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Forecast-based interventions can reduce the health and economic burden of wildfires

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Abstract (≤200 words)

We simulated public health forecast-based interventions during a wildfire smoke episode in rural North Carolina to show the potential for use of modeled smoke forecasts toward reducing the health burden and showed a significant economic benefit of reducing exposures. Daily and county wide intervention advisories were designed to occur when fine particulate matter ($PM_{2.5}$) from smoke, forecasted 24 or 48 hours in advance, was expected to exceed a predetermined threshold. Three different thresholds were considered in simulations, each with three different levels of adherence to the advisories. Interventions were simulated in the adult population susceptible to health exacerbations related to the chronic conditions of asthma and congestive heart failure. Associations between Emergency Department (ED) visits for these conditions and daily $PM_{2.5}$ concentrations under each intervention were evaluated. Triggering interventions at lower $PM_{2.5}$ thresholds (≤20µg/m^3) with good compliance yielded the greatest risk reduction. At the highest threshold levels (50µg/m^3) interventions were ineffective in reducing health risks at any level of compliance. The economic benefit of effective interventions exceeded $1 million in excess ED visits for asthma and heart failure, $2 million in loss of productivity, $100K in respiratory conditions in children, and $42 million due to excess mortality.

Introduction

Wildfires are episodic events that emit high concentrations of air pollutants, including fine particulate matter ($PM_{2.5}$) and ozone (O_3), that adversely affect human health [1, 2]. A recent assessment [3] attributed over 5,000 premature deaths, 5,000 non-fatal heart attacks, 4,000 respiratory and cardiovascular hospital and emergency department visits, 200,000 cases of upper and lower respiratory symptoms, and over 840,000 days of school lost to wildfire-related $PM_{2.5}$ and O_3 emissions in 2005 nationwide. Because the wildfire events are expected to increase in size and severity [4, 5], it is increasingly important to develop cost effective tools that communities can use to reduce the public's exposure to wildfire-related smoke.

The frequency and intensity of landscape fires in the U.S. have steadily increased in recent decades. A growing number of communities affected by smoke events need decision support tools that characterize the scope and magnitude of smoke-related risks, communicate these health risks and identify effective intervening actions in real time. Costly and disruptive recommendations such as canceling social and business activities can reduce the public's confidence in smoke advisories and thus make them less effective in reducing exposure. Recent technological advances in forecasting of smoke plumes may be an important tool in informing these decisions, but their effectiveness in reducing the health and economic burden during smoke events has not been evaluated.

Over the past decades, public health tools such as AirNow have been developed to communicate health risks associated with daily fluctuations in ambient air quality [6]. AirNow is a real-time web based tool that provides individuals with the information they need to alter their own daily exposure to air pollution. However, these tools use data from air pollution monitors mostly located in urban areas and cannot predict the location of a smoke plume in advance—particularly those plumes in remote areas where fires often occur. Using satellite observations, data about weather patterns, and information regarding fire emissions, smoke forecasting models can predict rapidly moving plumes and emissions of air pollutants at a fine spatial and temporal resolution. Smoke forecasting models can also predict pollutant levels up to several days ahead and thus provide timely data needed to inform public health interventions before the exposures occur.

In this study, we explore the human health economic benefits that could be realized by using smoke forecast-based interventions to provide timely information to communities. We used the case of the 2008 North Carolina Evans Road peat wildfire for which we previously reported statistically significant increases in Emergency Department (ED) visits associated with smoke exposure for asthma, COPD, pneumonia and acute bronchitis, and congestive heart failure, as well as symptoms involving the respiratory system and other chest pain symptoms [7]. Here, we simulate forecast-based interventions implemented at the county level, designed to reduce personal exposure in populations susceptible to complications from smoke. Based on the previous report we use asthma and congestive heart failure related ED visits. The interventions hypothetically take place on days in which a 24hr-ahead or 48hr-ahead smoke forecast model predicted $PM_{2.5}$ concentrations that exceeds a predetermined threshold and where the targeted population assumes a level of adherence to the advisories. The simulated interventions vary by the levels of smoke used to trigger advisories and by the level of adherence to these advisories. For each intervention we evaluate the association between asthma and congestive heart failure related ED visits and smoke based $PM_{2.5}$ and then quantify the economic value of non-avoidance of smoke in these outcomes as well as in number of general health outcomes to show that forecast-based interventions can significantly reduce the health burden and thus bring economic benefit to wildfire affected communities.

Methods

The Affected Population

We used the North Carolina 2008 Evans Road fire as a case study. The details about this fire and its impacts on respiratory and cardiovascular ED visits have been previously described [7]. Briefly, the fire was initiated by lightening on June 1, 2008 after which it burned through 42 thousand acres of peat soil in the Pocosin Lakes National Wildlife Refuge. The study period was defined between the onset of the wildfire (June 1, 2008) and mid-July (July 14th, 2008) although a small fire continued to smolder through January 2009. During this time smoke intermittently affected populations in nearby counties. The largest smoke episode took place between June 10th and June 12th when winds shifted inland. The affected population was largely economically disadvantaged, inhabiting rural areas with no other significant sources of air pollution. For the purpose of this study we defined the affected population to include the residents of the 31 counties in eastern North Carolina where cumulative exposure over the study period exceeded $50 \mu g/m^3$ of $PM_{2.5}$. The total population in these counties was 1.2 million adults over 18 years of age.

Exposure Estimates

We obtained estimates and forecasts of $PM_{2.5}$ concentrations originating from this wildfire using the Smoke Forecasting System (SFS) developed by National Oceanographic and Atmospheric Administration [8]. The SFS determined the location and daily progression of fires using satellite-based instrumentation. It estimated wildfire smoke emissions using the BlueSky smoke modeling framework [9], including modules for emissions production, fuel consumption, and the National Fire Danger Rating System. These modules are used in conjunction with meteorological conditions are used as inputs for dispersion and transport simulations from the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) to estimate concentrations of $PM_{2.5}$ emitted by the fire.

NOAA operates a daily Smoke Forecasting System at the national level in *forecast* and *re-analysis* mode. Forecast modes include 24hr and 48hr ahead predictions of smoke plume transport while the re-analysis mode retrospectively estimates previous day (24hr) concentrations using fire specific situation reports and estimated burned acreage. Illustrations of forecast and re-analysis predictions for two days are given in **Supplemental Figure 1**. The SFS outputs are resolved as vertical-column integrated hourly averages at 0.15 degree latitude and longitude grid (~13.5 km). We used concentrations for the lowest 100m surface layer and averaged over a 24 hour period starting with midnight EST. Daily averages at the county level used for exposure were subsequently calculated by averaging over the county boundaries. HYSPLIT simulation for June 4th GMT was not available, thus leading to underpredicted $PM_{2.5}$ concentrations on June 4th and the night of June 3rd after converting to EST. Concentrations below 1µg/m^3 were rounded down to 0µg/m^3.

Health Data

We obtained daily ED visits reported through the statewide syndromic surveillance system. The North Carolina Disease Event Tracking and Epidemiologic Collection Tool [10] is a statewide, early event detection and public health surveillance system which records daily ED visits together with up to 11 discharge ICD-9-CM codes and county of residence. The tool has a high capture rate, including 111 out of 114 civilian statewide EDs during the year of the study. Based on a previous analysis [11] we considered asthma-related ED visits (at least one ICD-9-CM code being 493) in patients over 18 years old and congestive heart failure related ED visits (at least one ICD-9-CM code being 428) in patients over 45 years old. ED visits for asthma and congestive heart failure are associated with pre-existing chronic conditions that increase the susceptibility to air pollutant exposures. For the purpose of simulation, both health outcomes were defined for patients discharged with at least one of the corresponding ICD 9-CM codes. Approximately five percent of asthma related visits also had congestive heart failure related codes.

The Human Subjects Institutional Review Board of the University of North Carolina at Chapel Hill approved this study. It was also reviewed and approved by officials at the Environmental Protection Agency.

Statistical Analysis

The primary goal of the analysis was to estimate the relative risk (RR) of adverse health outcomes associated with SFS-estimated smoke-$PM_{2.5}$ and to contrast it against the RR estimated under simulated forecast-based intervention programs. Because respiratory and cardiovascular outcomes are most commonly associated with the exposure to air pollution smoke we used ED visits for asthma and congestive heart failure to estimate RR with and without simulated interventions. A decline in the RR under an intervention program would provide evidence that the simulated intervention is effective in reducing the wildfire-related health burden in a population susceptible to asthma or congestive heart failure exacerbations. The secondary goal of the analysis was to quantify the excess incidence and economic value of the health outcomes and the loss of productivity attributable to smoke exposure. All $PM_{2.5}$ concentrations generated by SFS refer to only to the portion of total $PM_{2.5}$ that was emitted by the fire above the daily background levels.

We simulated forecast-based public health interventions by setting a threshold concentration of smoke-$PM_{2.5}$ forecast at which an intervention is triggered and by setting an adherence level that describes the extent to which public responds to the intervention. First, we used a threshold concentration of smoke-$PM_{2.5}$ forecast to identify days when counties were at risk for smoke and to implement hypothetical advisories. Three threshold concentrations of 5, 20, or 50μg/m^3 defined interventions triggered at low, intermediate, or high levels of smoke-$PM_{2.5}$. The three concentrations respectively approximated 40^{th}, 75^{nd}, and 90^{th} percentile of $PM_{2.5}$ distribution on smoke days (excluding non-smoke days). An intervention scenario at low levels of smoke can be described as the most responsive because it implied that the advisories were issued when a minimum exposure to smoke (forecast smoke-$PM_{2.5} > 5$μg/m^3) was predicted. On the other hand the least responsive intervention was triggered when county-day $PM_{2.5}$ exceeded very high levels (forecast smoke-$PM_{2.5} > 50$μg/m^3). As defined, the responsive interventions would affect the largest number of counties on many days while the least responsive interventions would target only county-days with high forecasted-concentrations. The intermediate concentration of 20μg/m^3 approximated the level that when added to the background air pollution would likely exceed the national standard. Statewide average $PM_{2.5}$ in the warm season over a three year period 2006-2008 was 13.2μg/m^3 [12]. However daily background levels are difficult to be determined exactly as they vary from day to day and are not measured in all counties.

For each of the three thresholds used to trigger advisories we then simulated three "adherence levels". A "Good" adherence to the intervention implied the population in the counties implementing intervention was able to reduce exposure to near background levels, i.e. 5μg/m^3 of smoke-PM$_{2.5}$. A "Poor" adherence level implied that the population in the counties implementing intervention reduced the exposure only on days predicted to exceed 50μg/m^3 of smoke-PM$_{2.5}$. The combination of three intervention thresholds and three adherence thresholds produced 9 distinct forecast-based interventions for each forecasting period (24hr and 48hr ahead).

To build forecast-based interventions we first established a baseline risk model without any intervention, using the retrospective SFS re-analysis concentrations as the true population exposure for each county on each day (county-day). This baseline risk model was fitted using a generalized linear mixed effects model for Poisson daily counts of ED visits with PM$_{2.5}$ re-analysis term, a logarithm of county population for adults (≥18 years of age) as an offset, and a random county level baseline to adjust for the seasonal variation from the annual baseline rate ([13] R version 2. 15. 0, lme4 package).

To estimate RR for each of the 9 interventions we used the baseline risk model coefficients and PM$_{2.5}$ coefficient but altered the exposure covariate as follows. Using the 24hr ahead daily forecasts we identified county-days for which smoke was predicted to exceed the intervention threshold level. Population compliance was then simulated, for these days and counties, as the lesser of the true exposure (re-analysis) and the adherence level. Thus, on a day when the forecast was above the intervention threshold, but the true exposure was below the adherence level, the exposure covariate was not changed; only if the forecast was above the threshold and the true concentration was above the adherence level was the exposure concentration in the prediction model altered. Steps used to simulate interventions are described in the diagram of Figure 1.

Using a multiple imputation technique, we replaced the observed counts with simulated outcomes for county-days impacted by intervention, creating 1,000 simulated 'complete' datasets. For each of these data sets, we performed the original estimation keeping track of the mean and standard error of the log RR parameters. The final log RR estimate for each intervention threshold and adherence level was given as the average over the estimated log RR parameters from all 1,000 simulations and, the corresponding variance was given by adding the variance within and across the 1,000 simulations. Finally, we repeated this process of creating prediction models with the 48hr forecast in place of the 24hr forecast; leaving us with nine models simulating ED visits for each time period.

Health Burden of Asthma and Congestive Heart Failure ED Visits

To evaluate the potential economic benefit of intervention programs we evaluated the excess incidence and the economic value of ED visits from the data and the model described above. We next estimated the cost (i.e., "unit value") of ED visits using nationally averaged ED visit costs. The cost of ED visits were extracted from the 2008 Nationwide Emergency Department Sample (NEDS) from the Healthcare Cost and Utilization Project (HCUP)[14]. We estimated the average charge for ED visits, the average charge for only the ED visits resulting in hospital admissions, and the average charge of ED visits including those that are discharged and those that are admitted to the hospital.

Total Wildfire-Attributable Public Health Burden

Characterizing the total health burden attributable to this wildfire episode provides context to the avoided health impacts. Because $PM_{2.5}$ exposure is associated with an array of health outcomes beyond asthma and congestive heart failure ED visits, we also performed a health impact assessment, for a comprehensive suite of acute and chronic endpoints using risk estimates published from single and multi-city epidemiologic air pollution studies; these are studies that the U.S. EPA commonly applies when quantifying health impacts for its regulatory analyses[15]. In this phase of the project we use the environmental daily SFS re-analysis of smoke related $PM_{2.5}$ concentrations and the Benefits Mapping and Analysis Program –Community Edition (BenMAP-CE) tool (v0.63) to evaluate health and economic impacts. The BenMAP-CE tool automates the process of aggregating across health endpoints and calculating excess incidence, and contains a library of health impact functions for outcomes including acute myocardial infarctions, exacerbated asthma, acute respiratory symptoms and lost work days among other impacts (**Supplemental Table 1**). BenMAP-CE also includes the demographic information and baseline health incidence rates needed to calculate these impacts (**Supplemental Table 2**).

Results

Evaluating the Effectiveness of Interventions Reducing the Health Burden

There was a high correlation (ρ=0.8) between smoke $PM_{2.5}$ estimated using the SFS re-analysis and 24hr ahead daily forecasts of smoke $PM_{2.5}$ and a somewhat lower correlation with 48hr ahead daily forecast of smoke $PM_{2.5}$ (ρ=0.6). Out of 1364 county-days, 238 had estimated smoke-related $PM_{2.5}$ concentrations above 5µg/m^3, 107 had concentrations above 20µg/m^3, and 37 had concentrations above 50µg/m^3 (Table 1). True positive rate of 24hr forecast based intervention was approximately equal at 74%, 74% and 76% for interventions triggered at low, intermediate, and high smoke $PM_{2.5}$ levels respectively. Overall, false positive rate was low due to high number county days with low smoke, but twice as high at low (3.7%) and intermediate levels (3%) than at high level of smoke (1.6%). Finally, the positive predictive value of 24hr smoke forecasts was the highest at low smoke threshold (81%), and lowest at high smoke threshold at 57%. Counties in the immediate proximity of the fire were most affected but had the smallest population size. The largest population fraction was affected by smoke $PM_{2.5}$ on June 10th-June 12th. Contributions of daily smoke-$PM_{2.5}$ to cumulative exposure among 31 counties are illustrated in **Figure 2**.

Similar to what we previously reported, smoke exposure from wildfire was associated with an excess relative risk (RR) for asthma-related ED visits. In the case of asthma, the strongest association was observed with the day of the exposure (lag day 0) with an increase of 4.9% (2.3, 7.6) cases per 10µg/m^3 of $PM_{2.5}$ (Table 2) (95% confidence intervals in parentheses) using the re-analysis as an exposure metric. We observed an increase of 4.2% (1.2, 7.1) cases per 10µg/m^3 of 24hr ahead forecast of $PM_{2.5}$, and an increase of 4.3% (1.2, 7.4) of cases (**Figure 3**) with a

48hr ahead forecast of $PM_{2.5}$ (**Supplemental Material Figure 2**). The greatest reduction in RR for asthma related outcomes was estimated for an intervention program triggered at low and moderate smoke levels (5, 20 μg/m^3 threshold) with a good compliance. In contrast, no reduction in RR was observed when the same intervention programs were simulated with poor adherence levels keeping exposures below 50 μg/m^3. Therefore, for the interventions implemented at low and moderate smoke levels to be effective in achieving health benefits, a good compliance was important. When intervention programs were simulated for high smoke levels only a small reduction in RR was achieved at all compliance levels. This result suggests that interventions implemented at high smoke levels would not be protective of asthma related visits and that the increased incidence of asthma related visits were not associated with the days of highest exposures alone.

At lag day 1 we estimated an increase of 3.5% (0, 6.7) per 10μg/m^3 of $PM_{2.5}$ in congestive heart failure-related visits. The related association with a 24hr ahead forecast was 1.9% (-1.8, 5.6) (**Figure 3b**), and with 48hr ahead forecast was 4.6% (0.9, 8.2) (**Supplemental material Figure 1**). Associations between forecast $PM_{2.5}$ and daily ED visits for congestive heart failure were weaker overall than for asthma; however, similar patterns emerged. In interventions simulated at low, moderate, and high smoke levels, reduction in RR depended on the adherence to these interventions. Similar to the results with asthma-related visits, the least effective interventions were those implemented at the highest levels of predicted smoke and those where only a reduction in highest exposures was achieved (cap of 50μg/m^3).

Economic Value of Preventable Health Burden Due to Smoke

Cost of Illness for Asthma and Congestive Heart Failure ED Visits

Using the baseline model of risk for ED visits and $PM_{2.5}$ re-analysis concentrations, we estimated an excess of 48.9 (95% CI: 20.9-81.2) asthma-related visits and 24.2 (1.6-51.2) congestive heart failure-related visits attributable to smoke during the duration of study (**Table 2**). The average cost of an asthma-related ED visit was estimated at $1,800 while the average cost of hospital admission resulting from an ED visit was estimated at $27,000. These estimates are obtained from HCUP data and reported in 2010 dollar values. The average total cost of an asthma-related ED visit, including ED and hospital admission charges, was estimated at $8,100. The average cost of a congestive heart failure-related ED visit was estimated at $1,900 while the average cost of a hospital admission resulting from an ED visit was estimated at $38,000. The average total cost, including ED and hospital admission charges, was estimated at $27,000. The total cost attributable to smoke from this 45-day episode was therefore estimated at $400,000 for asthma and $660,000 for congestive heart failure, exceeding $1 million in sum.

Cost of Illness Estimated for General Health Outcomes Using BenMAP-CE

In the air pollution literature $PM_{2.5}$ exposures have been associated with an array of health outcomes beyond asthma and congestive heart failure ED visits. To estimate the number of cases and economic value of $PM_{2.5}$ related health outcomes we used BenMAP-CE tool and the library of relative risk estimates that the U.S. EPA commonly employs to quantify the benefits of air quality policies (U.S. EPA, 2013) (**Table 3**). We estimated 4.4 premature deaths (95% confidence intervals in parentheses, 0-12); and 31 non-fatal heart attacks (7.9 to 56). In younger populations we estimate 41 excess cases of acute bronchitis (-9.8 to 91); 530 excess cases of lower respiratory symptoms (200 to 850); 760 cases of upper respiratory symptoms in children of age 7 through 14 (210 to 530); and 810 cases of aggravated asthma (-94 to 1,900). In terms of loss of productivity we estimated 3,700 days of work lost (3,200 to 4,300) and 22,000 minor restricted activity days have occurred (18,000 to 27,000). The economic value of these additional endpoints is approximately $48.4 million (2010$) substantially surpassing the economic value of the ED and hospital admissions alone. The largest portion, approximately 87% of the burden, is attributable to the value of premature mortality, chronic cardiovascular conditions and loss of productivity due to days of restricted activities and days of work lost.

Discussion

In the present study we demonstrated the potential benefit of wildfire smoke forecasts as a tool to protect public health. Using simulated forecast-based interventions we show that substantial reductions in RR for asthma and congestive heart failure related ED visits could be achieved when limiting exposure based on forecasted information. We estimated the economic value of ED and other chronic and acute outcomes as well as loss of productivity and premature mortality attributable to smoke exposure that could be prevented by effective interventions.

We show that the largest reduction in RR occurred when intervention programs were implemented at low and intermediate smoke level thresholds (5 and 20 $\mu g/m^3$ of smoke $PM_{2.5}$) and if the population complied with the advisory. In contrast, in non-aggressive interventions, simulated for high levels of forecasted smoke, even with full compliance, we did not observe a decrease in risk. Because intervention strategies implemented at high smoke levels excluded a number of county-days with non-trivial exposure (below $50 \mu g/m^3$) from simulating interventions, the results suggest that the increased incidence of ED was not associated with the days of highest exposures alone. Results were similar among the lower two thresholds. There was a tradeoff between the threshold level used to trigger interventions and the predictive value of smoke forecasts to correctly identify county-days that should have implemented intervention.

Interventions implemented at low levels of smoke had a highest false positive rate but also the highest positive predictive value. In contrast, interventions triggered at high levels of smoke had the lowest number of false positive county days with interventions but also a lowest precision of correctly identifying the need for intervention. Together, these results have potentially far-reaching consequences suggesting that interventions should be implemented when $PM_{2.5}$ levels are forecast to exceed even moderate threshold values to derive the greatest benefit, and not only on the days with very high levels of air pollution.

Our simulated interventions were based on the 2008 Evans Road wildfire in North Carolina using publicly available smoke attributable $PM_{2.5}$ concentrations generated by NOAA Smoke Forecasting System and information on daily visits to the ED. In a population of 1.6 million people, this brief but acute smoke episode induced a substantial health care utilization burden. The cost of the additional health care to society, related to excess asthma and congestive heart failure fire-attributable ED visits during this period was estimated to exceed $1 million. Yet, the cost of the total health burden associated with smoke exposure reaches far beyond these outcomes. The cost of general health outcomes was estimated to exceed $48.4 million with 87% of the total burden accounted for by increased mortality.

In certain instances, we employed simplifying assumptions that introduced important uncertainties. First, we simulated responses and assumed the population to be able to reduce their exposure in response to the intervention. There are a number of economic barriers to effective protection of individual exposure through relocation or by the availability of HEPA filters and personal masks. Moreover, it is unlikely that alerts would persuade all individuals to mitigate their smoke exposure. Identifying the most cost-effective measures, comparing the cost of such measures with the monetary value of the avoided premature deaths and accounting for the proportion of individuals that respond to such alerts are tasks beyond the scope of this article, but are important areas for future research. Another important area for research is to observe and examine the public's response to advisory messages. In particular, studies of how, and whether, individuals respond to the advisories triggered at varying levels could help identify the most effective strategies to reduce public health burden. Another possible limitation lies in how we defined cases of asthma and congestive heart failure related outcomes in Table 1. Our definition of condition-related outcomes is based on all ICD 9 codes assigned to an individual and not only the primary diagnosis. The individuals are not counted twice for the same health outcome. Broader definitions of the outcomes increased the pool of visits, which was desired to fully demonstrate the utility of simulations; however, a definition based on primary codes was typically more specific. Coding practices dictate that all listed health diagnostics are related to the reason for the ED visit. As a consequence, a broader definition of health outcome decreases specificity, increases the variability of the estimated associations, and possibly biases the actual risk toward the null hypothesis. We indeed found outcomes defined both ways to be strongly associated with smoke but higher for outcomes defined by primary codes (asthma: 1.09 vs. 1.049 per 10μg/m^3, congestive heart failure: 1.07 vs. 1.035). In addition to the relative risk being higher, the cost per visits was also substantially higher for primary outcomes ($8,000 vs. $26,000 for asthma, and $37,000 vs. $51,000 for congestive heart failure) leading to the overall burden estimated at $870,000, which is slightly lower than that for broadly defined outcomes.

The use of hospital charges to estimate cost of visits may also contribute to uncertainty in the estimated costs of morbidity impacts. True costs vary across individuals, regions, and willingness to pay, and by preexisting conditions, though such individual level of data are rarely available. Charges are typically substantially greater than expenditures paid by individuals and insurers; however they reflect hospital facility and physician costs prior to adjustment for group insurance rates. The cost estimates reported here represent market-based estimates that are commonly used to estimate aggregate impacts. And finally, the estimated values also do not include the impacts on the quality of life, which in the case of preexisting conditions of asthma and congestive heart failure can be substantial and extensive.

In spite of these limitations, the results of this study suggest that developing public health tools and educational programs that reduce population exposure will yield significant human health benefits in the form of fewer deaths and exacerbations of pre-existing illnesses. This is important because the intensity of landscape fires has steadily increased in the US. In the year 2011 for example, 74,126 fires burned through more than 8.7 million acres [16], a threefold increase over the five-year averages just a few decades ago. In the same year, 20% of total $PM_{2.5}$ emissions were estimated to be due to landscape fires, according to the most recent U.S. EPA National Emission Inventory. The contribution of wildfire smoke exposures to the total air pollution related health burden, however, is not well characterized. One caveat is that the relative toxicity of wildfire smoke compared with $PM_{2.5}$ derived from other combustive sources is not known. Another caveat is that the exposures to greatly increased concentrations of air pollutants emitted during wildfires over a brief period may not be equivalent to the exposures to daily variations in the background air quality and over longer periods. Nevertheless, numerous studies have shown increased risk for adverse respiratory outcomes following smoke exposures with the magnitude of risk often exceeding that estimated in association with urban air pollution. In addition to increased risk of asthma-related ED visits, studies have reported increased odds of asthma physician visits, dispensation of asthma relief medication, respiratory-related physician visits and respiratory hospital admissions in British Columbia, California, and Australia [17-20].

Compared to respiratory effects, less is known about smoke-related cardiovascular effects. In addition to the association between smoke from Evans Road fire and congestive heart failure ED visits [11], associations with ischemic heart disease in Aboriginal Australians [21] have been reported; however a number of other studies reported null or inconclusive results. A number of studies also have reported associations between short-term smoke exposure and mortality [22-25] with the estimated average mortality of 339,000 premature deaths annually attributable to landscape wildfire smoke exposures [26]. In recent years a number of smoke forecasting models have been developed providing important data for fire managers, incident support and air quality regulators. The results of this study suggest that they could be considered for protecting public health. In a recent study of Canadian forest fires [27] results showed that forecasts from a different model were also associated with health outcomes, thus suggesting that results found in this study may apply to other events as well.

Identifying susceptibility factors and reaching the most at risk populations during smoke events through educational programs are likely to be critical in reducing the health burden. Evidence shows that not all people are affected equally by air pollution and smoke [28-32]. Individuals with asthma and other respiratory diseases, individuals with cardiovascular disease, the elderly, children, pregnant women and smokers may experience more severe effects and need a longer time to recover following smoke exposure [33]. Because ED visits for both asthma and congestive heart failure are typically associated with related preexisting conditions the results of this study suggest that a forecast based intervention could be particularly beneficial to this segment of the susceptible population and that the economic value extends beyond those subpopulations.

It is evident from the health impacts assessment that the economic burden from wildfire smoke extends beyond ED cases for the two outcomes considered in simulations including the loss of productivity and mortality. In many parts of the country, the health burden may extend beyond human health to the health of domestic and farm animals that are also exposed to smoke during wildfire episodes. However, in considering the implications of present results it is important to note that healthy individuals are likely to respond differently to the smoke and consequently to the advisories than those such as asthmatics who are susceptible to the effects from smoke such as asthmatics. Healthy individuals may be burdened by smoke but susceptible individuals can have exacerbations that require urgent medical attention and may be more likely to consider measures to reduce their exposure. Identifying sub-populations susceptible to the effects from smoke and characterizing concentrations at which these groups as well as healthy individuals are likely to experience health complications are critical steps to establishing health guidelines and comprise an important area of future research.

To reduce the burden across a growing number of affected communities it is imperative we consider new ways of delivering information across communities as well. Public Service Announcements (PSAs) are currently the primary vehicle for communicating health risks during smoke events but are not linked to the forecasts of smoke in real time, limiting their effectiveness across communities. One of the most important challenges faced by public health officials is the ability to provide information related to shorter time periods, at hourly rather than daily intervals and at a finer geographic resolution. With shorter averaging times and fine geographic resolution, accurate smoke forecasts have a potential to improve on the delivery of information and on the timing when the recommended measures should be adopted. Further studies on evaluation of forecasts and modeled output can provide evidence on accuracy and reliability of different forecasting methods. If accurate, smoke forecasts can help minimize the implementation of unnecessary interventions by identifying areas that are predicted to be at most impact and thus minimize the implementation of unnecessary interventions. In the extreme cases where relocation of the most vulnerable individuals is needed, the geographic resolution of smoke accurate forecasts can be helpful in identifying where and how far should individuals should be relocated and for how long. PSAs linked to specific events through smoke forecasting models may be one example of a cost effective decision support tool that can be accessed by individuals and communities. Alternatively, easily accessible air quality and public health tools such as AIRNow linked to smoke forecasts can be effective in reaching populations at high risk and extending the public health benefit to episodes of wildfire beyond a single episode. Given the current availability of smoke forecasts to the public, improvements in delivery of information to and education of the most susceptible population during these events are likely to lead to more desired health outcomes by averting the exacerbation of common and debilitating conditions that affect many.

CONCLUSION

A growing number of communities are been impacted by smoke events and are in need of decision support tools to communicate health risks and identify necessary actions. This study uses smoke forecasts and simulated interventions to demonstrate an alternative to community based studies and shows that simulated interventions based on forecast data reduced the relative risk of adverse health outcomes and have the potential for a large economic benefit.

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Table 1.

Summary table of number of days below or above a threshold used to trigger interventions (T_i) as predicted by a 24hr forecast and re-analysis.

24hr Forecast $PM_{2.5} > T_i$	Re-analysis $PM_{2.5} > T_i$	Low Smoke Level $T_i = 5$	Intermediate Smoke Level $T_i = 20$	High Smoke Level $T_i = 50$
TRUE	TRUE	177	79	28
TRUE	FALSE	42	38	21
FALSE	TRUE	61	28	9
FALSE	FALSE	1084	1219	1306

Table 2.

Summary table of ED visits for asthma and congestive heart failure, cost of illness, and impacts attributable to smoke. Monetary value is estimated from the HCUP data and reported in 2008 dollar with two significant digits.

	Asthma	CHF
Age	18-99	45-99
Number of visits	2840	2348
RR per 10ug/m3 (95% Confidence Intervals)	1.049(1.022-1.076)	1.035(1.004-1.066)
ED cost	$1,800	$1,900
HA cost	$27,000	$38,000
Total Average Charge	$8,100	$27,000
Excess Count	48.9(20.9-81.2)	24.2 (1.6-51.2)
Cost attributable to smoke (95% Confidence Intervals)	$400K	$660K

Table 3.
Estimated Incidence and Impact of Premature Deaths and Illness attributable to PM2.5 from 2008 Evans Road Fire, North Carolina. Estimates are obtained through environmental BenMAP-CE utilizing the library of health impact functions from published air pollution epidemiologic studies.

Endpoint	Health Outcomes	Study	Age Group (years)	Excess Incidence (95% CI)	Value (in $1,000 2008)
Premature Mortality	Mortality	Zanobetti and Schwartz (2009)	0-99	4.4 (0, 12)	42,000 (0, 190,000)
Chronic Illness	Nonfatal heart attacks	Peters et al. (2001)	>18	31 (7.9, 56)	3,900 (580, 9,800)
Hospital Admissions	Cardiovascular Hospital Admissions*	*Moolgavkar (2000), Zanobetti et al. (2009), Bell et al.(2008), Peng et al.(2009)*	18-64	4.3 (2.3, 6.4)	180 (91, 260)
	Respiratory Hospital Admissions**	*Moolgavkar(2000) Zanobetti et al(2009), Kloog et al.(2012) Babin et al.(2007), Sheppard(2003)*	18-64	4.7 (-3.0, 9.8)	150 (-96, 310)
	Asthma ED visits	Mar et al. (2010), Slaughter et al. (2005), Glad et al. (2012)	All ages	16 (-4.4, 33)	6.7 (-1.9, 15)
Other Health Endpoints	Acute Bronchitis	Dockery et al. (1996)	8-12	41 (-9.8, 91)	20 (-4.2, 56)
	Lower Respiratory Symptoms	Schwartz and Neas (2000)	7-14	530 (200, 850)	11 (3.2, 23)
	Upper Respiratory Symptoms in asthmatics	Pope et al. (1991)	9-11	760 (140, 1400)	25 (3.7, 62)
	Asthma Exacerbations, Asthma Attacks	*Ostro et al. (2001), Mar et al.(2004)*	6-18	810 (-94, 1,900)	47 (-5, 140)
	Minor Restricted Activity Days	Ostro and Rothschild (1989)	18-65	22 (18, 27) x 1000	1,500 (800, 2,300)
	Work Loss Days	Ostro (1987)	18-65	3.7 (3.2, 4.3) x 1000	520 (440, 600)

* excluding nonfatal heart attacks, includes congestive heart failure, **includes asthma

Figure 1.

Diagram of steps in the simulation of interventions. ED_{ij} stand for Emergency Department visits in county i, on day j. PM_{ij} refer to PM2.5 from the re-analysis, and $PM^{forecast}$ refers to the forecasted $PM_{2.5}$. T_i refers to the threshold used to trigger intervention while T_a refers to the threshold used to simulate adherence level.

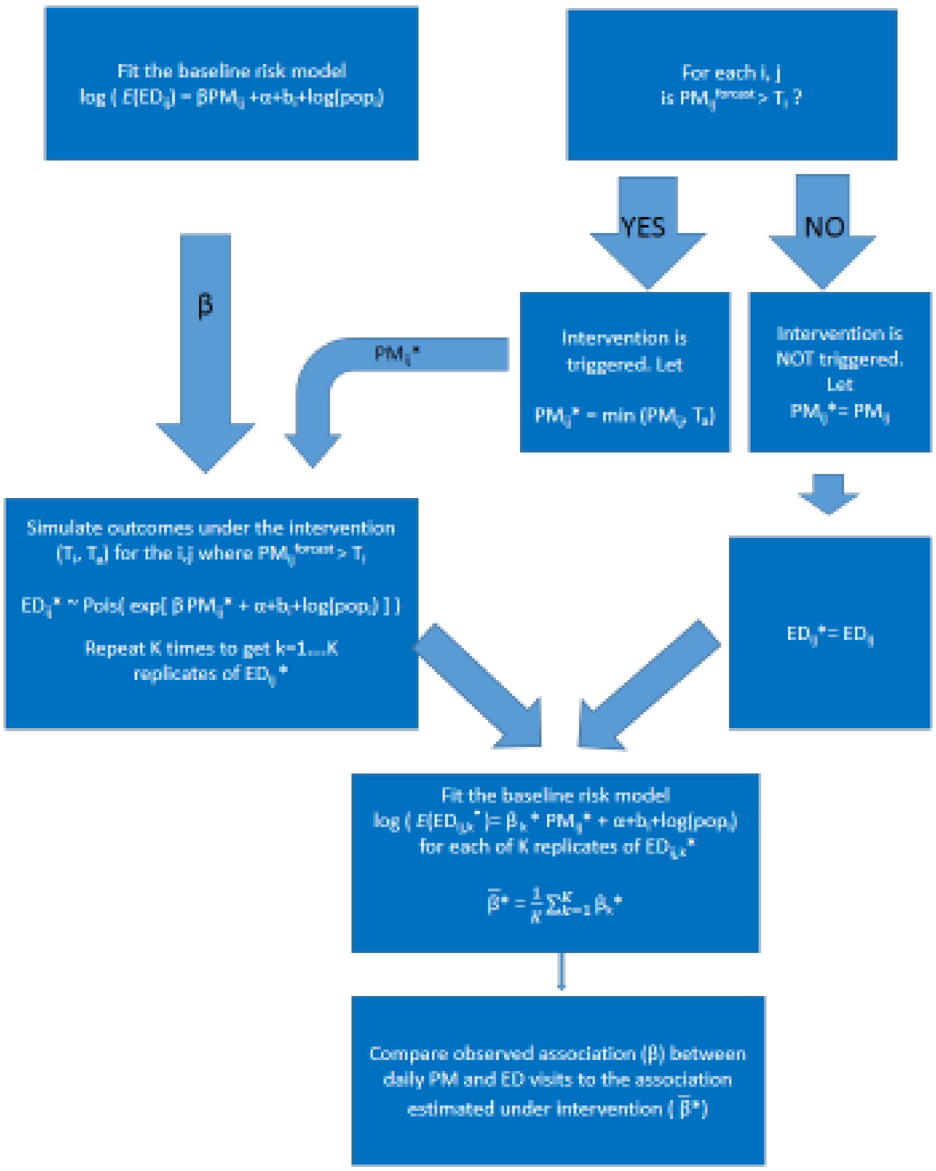


Figure 2.

Cumulative exposure to smoke $PM_{2.5}$ estimated by the Smoke Forecasting System during the time defined as study period. Population size at risk is given in parentheses next to the county name.

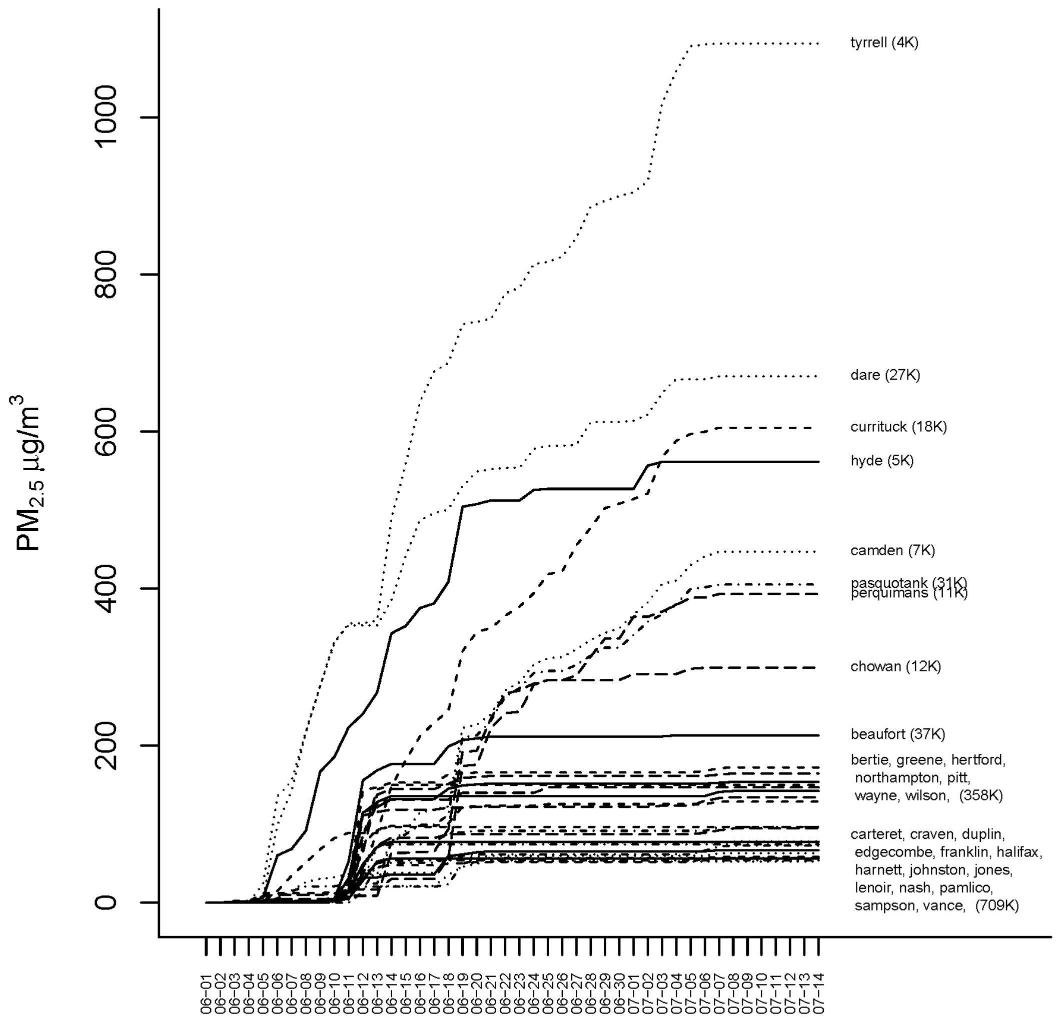
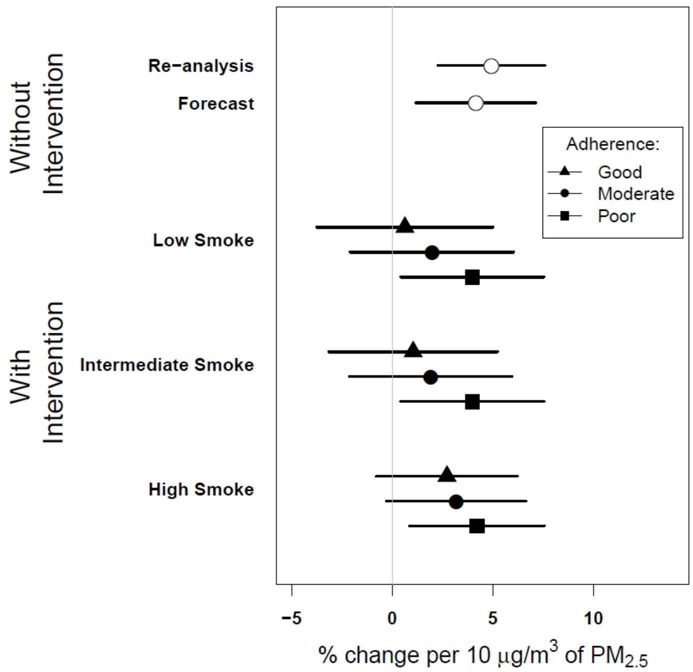


Figure 3.

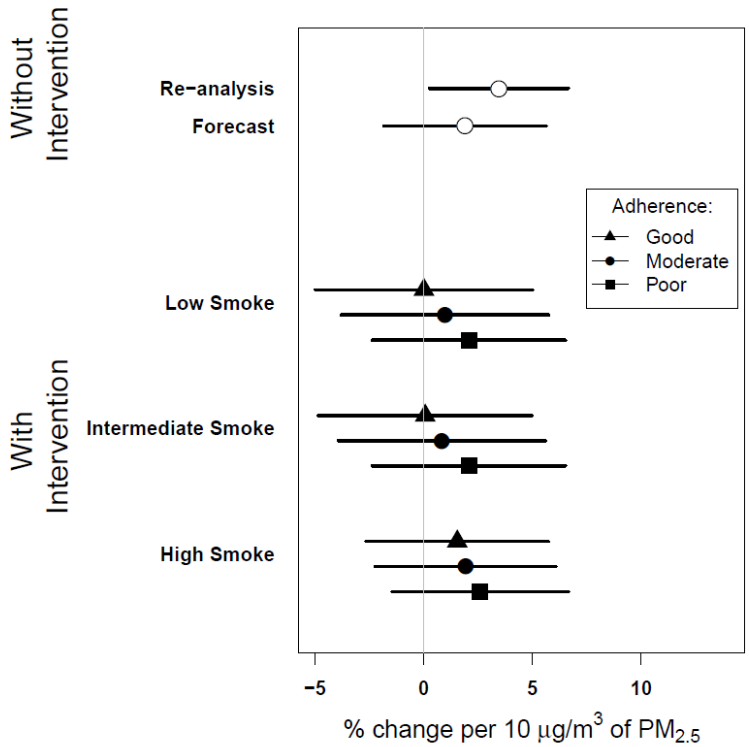
Excess relative risk (%) for (a) asthma and (b) congestive heart failure related ED visits per 10 µg/m^3 of $PM_{2.5}$ using re-analysis, the 24hr ahead forecasts, and simulated forecast-based interventions.

(a)



Without Intervention
Re−analysis
Forecast
Adherence:
Good
Moderate
Poor
With Intervention
Low Smoke
Intermediate Smoke
High Smoke
−5
0
5
10
% change per 10 μg/m3 of PM2.5

(b)


Without Intervention
Re−analysis
Forecast
Adherence:
Good
Moderate
Poor
With Intervention
Low Smoke
Intermediate Smoke
High Smoke
−5
0
5
10
% change per 10 µg/m3 of PM2.5

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Forecast-Based Interventions Can Reduce the Health and Economic Burden of Wildfires

Supplemental Material

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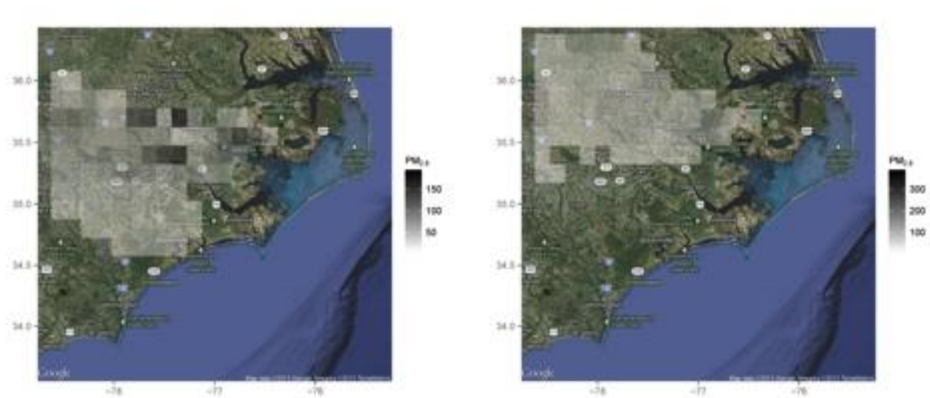
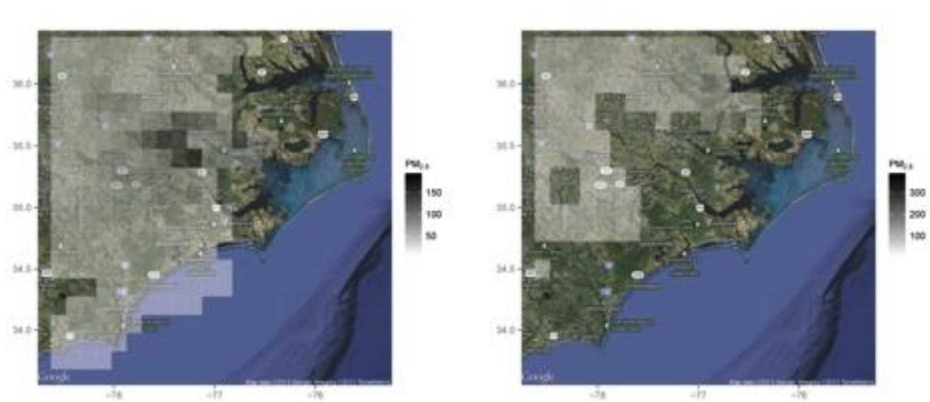
Supplemental Material Figure 1.

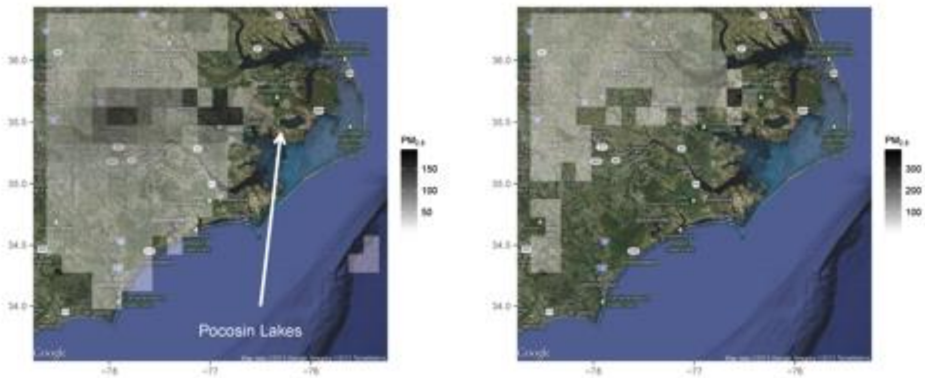
a) 48 hour ahead forecast for June 12th and June 13th, 2008



b) 24 hour ahead forecasts for June 12th and June 13th, 2008

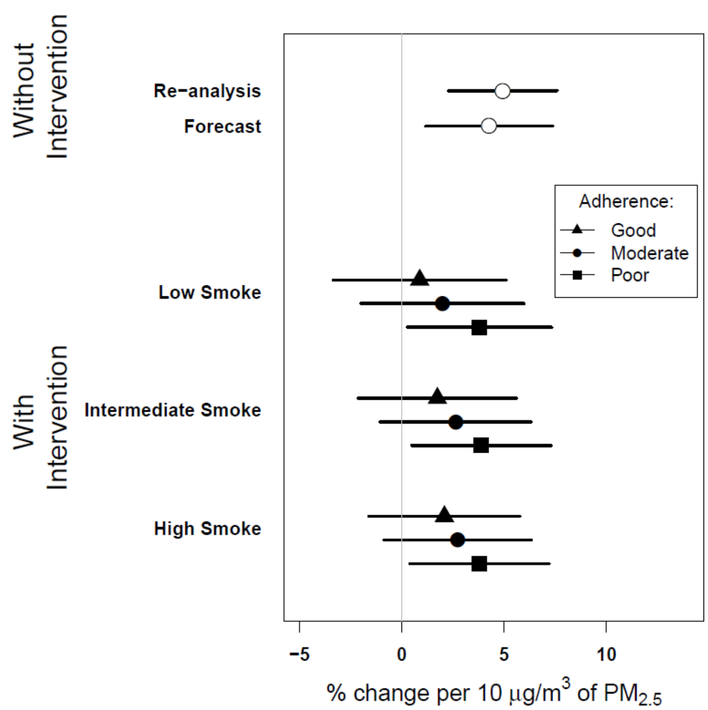


c) Re-analysis for June 12th and June 13th, 2008

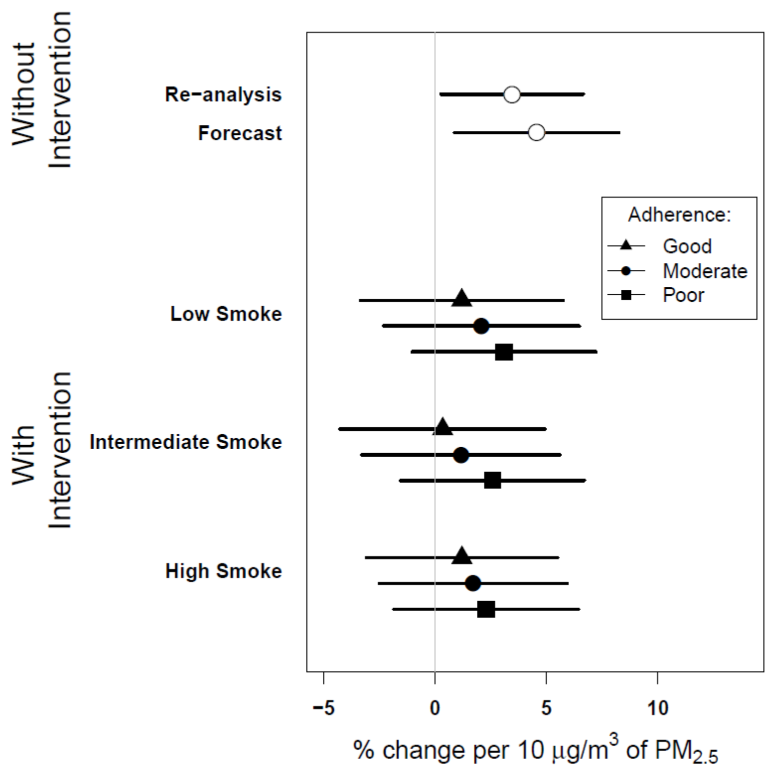


An illustration of spatial prediction of PM2.5 (µg/m3) estimated by NOAA's Smoke Forecasting System and averaged over 24 hours. The columns of the panels represent a) 48hr ahead forecast; (b) 24hr ahead forecast; and (c) re-analysis, while rows illustrate two days of data (June 12th and June 13th, 2008).

Supplemental Material Figure 2.



(a)



(b)

Excess relative risk (%) for (a) asthma and (b) congestive heart failure related ED visits per 10 μg/m3 of PM2.5 using re-analysis, the 48hr ahead forecasts, and simulated forecast-based interventions.

Supplemental Table 1: Ozone- and PM –related Health Endpoints and Studies Included

Endpoint	Study	Study Population	Risk Estimate (95th Percentile Confidence Interval)[a]
Premature Mortality			
Premature mortality, time series, all-cause	Pooled estimate of Zanobetti et al. (2009)	All ages	*Charlotte:* β = 0.000998 (0.000482) *Durham:* β = 0.001033 (0.00519) *Raleigh*: β = 0.001293 (0.000499)
Chronic Illness			
Nonfatal heart attacks	Peters et al. (2001)	Adults (>18 years)	OR = 1.62 (1.13–2.34) per 20 μg/m^3
Hospital Admissions			
Respiratory	Zanobetti et al. (2009)—ICD 460-519 (All respiratory)	>64 years	β=0.00207 (0.00446)
	Kloog et al. (2012)—ICD 460-519 (All Respiratory		β=0.0007 (0.000961)
	Moolgavkar (2000)—ICD 490–496 (Chronic lung disease)	18–64 years	1.02 (1.01–1.03) per 36 μg/m^3
	Babin et al. (2007)—ICD 493 (asthma)	<19	β=0.002 (0.004337)
	Sheppard (2003)—ICD 493 (asthma)	< 18	RR = 1.04 (1.01–1.06) per 11.8 μg/m^3

(continued)

Endpoint	Study	Study Population	Risk Estimate (95th Percentile Confidence Interval)[a]
Cardiovascular	*Pooled estimate:*	>64 years	
	Zanobetti et al. (2009)—ICD 390-459 (all cardiovascular)		β=0.00189 (0.000283)
	Peng et al. (2009)—ICD 426-427; 428; 430-438; 410-414; 429; 440-449 (Cardio-, cerebro- and peripheral vascular disease)		β=0.00068 (0.000214)
	Peng et al. (2008)—ICD 426-427; 428; 430-438; 410-414; 429; 440-449 (Cardio-, cerebro- and peripheral vascular disease)		β=0.00071 (0.00013)
	Bell et al. (2008)—ICD 426-427; 428; 430-438; 410-414; 429; 440-449 (Cardio-, cerebro- and peripheral vascular disease)		β=0.0008 (0.000107)
	Moolgavkar (2000)—ICD 390–429 (all cardiovascular)	20–64 years	RR=1.04 (t statistic: 4.1) per 10 μg/m^3
Asthma-related ER visits	*Pooled estimate:* Mar et al. (2010)	All ages	RR = 1.04 (1.01–1.07) per 7 μg/m^3
	Slaughter et al. (2005)		RR = 1.03 (0.98–1.09) per 10 μg/m^3
	Glad et al. (2012)		β=0.00392 (0.002843)
Other Health Endpoints			
Acute bronchitis	Dockery et al. (1996)	8–12 years	OR = 1.50 (0.91–2.47) per 14.9 μg/m^3
Asthma exacerbations	*Pooled estimate:* Ostro et al. (2001) (cough, wheeze and shortness of breath) [b]	6–18 years	OR = 1.03 (0.98–1.07) OR = 1.06 (1.01–1.11) OR = 1.08 (1.00–1.17) per 30 μg/m^3
	Mar et al. (2004) (cough, shortness of breath)		RR = 1.21 (1–1.47) per RR = 1.13 (0.86–1.48) per 10 μg/m^3
Work loss days	Ostro (1987)	18–65 years	β=0.0046 (0.00036)
Acute respiratory symptoms	Ostro and Rothschild (1989) (Minor restricted activity days)	18–65 years	β=0.00220 (0.000658)
Upper respiratory symptoms	Pope et al. (1991)	Asthmatics, 9–11 years	1.003 (1–1.006) per 10 μg/m^3
Lower respiratory symptoms	Schwartz and Neas (2000)	7–14 years	OR = 1.11 (1.58–1.58) per 15 μg/m^3

Supplemental Table 2: Baseline and Prevalence Rates for Included Morbidity and Mortality Endpoints

Endpoint	*Parameter*	*Rates* *Value*	*Rates* *Source*[a]
Mortality	Daily or annual mortality rate	Age-, cause-, and county-specific rate	Centers for Disease Control (2008) (rates for 2004–2006)
Hospitalizations	Daily hospitalization rate	Age-, region-, and cause-specific rate	Agency for Healthcare Research and Quality (2007)
Asthma ER Visits	Daily asthma ER visit rate	Age- and region- specific visit rate	Agency for Healthcare Research and Quality (2007)
Nonfatal Myocardial Infarction (heart attacks)	Daily nonfatal myocardial infarction incidence rate per person, 18+	Age-, region-, state-, and county-specific rate	2007 AHRQ data files; adjusted by 0.93 for probability of surviving after 28 days [31]
Asthma Exacerbations	Incidence • daily wheeze • daily cough • daily dyspnea	0.076 0.067 0.037	Ostro et al. (2001)
	Prevalence among asthmatic children	0.0780	American Lung Association [32]
Acute Bronchitis	Annual bronchitis incidence rate, children	0.043	American Lung Association (2002) Table 11
Lower Respiratory Symptoms	Daily lower respiratory symptom incidence among children[d]	0.0012	Schwartz (1994b, Table 2)
Upper Respiratory Symptoms	Daily upper respiratory symptom incidence among asthmatic children	0.3419	Pope et al. (1991, Table 2)
Work Loss Days	Daily WLD incidence rate per person (18–65) • Aged 18–24 • Aged 25–44 • Aged 45–64	0.00540 0.00678 0.00492	US Bureau of the Census (2001)

Minor Restricted-Activity Days	Daily MRAD incidence rate per person	0.02137	Ostro and Rothschild (1989)

[a] Healthcare Cost and Utilization Program (HCUP) database contains individual level, state and regional-level hospital and emergency department discharges for a variety of ICD codes.

[b] See ftp://ftp.cdc.gov/pub/Health_Statistics/NCHS/Datasets/NHDS/.

[c] See ftp://ftp.cdc.gov/pub/Health_Statistics/NCHS/Datasets/NHAMCS/.

[d] Lower respiratory symptoms are defined as two or more of the following: cough, chest pain, phlegm, and wheeze.

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