

# Detecting Smoke Plumes and Analyzing Smoke Impacts Using Remote Sensing and GIS for the McNally Fire Incident

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Remote sensing and GIS techniques were developed and evaluated to retrospectively analyze the impacts of the McNally Fire on air quality. The McNally Fire was a large wildfire over 54,700 ha (150,000 acres) in size that occurred in the Sequoia National Forest, California, 21 July through 26 August 2002. MODIS satellite images and NOAA pictures were used to digitize smoke plumes. Smoke plumes were analyzed using ESRI ArcGIS Spatial Analyst. Air monitoring data was acquired from 23 locations for  $PM_{10}$ . Ozone data was acquired from 40 locations. ArcGIS Geostatistical Analyst was used to analyze and produce prediction maps using Kriging as an interpolation method. A strong positive correlation between  $PM_{10}$  maximums and number of smoke plumes was observed. The correlation between  $PM_{10}$  averages and number of smoke plumes observed was not as strong. Very high ozone concentrations generated by the McNally fire were observed northeast of the fire, and affected mainly mountain sites. Ozone impacts due to the fire were not observed at valley sites. Remote sensing and GIS techniques were useful in assisting with the evaluation of fire smoke impacts on air quality.

Keywords: *wildfire, air quality, smoke, remote sensing, GIS,  $PM_{10}$ , ozone*

## INTRODUCTION

Wildland fires are a complex combustion source that involve several categories of fuels, and are characterized by fire behavior that changes over time with fuel and weather conditions. Smoke from wildfires is composed of hundreds of chemicals in gaseous, liquid, and solid forms (Ottmar and Reinhardt 2000). Some of the main concerns for land managers are the production of particulate matter and ozone from prescribed burns and wildfires. Managing fire to comply with national ambient air quality standards (NAAQS) requires an increasingly detailed base of scientific knowledge and information systems. Wildfire smoke is transported across state and land management agencies. Smoke impacts during these episodic events can threaten public health and may be the dominant cause of visibility

reduction. Particulate matter (PM), the direct product of smoke is one of the greatest concerns due to its impacts on public health and visibility (Billington et al. 2000). Burning of forests can generate the precursors for substantial ozone concentrations downwind of the fire (Cheng et al. 1998). But, there is little research that links fire emissions with ground-level ozone concentrations. Also, there is uncertainty about the effects of ozone formation caused by mixing of fire emissions with urban sources (Sandberg et al. 2002).

The McNally fire was a large-scale wildfire, over 54,700 ha (150,000 acres). It occurred in the Sequoia National Forest, in the Sierra Nevada of California, during the period of 21 July through 26 August 2002. Smoke from this fire was transported over hundreds of kilometers across the California state boundary, degrading air quality and reducing scenic values. Characterization of effects of wildland fires on ambient air quality is incomplete due to the deficiency of air quality monitoring sites in rural areas. Knowledge about fire's effects on air is needed to meet regulatory and management requirements. New methods

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and information are needed to assess, monitor and predict smoke plumes.

This report evaluates the use of remote sensing and GIS techniques as a decision support tool to retrospectively analyze the McNally fire impacts on air quality. Also, the report evaluates the extent and duration of wildfire smoke on communities and provides insight to the magnitude of smoke impact from the fire on  $PM_{10}$  (particulate matter, 10 microns or less) and ozone.

## METHODS

### Aerial Data Acquisition

The MODIS images came from the TERRA satellite. MODIS or Moderate Resolution Imaging Spectroradiometer is an instrument aboard NASA's TERRA and AQUA satellites. The daytime pass of TERRA goes over California at approximately 12:00 pm (1900 UTC). MODIS images were compiled and processed over the duration of the McNally Fire by the Remote Sensing Application Center (RSAC). The bounding coordinates of the image subset were: (west) 119.95° W, (east) 116.96° W, (north) 37.41° N, and (south) 34.41° N. The images were set to a spatial resolution of 250 meters, and georeferenced using the Lambert Azimuthal projection parameters. MODIS data were input into NASA processing software application for reflectance correction. The images were then imported into ERDAS Imagine<sup>1</sup> and saved in IMG (.img) format. Twenty-five images were collected.

Pictures were also collected from National Oceanic & Atmospheric Administration (NOAA) in JPG format. NOAA pictures helped us digitize plumes that went across state boundaries, as NOAA pictures covered a larger area than MODIS images. There were a total of 15 NOAA pictures collected for the whole incident.

### Plume Analysis Procedures

To view smoke plumes, the best band combination to use is the natural color composite. The bands are 1 (red), 4 (green), and 3 (blue). Imagine files have seven bands (Table 1).

MODIS images were screen digitized in ArcGIS, as shown in Figure 1, and further processed in ArcInfo Workstation. ArcInfo Workstation was used to clean and build the topology of the polygons created in ArcGIS.

NOAA pictures were used to help digitize smoke plumes that went across state boundaries, because they covered

a larger area than MODIS images. It was complicated to differentiate between clouds and smoke using NOAA pictures, but these pictures were good for depicting the overall direction and distance of the plume.

Table 1. The seven bands and wavelengths of MODIS imagery.

MODIS Band	Wavelength (nm)	Name
1	620-670	red
2	841-876	near IR
3	459-479	blue
4	545-565	green
5	1230-1250	mid IR
6	1628-1652	mid IR
7	2105-2155	mid IR

Figure 1. MODIS images were screen digitized.

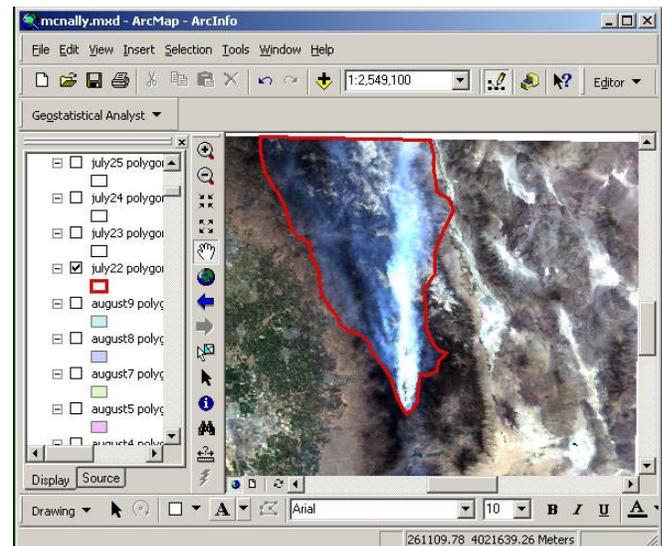
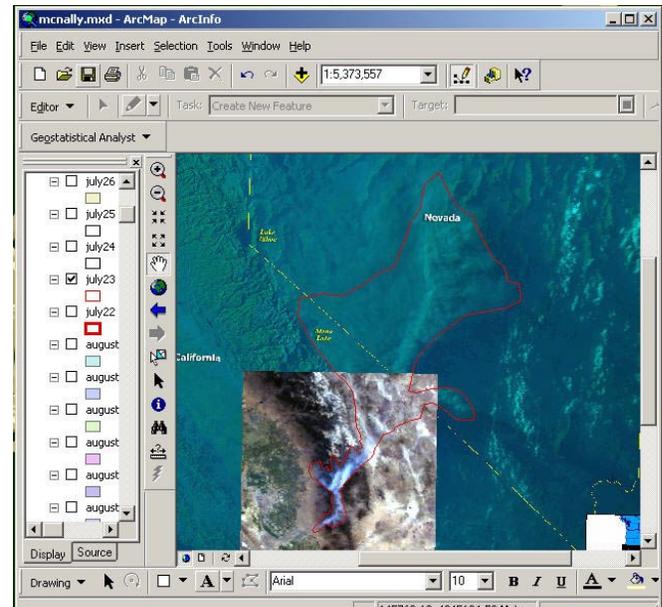
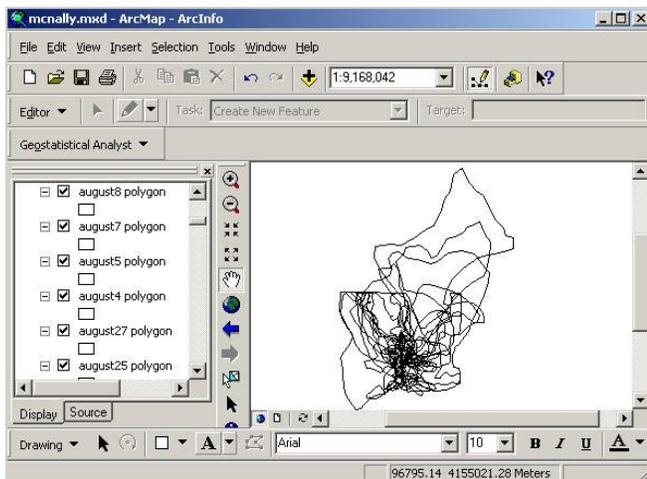


Figure 2. NOAA pictures were used in conjunction with MODIS images to digitize plumes that went past MODIS extent.



<sup>1</sup>The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 3. Twenty-five smoke plume polygons were digitized over the entire duration of the fire.



A total of 25 smoke plume polygons were created (Figure 3), each representing a smoke plume observed one time per day. The MODIS satellite takes a snapshot once per day around noon. The fire lasted for 35 days. Plumes were digitized for 25 days out of a total of 35 days possible days of the fire, because on some days the images weren't available, or the image wasn't clear. All polygon coverages created were projected in NAD 1927, UTM Zone 11N. The Geographical Coordinate System used was GCS North American 1927.

All polygons were converted to raster format (Figure 4, Figure 5). The area inside the polygon was given a band value of 1, and a band value of 0 was assigned for the area outside of the polygon.

Raster datasets were created from each polygon and became thematic data. The Spatial Analyst extension in ArcGIS was used to describe the raster created from polygons. The cells created had a size of 3108 m with a total of 250 rows and 266 columns, and one band. This output resolution was determined by the Spatial Analyst. The optimum cell size to capture the appropriate detail varies from study to study. The smaller the cells, the greater the resolution and accuracy, but coding, database storage, and processing speed are more costly.

A zonal function was chosen to continue with the processing of all 25 raster datasets. Zonal functions compute an output raster dataset. The output value for each location depends on the value of the cell at that location and the association that the location has within a cartographic zone. All raster datasets must share the same coordinate system and the same projection.

The Raster Calculator provides the tools to perform mathematical calculations such as arithmetic operations. All 25 raster datasets were added together to produce the final raster. Each single input raster had a band value of 0 and 1, which represents the times that a plume was

Figure 4. A single smoke plume polygon.

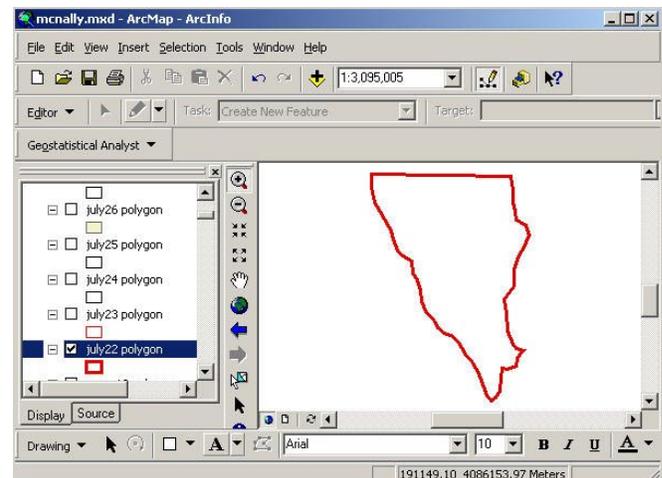


Figure 5. The polygon in figure 4 is converted to raster format.

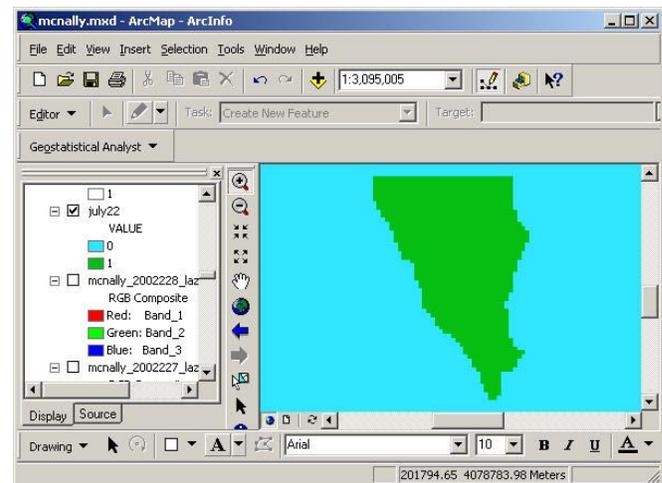
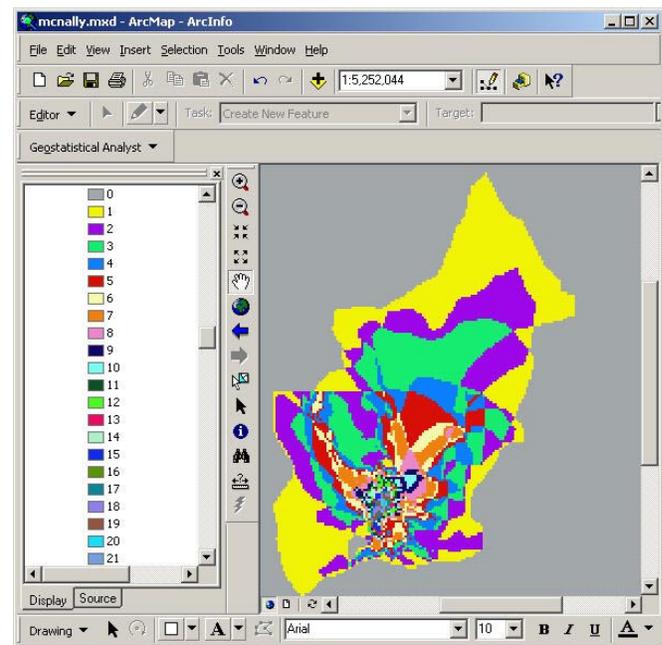


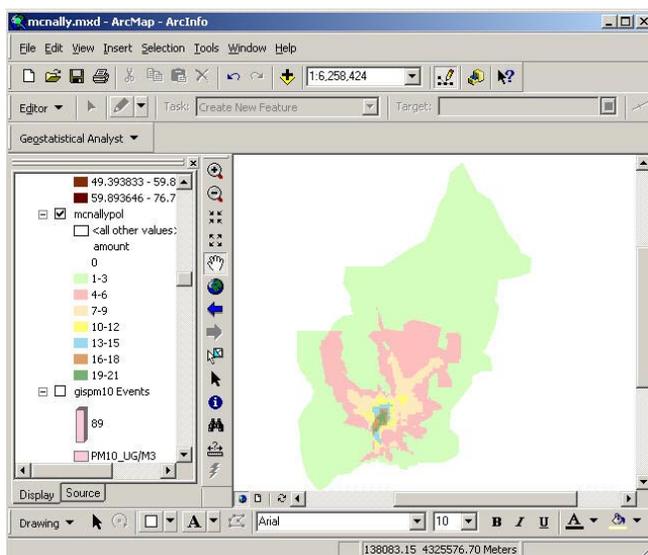
Figure 6. Map produced by the Raster Calculator.



observed. The final raster has a band value of 0-21; the value describes the number of times or days a plume was observed over a given location. The highest value was 21, which indicates that when overlaying all of the 25 plumes (raster) together only 21 overlapped. In other words, 21 out of the 25 plumes was the highest frequency observed over the same location (Figure 6).

The final raster was converted into a polygon coverage and classified by the number of plumes observed in a given location, grouped in threes. There were a total of seven groups (1-3, 4-6, 7-9, 10-12, 13-15, 16-18, and 19-21). The coverage was classified into seven groups because it is easier to interpret output images with seven colors than with twenty-one colors (Figure 7).

*Figure 7. Frequency of plume occurrence classified into seven groups. The numbers refer to the frequency of plumes observed.*



### Air Quality Data Acquisition for Particulate Matter

Air monitoring data for particulate matter was acquired from 23 locations. The air monitoring data collected hourly concentrations of  $PM_{10}$ , which were converted into 24-hour averages. The data included air quality data from the Air Resources Board network, IMPROVE (Interagency Monitoring of Protected Visual Environments), the Great Basin Air Pollution Control District in Bishop, CA (north and east of the fire), and the Forest Service's Kernville Work Center (just south of the fire). IMPROVE data is part of the long term monitoring program established to monitor visibility trends. The monitoring data from Bishop is part of the Great Basin Air Pollution Control District monitoring network. The data from the Kernville Work Center came from a monitoring station set up by the Forest Service at the beginning of the fire.

### Air Quality Data Acquisition for Ozone

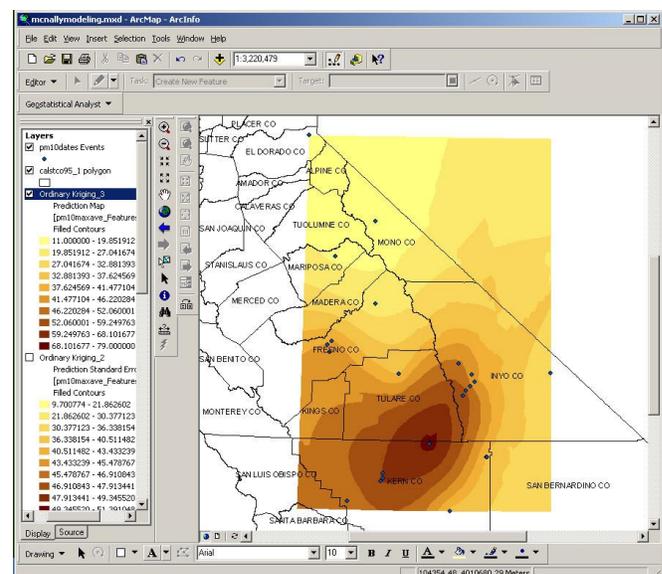
Air monitoring data for ozone was acquired from 40 locations. Twenty-four locations used ozone passive samplers and 16 used active monitors. The ozone passive concentrations were provided in two-week averages, thus hourly data from the active monitors was converted to two-week averages as well. The ozone passive data were provided by the USDA Forest Service Riverside Fire Lab. The active monitor data were provided by the Sequoia National Park, San Joaquin Air Pollution District and Air Resources Board network.

### Air Quality Data Analysis Procedures

Interpolation methodologies were used to create a prediction map (Figure 8 and 9) in Geostatistical Analyst to showcase what could be done using GIS. Ordinary Kriging is a quick interpolator that is very flexible, allowing investigation of spatial autocorrelation. Inverse Distance Weighting (IDW), the simplest of all interpolators, could also be used, but it does not provide a standard error map. IDW is a quick, exact deterministic interpolator. It allows a few choices regarding model parameters, and there are no assumptions required for the data. For the purpose of this project Ordinary Kriging was used because it allows the creation of a prediction standard error map, although no manipulations were done. Geostatistical Analyst was used to create a prediction map and a standard error map.

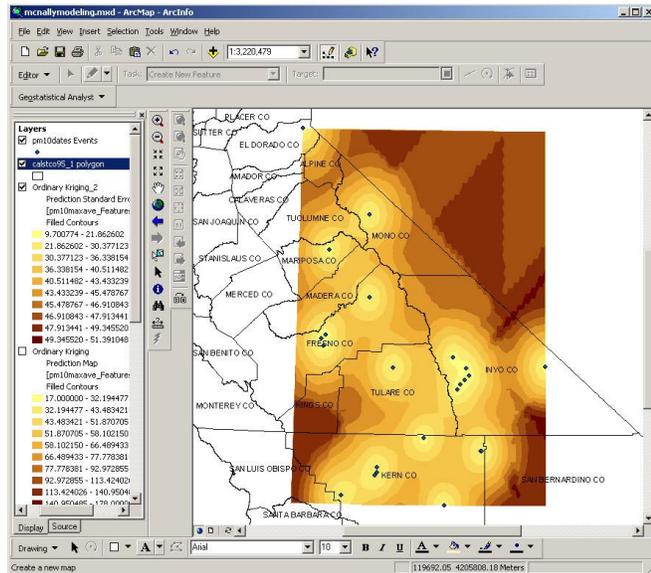
Air quality data from monitoring stations were transferred into ArcGIS, and a point coverage was created.

*Figure 8. Prediction map created using ordinary Kriging. Blue dots symbolize monitoring station locations. The map displays the  $PM_{10}$  24-hour average concentrations in  $\mu g/m^3$  averaged over the duration of the fire.*



The PM<sub>10</sub> 24-hour averaged data covered the duration of the fire from 21 July through 27 August. Ozone data was collected in two week averages and covered the following dates: 2 - 16 July, 16 - 30 July, 30 July - 13 August, and 13 - 28 August 2002.

Figure 9. Standard error map. The blue dots represent the monitoring sites. Predictions are more reliable closer to the monitoring sites.



RESULTS AND DISCUSSION

The following discussion used the satellite plume data, PM<sub>10</sub>, and ozone air quality data processes outlined in the methodology to analyze the impacts of the McNally fire.

Data Analysis Using Remote Sensing and GIS for PM<sub>10</sub>

Looking at Figure 10, it is evident that the locations with the highest frequency of smoke plume occurrences also had the highest PM<sub>10</sub> 24-hour Maximum concentrations. This finding indicates a positive correlation between frequencies of plume observed over the general fire area and production of particulate pollution measured as PM<sub>10</sub>.

The correlation between plumes and the average of the PM<sub>10</sub> 24-hour concentrations was not as strong (Figure 11).

When looking at the correlation coefficient  $r^2$  for PM<sub>10</sub> 24-hour averages and PM<sub>10</sub> 24-hour maximum, the interpretation is the same as the observations made before using GIS and remote sensing. A strong positive correlation between the frequency of smoke plumes and the concentrations of PM<sub>10</sub> 24-hour maximums for the duration of the fire was observed (with  $r^2 = 0.820$  and  $\alpha = 0.05$ ). For the duration of the fire, the correlation between frequency of smoke plumes and PM<sub>10</sub> 24-hour

Figure 10. The PM<sub>10</sub> 24-hour maximum concentrations ( $\mu\text{g}/\text{m}^3$ ) bar graph overlay over the plume layer.

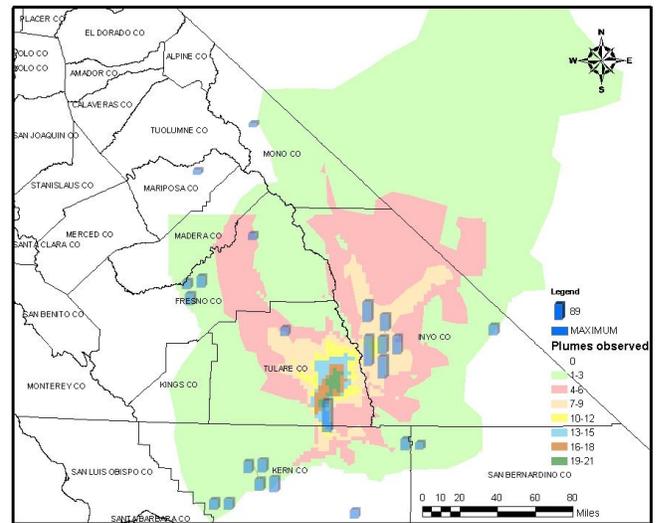


Figure 11. The average of the PM<sub>10</sub> 24-hour concentrations ( $\mu\text{g}/\text{m}^3$ ) bar graph overlay over the plume layer.

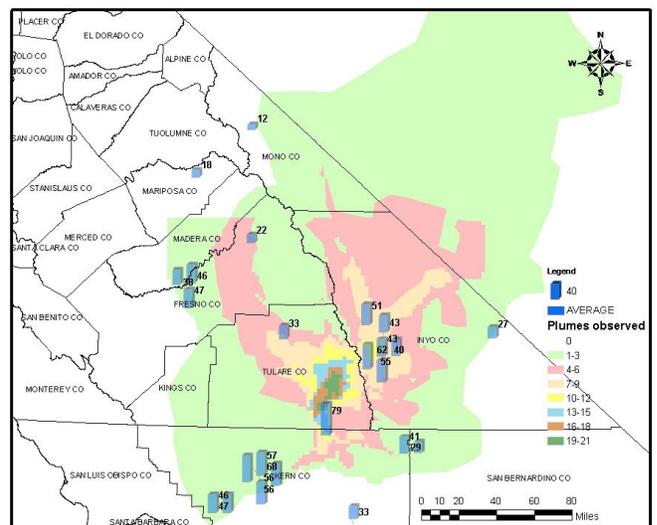


Figure 12. Two-week averages of ozone concentration (ppb) overlaid over the plume layer.

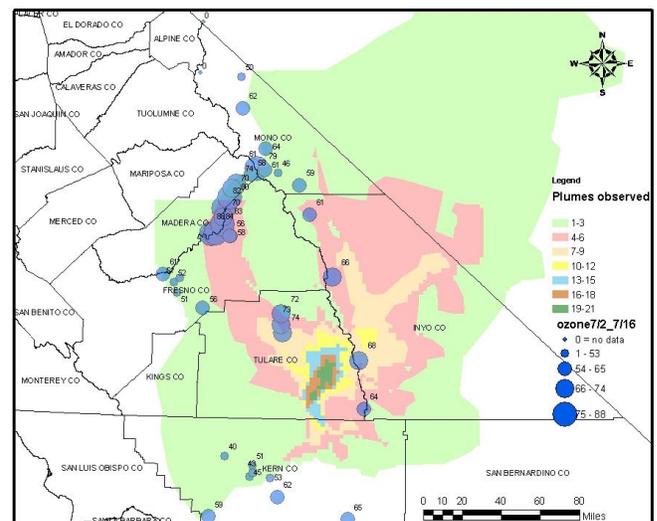


Figure 13. Ozone concentrations (ppb) and ozone monitoring locations, before the McNally fire.

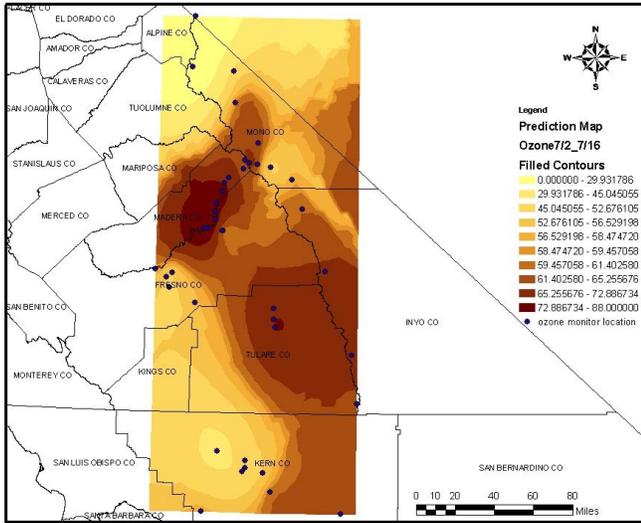
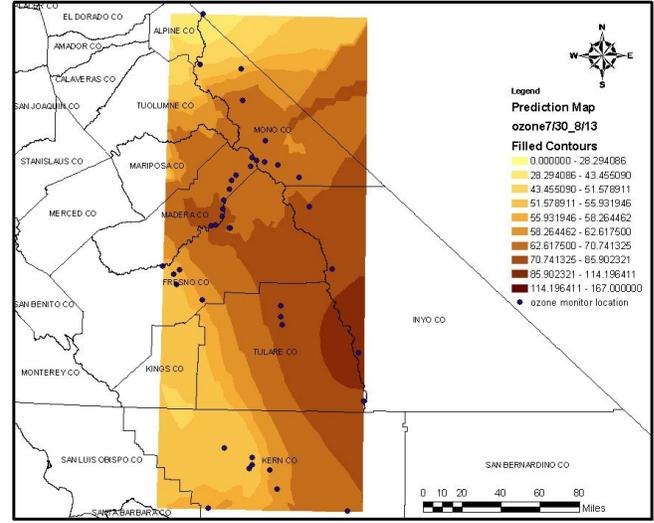


Figure 14. Ozone concentrations (ppb) and ozone monitoring locations, on 30 July 2002, during the McNally fire.



averages was also positive, but not as strong (with  $r^2 = 0.492$  and  $\alpha = 0.05$ ). It is clear that a large area of the Sierra Nevada experienced very high levels of  $PM_{10}$  concentrations during the fire.

**Data Analysis Using Remote Sensing and GIS for Ozone**

There is no observational evidence of correlation between frequency of smoke plumes and ozone concentrations (Figure 12).

Before the McNally fire started, the highest ozone two week concentration averages occurred in the mountain sites. Figure 13 illustrates a typical ozone distribution in the area before the fire started. During that period (2 - 16 July 2002), the maximum two week average did not exceeded 90 ppb.

During the fire (30 July - 13 August), the distribution of ozone concentrations is completely different. The highest concentrations occurred in the eastern part of the Sierra Nevada, downwind of the fire, with the maximum two week averages over 160 ppb. Figure 14 provides evidence of correlation between ozone generation and catastrophic

forest fires. In the Sierra Nevada, due to the proximity of the urban-related California Central Valley plume, which is rich in nitrogen oxides ( $NO_x$ ), there is a strong potential for generation of very high ozone concentrations when elevated concentrations of volatile organic compounds (VOCs) are present as a result of forest fires.

Ozone monitoring locations located in the San Joaquin Valley or in urban locations apparently were not affected by the McNally fire. Descriptive statistics are about the same before and during the fire for monitoring sites located in cities. Monitoring sites located in the mountains did show differences in ozone concentrations before and during the fire (Table 2).

**CONCLUSIONS**

In this paper, we outline a method for relating fire emissions to particulate matter and ozone concentrations using remote sensing and GIS. Locations that had the highest frequency of plume impacts also had the highest  $PM_{10}$  24-hour maximums concentrations. There is clear observational evidence of positive correlation between frequencies of plumes observed over a site with particulate

Table 2. Descriptive statistics of two-week ozone averages (ppb) for 40 ozone monitoring stations before and during the fire. The monitoring sites were classified as city (urban location), or mountain location.

Ozone Concentration (ppb)	2 - 16 July		16 - 30 July		30 July - 13 Aug.		13 - 28 Aug.	
	city	mtn.	city	mtn.	city	mtn.	city	mtn.
Mean	52.95	67.79	52.5	71.47	53.89	76.19	55.32	87.8
Maximum	65	88	65	90	68	167	73	186
Minimum	40	46	44	51	42	41	44	59
Average	24	42	21	39	25	126	29	127
Standard Deviation	7.4	10.8	6.4	11.2	9.2	24.1	9.7	24

matter air pollution. The highest  $PM_{10}$  maxima occurred in the eastern part of the Sierra Nevada closer to the fire and downwind of the fire. The McNally fire produced very high two-week average ozone concentrations in mountain sites, but there is no evidence that the fire affected sites in urban locations. During the fire, the highest ozone episodes occurred in the eastern part of the Sierra Nevada downwind of the fire.

Remote sensing and GIS approaches used in this paper could be beneficial for other air quality concerns such as for  $PM_{2.5}$ , and could be applied to analyze other wildfires. We conclude that GIS techniques and remote sensing could be extremely useful in evaluating wildfire impacts on air quality.

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