Wildfires and Respiratory Illness:
Linking Fire Events and Attributes to Health Outcomes

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Abstract

Existing studies on the economic impact of wildfire smoke have focused either on single fire events or entire fire seasons without distinguishing between individual occurrences. Neither approach allows for an examination of the marginal effects of fire attributes, such as distance and fuel type, on health impacts and costs. Yet, improved knowledge of these marginal effects can provide important guidance for efficient wildfire management strategies. This study aims to bridge this gap using detailed information on 35 large-scale wildfires in the California and Nevada Sierras that have sent smoke plumes to the Reno / Sparks area of Northern Nevada over a three-year period. We relate the daily acreage burned by these fires to daily data on local hospital admissions for acute respiratory syndrome. Using information on treatment expenses, we compute the per-acre cost of wildfires of different attributes with respect to respiratory admissions. We find that while nearby fires are four-five times more damaging than remote fires, hospital admissions can be causally linked to fires as far as 200-250 miles form the impact area. Our results highlight the economic benefits of fire suppression, and the importance of inter-regional agency collaboration in the management of forest fires.

Keywords: Wildfires, air quality, respiratory illness, distributed lag models, count data models

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1. Introduction

Optimal wildfire management policy requires information of the health effects and related economic costs caused by wildfire events. Kochi et al. (2010) synthesize existing studies that have examined the nexus of wildfires, air quality, and illness and conclude that there is still much to be learned about the causal impact of wildfires on health outcomes. Specifically, most existing contributions either consider a single fire event (Adamowicz et al., 2004; Viswanathan et al., 2006) or air quality changes over an entire fire season without controlling for individual burn events (Johnston et al., 2002a,b; Tham et al., 2009). This preempts a closer investigation of the marginal effects of even the most basic fire attributes, such as size, distance, and fuel load.

While there is a general notion that wildfire smoke can travel far before reaching population centers, the question of how health impacts change over fire distance remains unadressed. Similarly, existing studies considering a specific fire event have focused on the total health impact of the fire within a given time period, but not yet provided insights into the marginal effect per acre burned. Furthermore, given existing fuel models (Clinton et al., 2003) one can hypothesize that the latter will depend on the vegetation type consumed by a given fire.

Knowledge of these marginal effects can provide important guidance for wildfire management. For example, as noted in Kochi et al. (2010) and Kochi et al. (2011), averted health costs ought to be considered as one of the benefits of preemptive fuel reduction. Naturally, this requires knowledge on the marginal health cost per acre burned for areas that differ in fuel management or composition. By the same token, the benefits of wildfire suppression in remote areas will be under-estimated if no health cost avoidance value is assigned to such efforts, but smoke can nonetheless impact far away population zones.

This study aims at providing first estimates of wildfire-generated air pollution on health costs, differentiated along several dimensions of fire attributes. This requires detailed data on *daily* fire progression and health outcomes. To our knowledge such data have not yet been collected or combined in previous research. We benefit from what could be described as an ongoing natural experiment: The urban area of Reno / Sparks in Northern Nevada traditionally experiences smoke from numerous wildfire events every season. This is due to the typically dry conditions in the Sierra Nevada mountain range and foothills that border this area to the west, and the prevailing and persistent north-western to south-western wind patterns. Furthermore, some of these fires are as remote as 200 - 300 miles from the impact area, while others burn at the urban fringe. In addition, fires at any distance vary in fuel composition. They can occur in grassland, the sage/ juniper interface, or in large stands of mature timber. Thus, observing these fire events over several seasons provides the necessary variability in distance and fuel load to identify corresponding marginal effects.

At the same time, Nevada State law requires all hospitals to report data on inpatient admissions to research centers at State universities. This information allows us to track daily hospital admissions for illnesses traditionally related to severe air pollution over the same time period as the wildfire occurrences. We then take a Cost-of-Illness (COI) approach relating fire events and attributes to treatment costs (Kochi et al., 2010).

The following section provides details on the different components of our data set. Section III describes the econometric framework. Section IV discusses estimation results, and Section V concludes.

2. Data

2.1. Wildfire data

The time frame for our analysis ranges from March 3, 2005 to December 30, 2008, for a total of 1399 days. This is based on the availability of daily data on both air quality and and patient admissions. During this period the Reno / Sparks area experienced wind blowing from the northwest, west, and southwest for 67 percent of the time. Moreover, these wind directions governed the area for 80 percent of all days during the fire season months of May through September. On a typical summer day, winds start with a north-western direction in the morning, and then gradually rotate westward and stabilize at a south-western direction by mid-afternoon. Thus, we consider all separate wildfires that burned during this time period and occurred anywhere from the north-west to the west and south-west of the impact area. We allow for a distance radius of 500 miles and impose a minimum size threshold of 300 acres, thus focusing on larger wildfires.[1]

The spatial distribution of the resulting 35 separate fire events is depicted in Figure 1. Table 1 captures fire details, i.e. total acres burned (in units of 1000), start and end date, total duration in days, and distance from the Reno / Sparks area. Overall, these fires consumed over 1.2 million acres over the

[1]Holmes et al. (2008) estimate that fires exceeding 500 acres account for 94 percent of all acres burned in the Southern Sierra Nevada between 1910 and 2003.

research period. They range from a size of under 500 acres ("Vista Fire") to over 190,000 acres ("Klamath Theater Fire"), for an average of 35,000 acres. Some of them were extinguished within a few days, while others burned for many weeks. The mean duration is close to 22 days, yielding a total of 767 fire-days for our research period. Accounting for overlapping events, this translates into 296 separate days, or 21 percent of all research days, with at least one active fire upwind of the impact area. As shown in the last column of the table these fires occurred within a wide radius of Reno / Sparks, from the city limits to a distance of over 350 miles. The average distance is 148 miles.

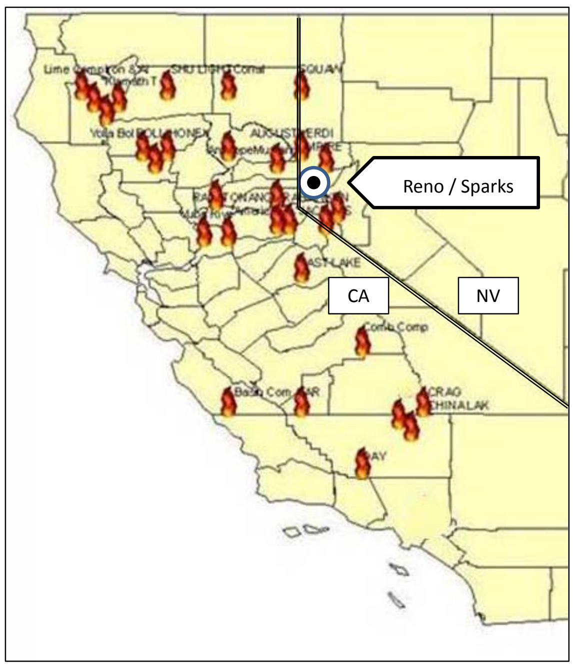

Figure 1: Location of wildfires and impact area

Wildfire information was obtained from the Western Great Basin Coordination Center (WGBCC) in Reno, Nevada, and the U.S. Forest Service's Incident Management Situation (SIT) reports for the affected areas, available online (National Fire and Aviation Management, 2011). Information on the daily acres burned was provided by a GIS specialist at the U.S. Forest Services Pacific Southwest Research Station in Albany, California. We augment and refine this Forest Service data with data from the daily fire tracking web site of the Western Institute for Study of the Environment (W.I.S.E.), a non-profit educational and research facility with headquarters in Corvallis, Oregon. This agency routinely collects daily fire information for the West and Northwest based on official media reports and updates provided by various federal and State agencies. It then posts the entire daily history for a given fire on its fire tracking web site (Western Institute for Study of the Environment, 2011). For burn days for which information on daily fire growth was not available (approximately 20-30% of fire-days) we estimate the consumed area via interpolation using the nearest known data points.

The entire time series of acres consumed by all relevant fires on a given calendar day is shown in the top panel of Figure 2. As is evident from the figure, the total number of daily acres burned ranges from a few hundred to over 40,000. There also appears to be a pattern of increasingly severe fire seasons over time, with the summer of 2008 marking the worst fire season in California since record keeping started in the 1970. We will relate this panel to the time series on patient admissions and air pollution below.

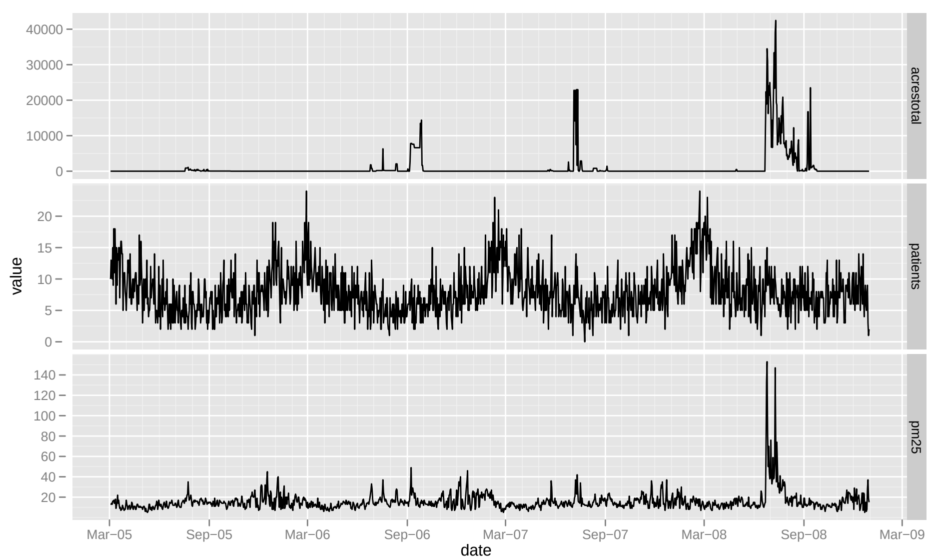

Figure 2: Daily time series of $pm_{2.5}$ ($\mu g/m^3$), patient admissions, and acres burned

On a given fire-event day in our series an average of 2.34 fires burned concurrently, with a maximum of 11 (June 29-30, 2008). Naturally, this preempts a clear identification of the exact source of a unit of $PM_{2.5}$ that reaches the impact area on or near those days. We thus settle for a distinction of total daily acres burned by the following distance zones: (I) 0-50 miles, (II)

Table 1: Large Wildfires upwind of Reno / Sparks, 2005-2008

name	State	acres	start	end	days	distance
China Lake	CA	5.3	7/19/2005	7/24/2005	5	123
Comb Complex	CA	8.675	7/22/2005	10/15/2005	85	96
Crag	CA	1.2	7/24/2005	7/29/2005	5	85
Empire	NV	3	6/25/2006	6/28/2006	3	95
Squaw	NV	2.095	6/25/2006	6/26/2006	1	100
Bootlegger	NV	6.669	7/6/2006	8/13/2006	38	40
Jackass	CA	6.255	7/17/2006	7/21/2006	4	80
Verdi	NV	5.661	8/11/2006	8/13/2006	2	5
August	NV	0.641	9/2/2006	9/2/2006	0	261
Day	CA	162.702	9/4/2006	10/2/2006	28	358
Ralston	CA	8.423	9/5/2006	9/17/2006	12	214
Mustang	CA	0.572	5/18/2007	5/19/2007	1	10
Bolli	CA	0.732	5/22/2007	5/27/2007	5	292
Honey	NV	0.688	5/22/2007	5/23/2007	1	267
Angora	CA	3.1	6/24/2007	7/2/2007	8	60
Antelope Complex	CA	136.777	7/5/2007	7/13/2007	8	101
Balls Canyon	CA	0.9	7/10/2007	7/13/2007	3	16
Hawken	NV	2.708	7/16/2007	7/23/2007	7	0
Sand Pass	NV	6.999	7/17/2007	7/19/2007	2	50
Tar	CA	5.642	8/10/2007	8/16/2007	6	33
Vista	CA	0.471	8/22/2007	8/27/2007	5	78
North	CA	2.2	9/2/2007	9/8/2007	6	103
East Lake	NV	0.962	4/29/2008	4/30/2008	1	15
Lime Complex	CA	99.586	6/20/2008	8/15/2008	56	346
Klamath Theater	CA	192.038	6/21/2008	9/30/2008	101	247
Iron & Alps Complex	CA	105.606	6/21/2008	9/1/2008	72	196
Yolla Bolly Complex	CA	89.663	6/21/2008	8/19/2008	59	311
Shu Lightning Complex	CA	86.5	6/21/2008	7/25/2008	34	326
BTU Lightning Complex	CA	59.44	6/21/2008	7/29/2008	38	109
Canyon Complex	CA	38.509	6/21/2008	8/14/2008	54	260
American River Complex	CA	20.541	6/21/2008	8/1/2008	41	221
Basin Complex	CA	147.114	6/21/2008	7/27/2008	36	241
Yuba River Complex	CA	4.254	6/21/2008	7/15/2008	24	70
Corral	CA	12.434	6/23/2008	7/7/2008	14	325
Gooseberry	NV	3.042	7/29/2008	7/31/2008	2	49.5

51-100 miles, (III) 101-250 miles, and (IV) $>$ 250 miles. This yields an approximately even distribution of fire incidents per zone. However, more distant fires tend to be substantially larger than fires that occurred near the urban interface. Specifically, the average fire size, in total acres consumed, lies at close to 4,000 acres for distance zones I and II, and, respectively, at

75,000 and 55,000 for zones III and IV. This is as expected, as remote fires in the heart of the Sierras are generally more difficult to combat and thus have more time to grow in size.

The SIT reports posted by the National Fire and Aviation Management (2011) also include information on the primary ecosystems affected by each fire. We ex ante consider four broad categories, based on the the standard 13 fuel types originally proposed by Deeming et al. (1978). These are (i) grass, (ii) sage brush, (iii) pinon juniper, (iv) timber, and (v) slash. Since the exact distribution of burned acreage over these fuel types is unknown, we assign equal weights to all fuel types involved. The resulting distributions of total acres consumed for each fuel type and distance category are shown in Figure 3. As is evident from the figure, near-distance fires occur primarily in grass / sage brush ecosystems, while the pinon-juniper type dominates the mid-distance zone of 51-100 miles. In contrast, timber constitutes the primary fuel type for the remote zones III and IV. This inter-dependency of fuel distributions and distance zones has important implications for our econometric modeling below. Specifically, both distance and fuel type need to be included in an econometric specification to avoid omitted confounding effects.

2.2. Air quality and meteorological data

We follow the bulk of existing studies at the interface of wildfire, air quality, and health and focus on fine particulate matter ($PM_{2.5}$) as the signature fire pollutant that has been found to cause respiratory problems in impacted areas (e.g. Fowler, 2003; Rittmaster et al., 2006; Viswanathan et al., 2006). Data on average daily levels of $PM_{2.5}$ and other pollutants were obtained via the Washoe County Health District's air quality management reports and data web site (Washoe County Health District, 2011). Daily meteorological data for the Reno/Sparks area were downloaded from the National Climatic Data Center (NCDC)'s data repository site (National Climatic Data Center, 2011). Summary statistics for the meteorological variables used in our econometric models (see below) are given in Table 2.

The average daily value for $PM_{2.5}$ for our entire time series is 15.8 $\mu g/m^3$, with a standard deviation of 9.6 $\mu g/m^3$. The 24-hour EPA standard of 35 $\mu g/m^3$ is exceeded on 38 or 2.7% of research days. The annual EPA standard of 15 $\mu g/m^3$ is slightly exceeded in 2006 and 2007, and clearly exceeded in 2008 (annual average = 18.1 $\mu g/m^3$). The daily series is plotted in the bottom panel of Figure 2. The graph depicts a clear seaonal pattern with increased $PM_{2.5}$ levels in the winter months. This is consistent with the Reno/Sparks basin's inversion pattern that often traps polluted air during

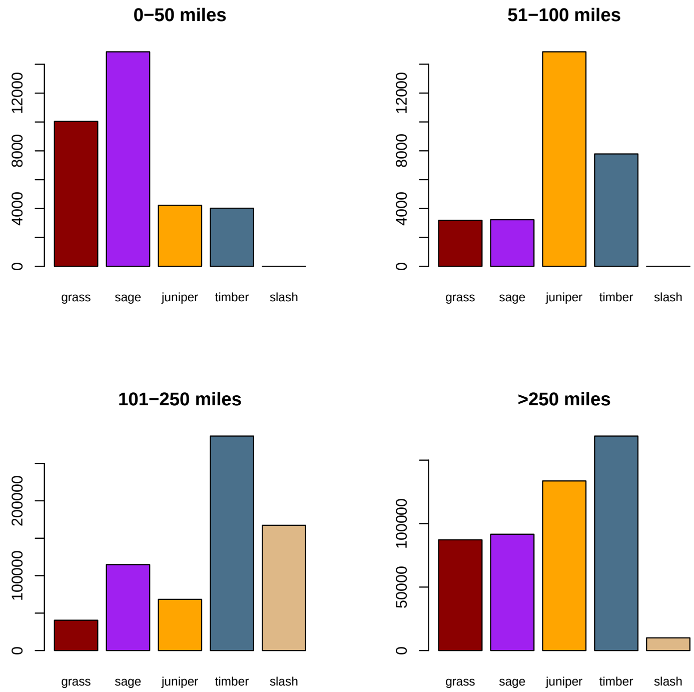

Figure 3: Acres burned by distance zone and fuel type

Table 2: Meteorological data, Reno / Sparks, 2005-2008

climat variable	units	mean	std	min	max
avg. temperature	Fahrenheit	55.28	16.59	14.00	89.80
min. temperature	Fahrenheit	40.78	13.96	3.00	73.40
max. temperature	Fahrenheit	71.52	18.25	28.00	108.00
avg. daily dew point	Fahrenheit	28.00	8.52	-2.40	54.80
avg. wind speed	knots	5.34	3.13	0.10	22.00
max. sustained wind speed	knots	15.21	6.05	2.90	42.00
precipitation	inches	0.02	0.09	0.00	1.54
minimum relative humidity	percent	22.34	14.16	3.00	89.00
maximum relative humidity	percent	64.89	17.51	26.00	100.00
avg. daily air pressure	inches of mercury	25.59	0.14	25.05	26.06

the cold season. In addition, more particulate matter is released during that time through domestic wood burning. However, and importantly for our research, the graph also shows a clear temporal correspondence of elevated $PM_{2.5}$ levels and daily acres burned, as can be gleaned from a comparison of the top and bottom panels of Figure 2. This correlation is especially apparent during the "record" 2008 fire season, with $PM_{2.5}$ levels reaching peaks of $140 \mu g/m^3$ and higher.

2.3. Hospital data

Patient admissions data were provided by The Center for Health Information Analysis (CHIA) at the University of Nevada, Las Vegas, and the Nevada Center for Health Statistics and Informatics at the University of Nevada, Reno. Under State law, these Centers collect and maintain billing records from Nevada hospital and ambulatory surgical centers. Among other information, these medical outfits are required to submit daily inpatient data to these Centers on a regular basis. For this analysis we consider all respiratory disease cases as captured by International Disease Codes (IDCs) 460.0-486.99, and 488.0-519.99, except for influenza (IDC 487.00-487.99). The Nevada Center for Health Statistics and Informatics also made available summary statistics of treatment length and costs for our targeted time period and illness codes.

As noted in Kochi et al. (2010) the effect of air pollution can vary greatly over demographic segments. Specifically, the very young and the elderly may be especially vulnerable to wildfire smoke. We therefore assign special attention to the age groups of "under five" and "over 64". Table 3 captures admission counts, treatment duration, and treatment costs for the three resulting population segments and the overall sample. Overall, 11,113 patients were admitted for acute respiratory syndromes over our research period. This translates into an average daily count of 7.94, with a standard deviation of 3.7. The sample average for length-of-stay is close to six days, resulting in average treatment costs of over $46,000. Admission counts, treatment duration, and costs are highest for the over-64 population segment, and lowest for the under-5 group.

The entire time series of daily admissions is plotted in the center panel of Figure 2. The graph shows a clear seasonal pattern with peaks in mid-late winter and troughs in late summer / early fall. The late winter highs likely reflect the poorer air quality during the cold season (see above), perhaps combined with the onset of the spring allergy season. There also seems to be a mild correlation of admissions with winter peaks of $PM_{2.5}$. Contemporaneous patterns with acres burned and resulting non-winter peaks of $PM_{2.5}$ are less obvious at this multi-year scale. However, when zooming in on a narrower time frame closer correlation patterns can be discerned. This is

Table 3: Patient counts and treatment details

	Admission counts				length of stay (days)	cost ($000)
age group	total	mean	std	median	mean	mean
under 5	1,236	0.88	1.14	1	3.27	16.837
5 - 64	4,485	3.2	1.94	3	5.74	47.245
over 64	5,392	3.85	2.2	4	6.24	51.293
all	11,113	7.94	3.7	7	5.74	46.215

shown in Figure 4, which focuses on the 2008 fire season. Acres burned and $PM_{2.5}$ are well-synchronized, and patient counts appear also reactive to fires, at least during the most intense burn period. We examine the relationship between wildfire intensity, fine particulate matter, and hospital admissions more rigorously in our econometric modeling framework.

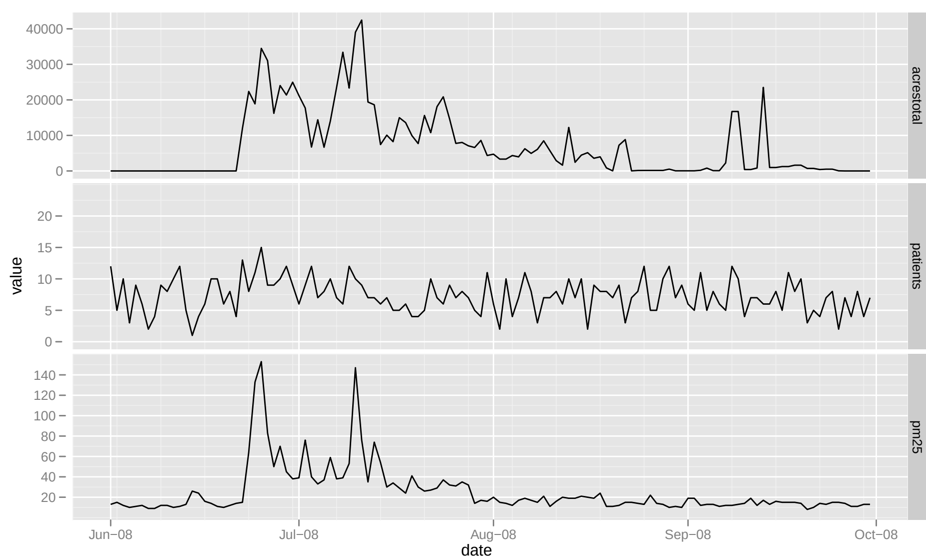

Figure 4: Daily time series of $pm_{2.5}$ ($\mu g/m^3$), patient admissions, and acres burned, 2008 fire season

3. Econometric Framework

3.1. $PM_{2.5}$ model

We first relate daily $PM_{2.5}$ measurements to wildfire activity and a set of control variables. Specification tests based on preliminary regression runs clearly indicate the presence of first-order autocorrelation. We thus employ an auto-regressive distributed lag (ARDL) regression model with the dependent variable given as daily $PM_{2.5}$ in micro-grams per cubic meter. Formally, the model can be stated as

$$\begin{aligned} y_{it} &= \mathbf{x}_f'\boldsymbol{\beta} + \mathbf{x}_m'\boldsymbol{\gamma} + \mathbf{x}_t'\boldsymbol{\delta} + \epsilon_t, \quad \text{with} \\ \epsilon_t &= \rho\epsilon_{t-1} + \mu_t, \quad \text{where} \quad \mu_t \sim n\left(0, \sigma^2\right) \end{aligned} \tag{1}$$

The first set of regressors, $\mathbf{x}_f$, includes interactions of acres burned by fuel types and distance zones. Given the limited cell counts for some of the resulting combinations, we combine fuel types "sage" and "juniper", and, respectively, "timber" and "slash" into common categories. Considering typical sustained wind speeds of 10-20 mph in the Sierras and eastern foothills, we assume that smoke from a given burn zone should reach the impact area within a day or two for even the most remote fires in our set. We thus allow for two lags for these fuel / distance interactions for all but the nearest zone. For the latter, we only consider current values.[2] For ease of exposition, all acres-burned measures are scaled to units of 100 in our empirical model.

The second set of covariates, denoted as $\mathbf{x}_m$, captures daily meteorological statistics for the Reno / Sparks area. These include average temperature (`avgtemp`), mean daily dew point (`dewp`), average and maximum sustained wind speed (`avgwind, maxwind`), precipitation (`prcp`), minimum and maximum relative humidity (`mnrh, mxrh`), and average daily air pressure (`pres`).

The final vector of explanatory variables, labeled $\mathbf{x}_t$ in (1), collects monthly indicator terms, with January as the baseline period. This controls for seasonal variation in $PM_{2.5}$, such as increased levels due to inversion conditions and wood burning in winter. The model is completed by three corresponding sets of coefficients, $\boldsymbol{\beta}, \boldsymbol{\gamma}$ and $\boldsymbol{\delta}$, and an autoregressive normal error term with first-order autocorrelation parameter ρ.

[2]Preliminary regression runs did not provide evidence of significant lags for the nearest distance zone.

3.2. Patients model

We follow existing contribution to the air pollution / health outcome literature (e.g. Smith et al., 2000; Clyde, 2000) and model the effect of $PM_{2.5}$ on the daily number of respiratory hospital admissions within a count data regression framework. Specifically, we assume patient counts to follow a Negative Binomial (NegBin) distribution with a log-linear parameterized mean function, i.e.:

$$\begin{aligned}
&f\left(y_t|\lambda_t\right)=\frac{\Gamma\left(y_t+\nu\right)}{\Gamma\left(y_t+1\right)\Gamma\left(\nu\right)}\left(\frac{\nu}{\lambda_t+\nu}\right)^{\nu}\left(\frac{\lambda_t}{\lambda_t+\nu}\right)^{y_t}, \quad \text{with}\\
&E\left(y_t\right)=\lambda_t, \quad V\left(y_t\right)=\left(\lambda_t+\frac{1}{\nu}\lambda_t^2\right), \quad \text{and}\\
&\lambda_t=exp\left(\mathbf{z}_p'\boldsymbol{\beta}+\mathbf{z}_m'\boldsymbol{\gamma}+\mathbf{z}_t'\boldsymbol{\delta}\right)
\end{aligned} \tag{2}$$

This corresponds to Cameron and Trivedi's (1986) NegBin II specification with expectation λ_t and precision parameter ν. The parameterized mean function λ_t includes three sets of regressors: $\mathbf{z}_p$, a vector of air pollutant measures, meteorological indicators $\mathbf{z}_m$, and temporal indicators $\mathbf{z}_t$. Pollutants include $PM_{2.5}$, carbon monoxide (CO), and Ozone (O^3). The second is another signature ingredient of biomass smoke (e.g. Fowler, 2003), and the third is another known irritant that can trigger respiratory ailments (U.S. Environmental Protection Agency, 2011). The vector of meteorological variables is identical to $\mathbf{x}_m$ in the $PM_{2.5}$ model, with the addition of daily minimum and maximum temperature (`mintemp, maxtemp`). The temporal variables in $\mathbf{z}_t$ include monthly indicators (baseline = January) and an indicator for "weekend".[3] We estimate separate admission count models for the entire sample, and the sub-populations of "under five" and "over 64".

4. Estimation results

4.1. $PM_{2.5}$ model

We estimate the $PM_{2.5}$ model via Full-Information-Maximum-Likelihood (FIML), which produces estimates of all slope coefficients, along with the error correlation coefficient ρ and the variance of the i.i.d. stochastic component σ^2. The results from this model are captured in Table 4. In general one

[3] Preliminary estimation runs did not suggest any significant lagged effects for either pollutants or meteorological indicators.

would expect positive marginal effects for all fuel / distance combinations that diminish over distance zones. While several of the estimated coefficients for fuel / distance regressors have counter-intuitive negative signs, they generally follow the pattern of diminishing marginal effects with increasing distance. The timber / slash fuel category exhibits the pattern most consistent with intuition, at least beyond the 50-mile range. When added over lags the marginal effects of acres burned for zones II, III, and IV are significant, positive and taper off with increasing remoteness from the impact area.[4] This is captured in Table 5. For example, an additional 100 acres burned in an area dominated by timber / slash within the preceding two days and including the current day increases the $PM_{2.5}$ count by 1.39 $\mu g/m^3$ for fires that occur between 50 and 100 miles from the impact area. This effect reduces to 0.30 $\mu g/m^3$ for fires in zone III (101 - 250 miles), and to 0.14 $\mu g/m^3$ for fires in zone IV ($>$ 250 miles).

Table 5 also suggests that the impact of grass burns is strongest for near-distance fires, while wildfires in the sage / juniper interface have the most detrimental impact on air quality if they occur in the 51-100 mile zone. While this may reflect different dispersion patterns, it may also be an artifact of small sample counts for these fuel types for some of the distance zones.

4.2. Patients model

The patients model is estimated via Maximum Likelihood (MLE), which generates estimates of the elements of the slopes in the parameterized mean function, and the inverse of the precision parameter ν. Estimation results for the three NegBin models of patient admissions are captured in Table 6. The key finding from this analysis is the significant to highly significant effect of $PM_{2.5}$ in all three population models. Furthermore, these effects differ across population segments. As shown in the first column of the table, the full-sample model estimates an increase in expected respiratory admissions by 0.63% due to a one $\mu g/m^3$ increase in $PM_{2.5}$ concentration. This effect is approximately 50% higher for young children (column three), and 24% lower for the elderly population (column five). In comparison, the other two pollutants, `co` and `ozone`, are not associated with significant effects on admission counts for any of the population categories. Of the meteorological

[4] In distributed lag models a combined or "cumulative" marginal effect can be computed by adding the estimated coefficients for current and lagged effects for a given regressor. See for example Koop and Tole (2004).

Table 4: Estimation results for $PM_{2.5}$ model

variable	coeff.	(s.e.)		variable	coeff.	(s.e.)	
grass (50)	0.990	(0.254)	***	avgtemp	0.058	(0.049)	
grass (100)	0.555	(1.542)		dewp	-0.049	(0.052)	
lag 1	-1.104	(1.076)		avgwind	-0.568	(0.092)	***
lag 2	-1.812	(0.877)		maxwind	-0.066	(0.047)	
grass (250)	-0.260	(0.068)	***	prcp	-4.572	(2.266)	**
lag 1	-0.330	(0.088)	***	mnrh	-0.011	(0.023)	
lag 2	0.829	(0.086)	***	mxrh	0.036	(0.024)	
grass (>250)	0.621	(0.057)	***	pres	-1.192	(1.699)	
lag 1	-0.345	(0.058)	***	feb	-4.337	(1.734)	**
lag 2	0.159	(0.090)		mar	-6.150	(1.838)	***
sage/junip. (50)	-0.126	(0.196)		apr	-5.952	(1.853)	***
sage/junip. (100)	0.110	(0.366)		may	-5.077	(1.813)	***
lag 1	0.900	(0.287)	***	jun	-5.149	(2.153)	**
lag 2	1.415	(0.242)	***	jul	-4.487	(2.052)	**
sage/junip. (250)	-0.308	(0.022)	***	aug	-5.877	(2.102)	***
lag 1	0.109	(0.017)	***	sep	-5.791	(1.970)	***
lag 2	-0.022	(0.025)		oct	-5.766	(1.890)	***
sage/junip. (>250)	-0.061	(0.022)	***	nov	-2.980	(1.424)	
lag 1	-0.072	(0.017)	***	dec	-0.185	(1.114)	
lag 2	0.123	(0.020)	***	constant	49.306	(44.405)	
timber / slash (50)	0.603	(1.041)					
timber / slash (100)	0.230	(0.265)		rho	0.458	(0.016)	***
lag 1	0.582	(0.138)	***	sigma	4.929	(0.058)	***
lag 2	0.578	(0.094)	***				
timber / slash (250)	0.250	(0.010)	***				
lag 1	-0.026	(0.010)	***				
lag 2	0.075	(0.011)	***				
timber / slash (>250)	0.060	(0.054)					
lag 1	0.155	(0.050)	***				
lag 2	-0.075	(0.074)					

significance levels: *** 1%, ** 5%, * 10%

covariates, only `avgtemp` has a (positive) marginal effect that is persistent across population groups. In addition, there is an - expected - significant negative weekend effect for the full sample (which includes all of the working residents). The month indicators reflect the pattern from Figure 2: patient admissions are highest in February / March, and lowest July - September, ceteris paribus.

Table 5: Marginal effects for $PM_{2.5}$ model

fuel (distance)	point		lower	upper	
	estimate	(s.e.)	(95% C.I.)	(95% C.I.)	
grass (50)	0.990	(0.254)	0.493	1.487	***
grass (100)	-2.362	(2.767)	-7.785	3.062	
grass (250)	0.238	(0.170)	-0.096	0.572	
grass (>250)	0.435	(0.090)	0.259	0.611	***
sage / juniper (50)	-0.126	(0.196)	-0.511	0.259	
sage / juniper (100)	2.425	(0.535)	1.375	3.474	***
sage / juniper (250)	-0.221	(0.030)	-0.281	-0.162	***
sage / juniper (>250)	-0.010	(0.034)	-0.076	0.056	
timber / slash (50)	0.603	(1.041)	-1.437	2.642	
timber / slash (100)	1.390	(0.416)	0.574	2.206	***
timber / slash (250)	0.299	(0.018)	0.263	0.335	***
timber / slash (>250)	0.140	(0.071)	0.002	0.279	**

significance levels: *** 1%, ** 5%, * 10%

4.3. Marginal fire effects on patient admissions

So far our estimation results suggest a clear link between fire events and $PM_{2.5}$ concentration in the impact area, as well as a link between the latter and patient admission counts. We combine these findings and compute a point estimate for the direct effect of acres burned (in units of 100) for a given fuel / distance combination on admissions by multiplying the cumulative marginal effect from the $PM_{2.5}$ model (as captured in Table 5) with the marginal $PM_{2.5}$ effect from the patients model for a given population group. We derive standard errors and confidence intervals for these combined effects via simulation. We then translate these marginal impacts into changes in treatment costs by multiplying the expected increase in daily admissions by the population-segment specific treatment costs as given in Table 3 above.

For this final step of our analysis we focus on the timber / slash fuel type, and on distance zones II, III, and IV, given the intuitively sound results for these combinations from the $PM_{2.5}$ model. Table 7 shows the percentage change in daily patient admissions, and the total change in daily treatment costs from an additional loss of 100 acres to wildfire in timber-dominated fuel systems. The first block of rows refers to the entire sample, while the second and third blocks capture, respectively, output for the "under 4" and "over 4"' population segments.

As is evident from the table, an additional 100 acres of burned timber

Table 6: Results for the respiratory admissions model

	all			under 4			over 64		
variable	coeff.	(s.e)		coeff.	(s.e)		coeff.	(s.e)	
constant	7.5977	(2.332)	***	-3.8757	(6.576)		4.9575	(3.289)	
pm25	0.0063	(0.001)	***	0.0090	(0.004)	**	0.0048	(0.002)	***
co	-0.0019	(0.078)		-0.1767	(0.227)		0.0547	(0.110)	
ozone	-3.0316	(2.126)		-3.5829	(6.533)		-0.9855	(2.958)	
avgtemp	0.0113	(0.005)	**	0.0288	(0.014)	**	0.0145	(0.007)	**
dewp	-0.0015	(0.003)		0.0205	(0.010)	**	-0.0053	(0.004)	
avgwind	0.0014	(0.006)		0.0050	(0.018)		0.0010	(0.009)	
maxwind	0.0038	(0.003)		0.0108	(0.008)		0.0032	(0.004)	
maxtemp	-0.0050	(0.003)		-0.0184	(0.009)	**	-0.0010	(0.005)	
mintemp	-0.0049	(0.004)		-0.0229	(0.010)	**	-0.0105	(0.005)	**
prcp	0.0637	(0.111)		-0.4499	(0.331)		0.1881	(0.154)	
mnrh	0.0008	(0.002)		-0.0065	(0.005)		0.0028	(0.002)	
mxrh	0.0004	(0.002)		0.0024	(0.004)		0.0016	(0.002)	
pres	-0.2131	(0.089)	**	0.1701	(0.250)		-0.1540	(0.125)	
weekend	-0.1439	(0.023)	***	-0.3198	(0.070)	***	-0.1306	(0.032)	***
feb	0.3573	(0.049)	***	0.4335	(0.118)	***	0.4177	(0.070)	***
mar	0.2217	(0.053)	***	0.1185	(0.135)		0.2624	(0.076)	***
apr	-0.0742	(0.061)		-0.4240	(0.164)	***	0.0077	(0.086)	
may	-0.2005	(0.070)	***	-0.9104	(0.204)	***	-0.0538	(0.099)	
jun	-0.3509	(0.081)	***	-1.1357	(0.241)	***	-0.1601	(0.113)	
jul	-0.5106	(0.092)	***	-1.4697	(0.282)	***	-0.3843	(0.129)	***
aug	-0.4774	(0.088)	***	-1.4792	(0.274)	***	-0.3201	(0.123)	***
sep	-0.4197	(0.076)	***	-1.3315	(0.232)	***	-0.2944	(0.107)	***
oct	-0.3147	(0.063)	***	-1.1051	(0.187)	***	-0.2446	(0.090)	***
nov	-0.3144	(0.055)	***	-1.0798	(0.162)	***	-0.2209	(0.079)	***
dec	-0.1720	(0.048)	***	-0.6689	(0.131)	***	-0.0983	(0.069)	
$1/\nu$	0.0074	(0.005)		0.0066	(0.037)		0.0023	(0.010)	

significance levels: *** 1%, ** 5%, * 10%

within 51-100 miles from the impact area increases patient admissions for acute respiratory illness by close to 1%, with an empirical 95% confidence interval of $[0.3\%, 1.5\%]$. Applying this marginal percentage effect to the sample mean of 7.94 admissions, and multiplying by the average cost per patient ($46,215) produces a marginal increment of $3,206 in treatment costs. For distance zone III the expected percentage change in admissions reduces to 0.19%, yielding an expected marginal increase in treatment costs of $696. The 100-acre marginal effect for wildfires in the > 250 mile range is 0.09% for changes in admission, and $329 for increased treatment costs.

Table 7: Marginal changes in patient admissions and treatment costs per 100 acres burned

	admissions (% change)				treatment cost ($)			
		all						
distance	estimate	s.e.	low	high	estimate	s.e.	low	high
51-100	0.874	(0.320)	0.308	1.544	3206	(1174)	1131	5667
101-250	0.190	(0.040)	0.116	0.268	696	(145)	424	984
>250	0.090	(0.050)	-0.001	0.198	329	(182)	-5	728
		under 4						
distance	estimate	s.e.	low	high	estimate	s.e.	low	high
51-100	1.244	(0.666)	0.133	2.737	184	(99)	20	406
101-250	0.271	(0.117)	0.031	0.499	40	(17)	5	74
>250	0.129	(0.091)	-0.004	0.357	19	(13)	-1	53
		over 64						
distance	estimate	s.e.	low	high	estimate	s.e.	low	high
51-100	0.660	(0.320)	0.141	1.368	1303	(631)	279	2702
101-250	0.143	(0.052)	0.044	0.239	282	(102)	86	473
>250	0.067	(0.043)	-0.001	0.146	132	(85)	-2	324

Considering the average fire size of 4,000 acres for distance zone II during our research period, we can thus infer that the typical (timber-dominated) wildfire event within 51-100 miles from Reno / Sparks causes damages of $128,246 in increased hospitalization costs for acute respiratory syndrome, with a 95% confidence interval of [$45,000, $227,000]. Similarly, a typical zone III timber fire with expected size of 75,000 acres translates into increased hospitalization costs of $522,000, with a 95% confidence interval of [$318,000, $728,000]. A 55,000 acre fire in remote zone IV still causes an expected $18,000 in increased costs, although the lower 95% confidence bound falls below zero.

4.4. Conclusion

To our knowledge this study constitutes the first effort to relate wildfire smoke related health costs to individual wildfire attributes. We find strong evidence that wildfire smoke affects health outcomes via an increase in ambient $PM_{2.5}$ concentration. Furthermore, our results indicate that the magnitude of this impact is dependent on distance from the smoke-affected population zone, and varies over fuel type. More refined data on the exact fuel composition associated with a given fire event will be needed to fully validate the latter result.

While our estimated marginal hospitalization costs are non-negligible, they should best be interpreted as lower bounds of broader smoke-related health-care costs, which would include costs of treatment for patients that sought medical assistance, but were not admitted to a local hospital. In turn, as has been discussed elsewhere (e.g. Rittmaster et al., 2006; Kochi et al., 2010) medical treatment-related costs are likely to constitute only a small fraction of total economic cost to the affected population, which would include components such as decreased productivity and forgone recreational opportunities.

Overall, our results clearly suggest that even wildfires that occur hundreds of miles from a given population zone can, under certain wind conditions, induce smoke-related health damages. These potential damages need to be taken into account in the design of optimal wildfire management policies.

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