg

Wildfires and Particulate Matter

Not only do wildfires threaten life and property, they also create air pollution that can have serious health impacts far beyond the burn zone. Plumes of thick smoke and hazy, yellow skies are a familiar sight for Californians who have experienced large fires. In satellite photos from October 2007, smoke can be seen blanketing most of coastal Southern California, blown westward by Santa Ana winds into the ocean. But even after the smoke dissipates, tiny atmospheric contaminants called **particulate matter** can remain suspended in the air and travel hundreds of miles before settling out.

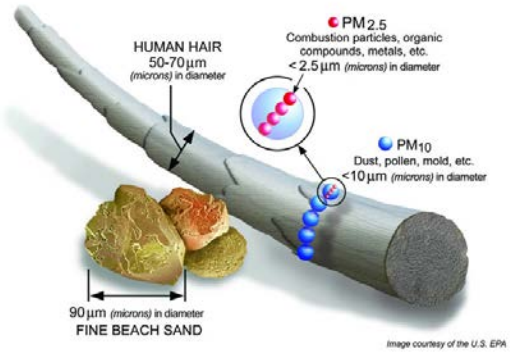

Figure 2. $PM_{2.5}$ particles are a fraction of the size of a human hair. Source: U.S. EPA.

Particulate matter is classified according to size. Particulate matter with an aerodynamic diameter of 2.5 micrometers or less – a fraction of the width of a human hair – is known as $PM_{2.5}$ (Figure 3). These type of particles are familiar to most people as soot and smoke. In the atmosphere, $PM_{2.5}$ comes from processes that combust organic matter, and this can include human activities – vehicle exhaust and coal power plants – as well as natural processes like forest fires.

Once $PM_{2.5}$ gets into the atmosphere, it creates haze that reduces visibility. But the most harmful effects occur when humans breathe in these particles. Because $PM_{2.5}$ is so tiny, it can enter deep into the lungs and get trapped within the alveoli, and with sustained exposure it can cause asthma, lung infections, cardiopulmonary diseases, and bronchial irritation.[3]

Due to the impacts of $PM_{2.5}$ to human health and the environment, the U.S. Environmental Protection Agency has established National Ambient Air Quality Standards that establish safe limits for $PM_{2.5}$ in outdoor air. The short-term (24 hour) standard that is considered to be protective of human health is 35 $\mu g/m^3$. The long-term (annual) limit is 15 $\mu g/m^3$.[4]

In October 2007, the levels of $PM_{2.5}$ measured in Santa Barbara County rose so high that the Santa Barbara County Air Pollution Control District issued an 'Exceptional Event' warning. This report explores the $PM_{2.5}$ data record over the course of 2007-8, examining the links between fire activity and harmful particulate matter in the atmosphere during this infamous fire year.

Data and Statistical Methods

A set of $PM_{2.5}$ data was obtained from the Center for Disease Control's Wonder website.[5] The dataset contains spatially-averaged daily $PM_{2.5}$ concentrations for Santa Barbara County from 2003 to 2011, reported as $\mu g/m^3$.

The data were analyzed using RStudio (0.97.551) and elegantly rendered using the *ggplot2* and *Cairo* packages. Comparisons of sample means were determined using two-sample unpaired *t*-tests with a significance level α of 0.05.

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[3] Fine particle (PM2.5) Frequent Questions. Environmental Protection Agency. Accessed online (11/24/13) at: http://www.epa.gov/pmdesignations/faq.htm

[4] Fine Particles Questions and Answers. New York State Department of Health. Accessed online (11/24/13) at: http://www.health.ny.gov/environmental/indoors/air/pmq_a.htm

[5] Outdoor Air Quality - Fine Particulate Matter: Daily Fine Particulate Matter (PM2.5) ($\mu g/m^3$), Years 2003 – 2011. Accessed online (11/21/13) at: http://wonder.cdc.gov/wonder/help/PM.html

Results

Daily $PM_{2.5}$ concentrations for the one-year period from June 2007 to June 2008 are shown in Figure 3. Notice first the pre-fire background concentrations of <15 µg/m³ during June 2007. Next, note the dramatic increase that occurred on October 22 as multiple fires ignited along the Southern California coast. A smaller but possibly significant peak occurred on July 4, the day the Zaca Fire started.

The data can be segmented into five 90-day quarters that roughly correspond to the timing of the fires:

Q1	Pre-Fire Quarter	April 4th – July 3rd, 2007
Q2	Zaca Fire Quarter	July 4th – October 3rd, 2007
Q3	October Fires Quarter	October 4th – January 3rd, 2008
Q4	Post-Fire Quarter	January 4th – April 3rd, 2008
Q5	One Year Later	April 4th – July 3rd, 2008

The divisions between these quarters are shown on Figure 3 as dashed lines. We can now consider the statistical effect of each of the fires on $PM_{2.5}$ concentrations by examining variations between quarters. Figure 4 shows the distribution of $PM_{2.5}$ concentrations for each of the five quarters.

The mean concentration for the Pre-Fire quarter was 7.3 µg/m³. This constitutes our baseline air quality in the absence of fire. During the Zaca Fire quarter, the mean increased slightly to 7.8 µg/m³, but this was not a statistically significant increase (p = 0.12, α = 0.05, $t(180)$ = 1.2). This suggests that the Zaca Fire had no significant impact on air quality in Santa Barbara County, but we will reconsider this conclusion in the next section.

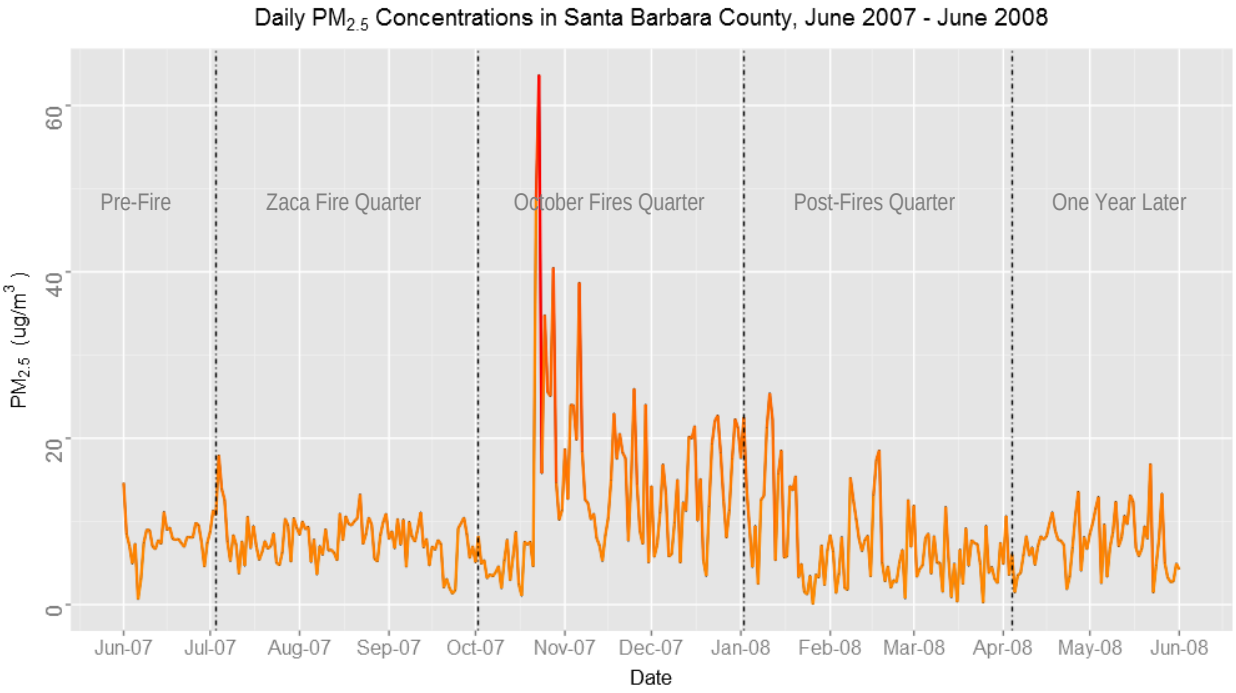

Figure 3. A time series of daily $PM_{2.5}$ concentrations (µg/m³) for the one year period from June 2007 to June 2008. Dashed black lines demarcate the ~90-day quarters referred to in the text. Data from the Center for Disease Control (http://wonder.cdc.gov).

The October Fires released significant $PM_{2.5}$ into the atmosphere which lingered into 2008

Beginning on October 20, multiple fires erupted across Southern California from Santa Barbara to the Mexico border, burning for four week before firefighters could extinguish them. The mean $PM_{2.5}$ concentration for the October Fires quarter was 14.1 µg/m³, a statistically significant increase above both the Pre-Fire quarter (p < 0.001, α = 0.05, t(106) = 6.1) and the Zaca Fire quarter (p < 0.001, α = 0.05, t(104) = 5.7).

The Santa Barbara County Air Pollution Control District later reported that on October 21, 22 and 23, the county had exceeded state and federal air quality standards for ozone, PM_{10}, and $PM_{2.5}$ – an event that it termed 'Exceptional'.[6] Figure 5 shows the distribution of daily $PM_{2.5}$ concentrations (µg/m³) for seven weeks in 2007 surrounding the onset of the October Fires. The week of October 22 had a mean $PM_{2.5}$ concentration of 36.3 µg/m³, significantly higher than both the preceding week (M = 5.6 µg/m³, p = 0.001, α = 0.05, t(6) = 4.9) and the following week (M = 16.5 µg/m³, p = 0.009, α = 0.05, t(7) = 3.0). Concentrations on October 22, 23, 28, and November 6 exceeded the federal 24-hour $PM_{2.5}$ standard of 35 µg/m³.

How quickly did $PM_{2.5}$ concentrations return to their baseline levels? Although air quality improved throughout the winter of 2007-8, the mean concentration in spring of 2008 during the One Year Later quarter (8.7 µg/m³) was nonetheless significantly higher than that of the Pre-Fire quarter (p = 0.01, α = 0.05, t(141) = 2.2), suggesting that concentrations still had not returned to the pre-fire baseline. This conclusion is uncertain because the mean concentration during the intervening Post-Fire quarter (January – April 2008) was 7.2 µg/m³, which was not significantly greater than the mean during the Pre-Fire Quarter (p = 0.57, t(144) = -0.17).

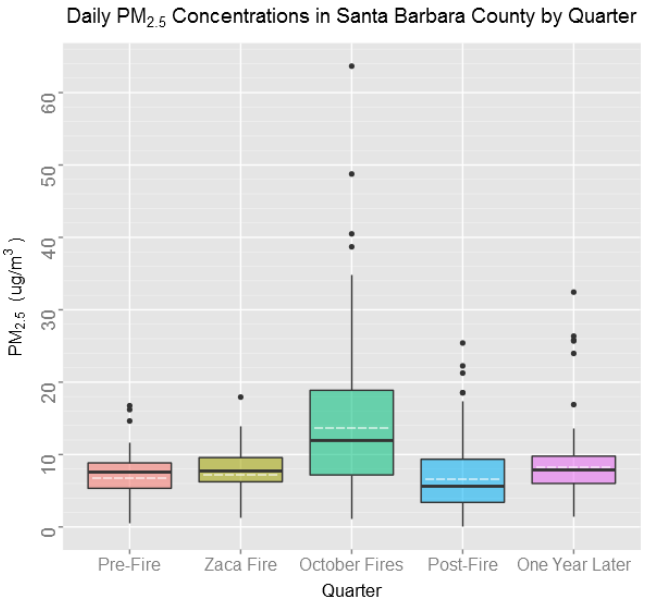

Figure 4. Box-and-whisker plots of daily $PM_{2.5}$ concentrations (µg/m³) for each of the five ~90-day quarters defined above. The white dashed lines indicate the mean. n for each quarter = 91, 91, 92, 92, 91.

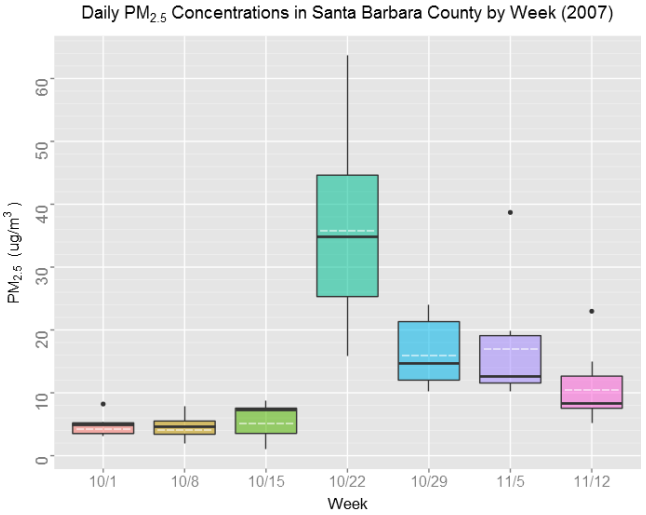

Figure 5. Box-and-whisker plots of daily $PM_{2.5}$ concentrations (µg/m³) for seven weeks in 2007 surrounding the onset of the October Fires. The white dashed lines indicate the mean. n = 7 for all weeks.

[6] Exceptional Event Demonstration for High Ozone in Santa Barbara County Due to Wild Fires. Santa Barbara County Air Pollution Control District. Accessed online (11/23/13) at: http://www.sbcapcd.org/airdata/sbcapcd-exc-event-october07.pdf

Summary

Did the Zaca Fire impact Santa Barbara County Air Quality?

The quarterly analysis reported above seems to show that the Zaca Fire had no statistical impact on Santa Barbara County air quality. This result may come as a surprise, given that the fire burned entirely within the county for four months! Two effects may be masking the true air quality impact of the fire:

Location of air quality monitoring stations and spatial averaging of the dataset. The data used in this analysis represent an average of data from 17 different air quality monitoring stations across Santa Barbara County (Figure 6). The stations are concentrated in the coastal north and west part of the county where most of the population lives. No stations are present in the central and northeast part of the county.

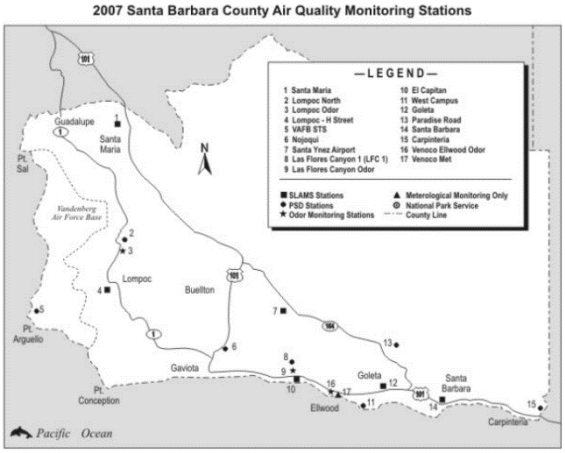

Figure 6. The locations of all 17 air quality monitoring stations in Santa Barbara County. Note that stations are concentrated in the southern and western part of the county, with no coverage in the northeast interior. Source: SBCAQMD.

Given that the Zaca fire burned in the east-central interior of the county, and that strong southwesterly winds were blowing the smoke further inland, it is likely that few monitoring stations were in the path of the particulate emissions. Indeed, satellite photos taken on August 5 and 12, 2007 show the smoke plume blowing to the northeast toward Kern County, leaving the coastal areas of Santa Barbara County unaffected (Figure 7). To truly understand the air quality impacts of the Zaca Fire, we would need to include data from Kern and other counties in our analysis.

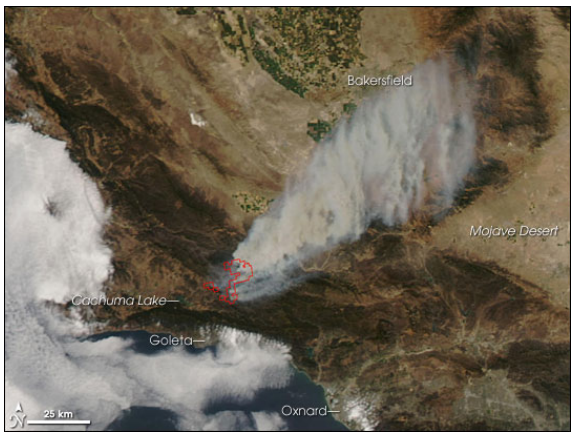

Figure 7. In this August 5, 2007 image from NASA's Aqua satellite, the smoke plume from the Zaca fire is seen blowing northeast towards Bakersfield. Coastal areas of Santa Barbara County, where air quality monitoring stations are located, appear unaffected by the smoke. Compare Figure 1, which shows winds blowing smoke from the October Fires to the west over the most populated areas of Southern California. Source: NASA.

This result illustrates why it is necessary to consider 1) the prevailing wind direction and 2) the geographic distribution of air quality monitoring stations in relation to the fire and smoke plume. Because particulate matter from fires can be carried long distances by winds (especially if it enters the upper atmosphere), wildfires may have air quality impacts on locations far from the fire itself, while areas that are closer but upwind from the fire may show little impact. Thus, *datasets that spatially average data from multiple stations can lead to misleading conclusions about the relationship between wildfire and air quality*.

Segmentation of the data. If there *is* a Zaca Fire signature buried in the data, the division of the data into quarters may actually be masking it. Looking closely at the weeks surrounding the onset of the Zaca Fire, there is an obvious peak on July 4, the date the fire started (Figure 8). Is this peak significant, or is it a random outlier?

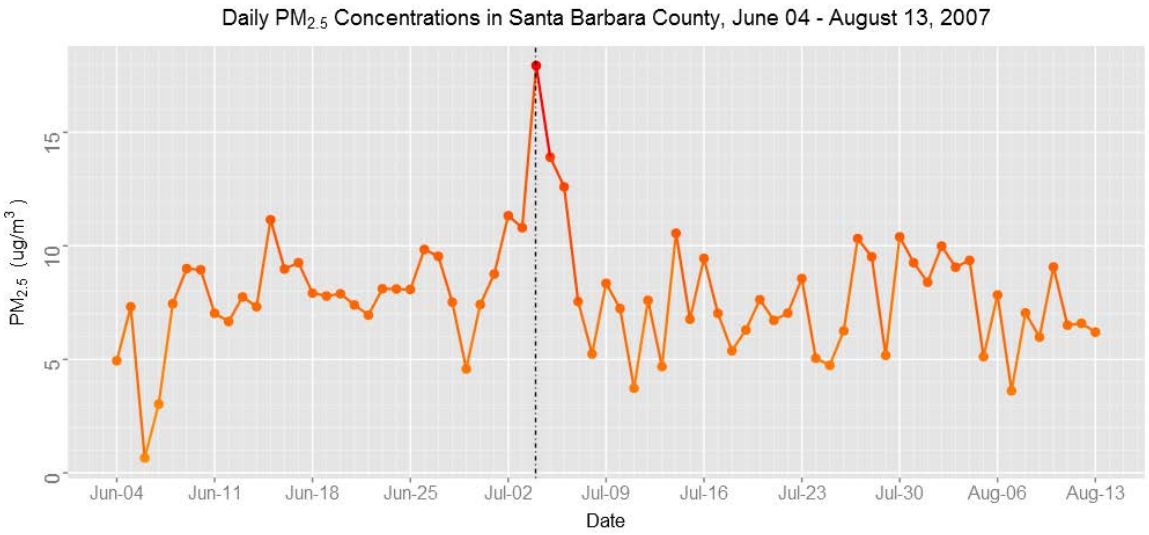

Figure 8. A time series of daily $PM_{2.5}$ concentrations ($\mu g/m^3$) for the weeks immediately preceding and following the outbreak of the Zaca Fire on July 4, 2007 (dashed black line).

The mean $PM_{2.5}$ concentration in the five weeks preceding the Zaca outbreak (May 30 to July 3) was 8.0 ± 2.4 $\mu g/m^3$ (*M* ± *SD*). On July 4, the daily concentration reached 17.9 $\mu g/m^3$, which is significantly above the five-week pre-Zaca mean ($z = 4.2$, $p < 0.001$). Thus, there is evidence for elevated $PM_{2.5}$ from the Zaca fire, at least in the first few days after the fire broke out.

The October Fires produced long-lasting impacts on air quality

In contrast to the Zaca Fire, the October Fires produced a far greater effect on Santa Barbara County $PM_{2.5}$ levels which persisted for months. Between October 22 and 23, daily concentrations across the county soared to 63.7 $\mu g/m^3$, 1.8 times the EPA's 24-hour health protective standard of 35 $\mu g/m^3$. $PM_{2.5}$ levels remained above the pre-fire baseline at least through mid-January, and possibly until the summer of 2008.

Recommendations

The discussion of the Zaca Fire data illustrates one of the limitations of Southern California's network of air quality monitoring stations. These stations are mostly situated near population centers because their main purpose is to quantify impacts to human health. Yet particulate matter also has adverse impacts on ecosystems. For example, particulate matter deposited on pine needles can reduce the trees' drought tolerance[7], while particulate matter deposited on the ground can affect the bacteria and fungi that contribute to nitrogen cycling in the soil.[8] Particulate matter also affects local climate by absorbing and scattering sunlight.

To address this monitoring limitation, networks of stations should be developed in more remote parts of Southern California, particularly in and around National Forests. Richer datasets from rural stations could help us to investigate the effects of particulate matter on surface water, forests, and organisms. They may also help to develop more accurate regional climate models.

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[7] The contribution of particulate matter to forest decline. University of Bonn. Accessed online (11/24/13) at: http://www3.uni-bonn.de/Press-releases/the-contribution-of-particulate-matter-to-forest-decline

[8] Grantz, D.A, J.H.B Garner, and D.W Johnson. 2003. "Ecological Effects of Particulate Matter." Environment International 29 (2-3) (June): 213–239. doi:10.1016/S0160-4120(02)00181-2.

Sierra Madre Mountains in winter. Photo by K. Lachshand. http://www.flickr.com/photos/lachshand/3273957451/