Final Report for NIH-NIEHS Climate Change Grant #1RC1ES018612-01

Respiratory Health Impacts of Wildfire Particulate Emissions under Climate Change Scenarios

Grant Period of Performance:
1 October 2010 - 31 July 2012

Primary Investigator:
Nancy HF French, Michigan Tech Research Institute (MTRI)

Co-Investigators:
Tyler Erickson, MTRI
Michele Ginsberg , San Diego County Health & Human Services Agency
Tatiana Loboda, University of Maryland, Department of Geographic Sciences
Shiliang Wu, Michigan Technological University (MTU)

Key Personnel:
Brian Thelen, MTRI
Jeffrey Johnson, San Diego County Health & Human Services Agency
R Chris Owen, MTRI
Benjamin Koziol, MTRI
Michael Billmire, MTRI

Students:
Yaoxian Huang, MTU
Marlene Tyner, MTRI

Final Report
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Specific Aims of the funded grant and progress completed

Currently, there is no developed methodology to model and forecast the potential health effects of PM plumes from wildland fires, and in part this is due to a lack of methodology for rigorously relating the two. The contribution of this project specifically targets that absence by modeling explicitly the emission, transmission, and distribution of PM following a wildland fire in both space and time. A systematic approach to wildland fire respiratory health effects is invaluable when attempting to address additional uncertainties from climatic change and population vulnerability.

The challenge of this multi-dimensional, interdisciplinary study is to develop an approach that is process-driven and built upon recent research in fire ecology, climate change, atmospheric modeling, and centralized health monitoring. Specifically, the overall challenge is the integration of various model and measurement-based components to properly understand the impact and predictability of wildland fire emissions on the human population.

The specific primary objective of this project was to measure and statistically model a relationship between particulate emissions from wildland fires and respiratory illness and then assess the impact of future climatic conditions as manifest in respiratory health outcomes. We identified four specific aims to achieve this objective, all of which were carried out with minimal modifications from the originally proposed plan. The aims are as follows:

1. Conduct a geospatial model of fire emission particulate matter (PM) sources
2. Estimate PM concentrations for downwind regions
3. Develop a statistical model and framework to link spatial estimates of PM concentrations to respiratory illness using syndromic surveillance data
4. Evaluate climate change impacts on future fire regimes and respiratory health

There are three specific components to the integrated modeling activity for building the predictive model (Specific Aims #1-3): 1) modeling spatially-defined fire emissions taking into account vegetation fuels and weather, 2) accurately estimating particulate concentrations for downwind regions using transport/dispersion modeling, and 3) combining the smoke emissions with electronic health monitoring to relate the modeled spatial/temporal distribution of pollution to the rates and spatial location of respiratory symptoms (Figure 1). We carried out the development of the predictive model via a Generalized Additive Modeling (GAM) approach, able to accurately incorporate emissions-transport, demographics, weather, and scheduling (day of week) information to derive an accurate predictive relationship for describing the impacts of fire on respiratory health in San Diego County.

Application of the predictive model to the future was investigated based on the results achieved under Specific Aim #4 using a regional climate model (RegCM) for southern California. Details on the activities and outcomes from each Specific Aim are given in the sections that follow concluding with a review and summary of the project outcomes.

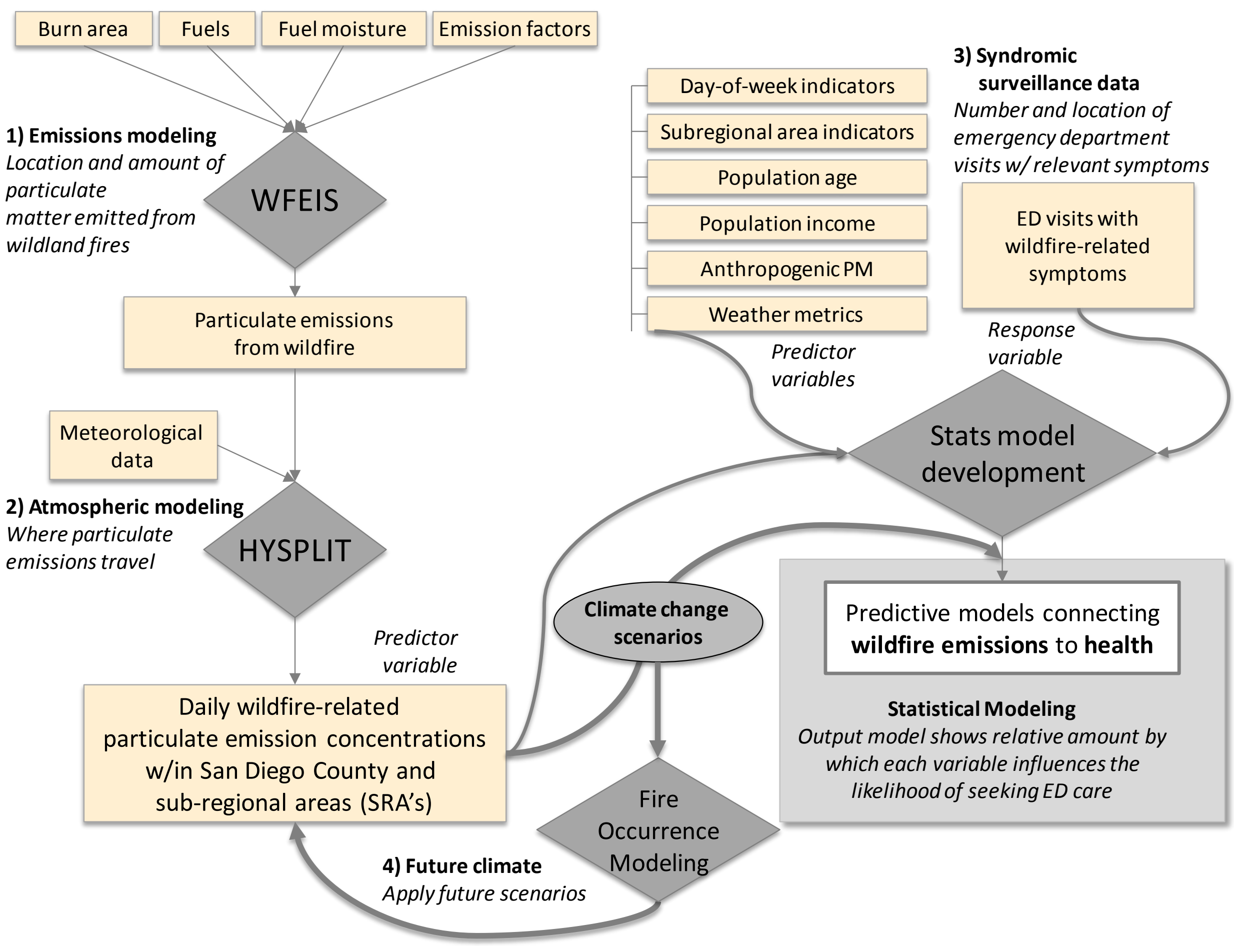

Figure 1. Project workflow overview.

The study region and study period were modified and refined from that proposed to include any fires that could influence air quality in San Diego County, based on a review of wind field data. The area of the study is shown in Figure 2. Emissions from fires for the extensive region (California south of 35°47' latitude, part of western Arizona and Northern Baja California, Mexico) were modeled and compared to health data collected from San Diego County (area outlined in green).

The time period of the analysis was 2003 to 2008 inclusive to capture the variability in air quality possible with and without Santa Ana wind-driven fire. The time period of August through November 2007 was used for statistical model development due to the availability of Syndromic Surveillance health data, which was more complete starting in 2007 than earlier years. Assessment of future fire occurrence was made for 30 years and was based on application of a regional climate model (RegCM) for southern California.

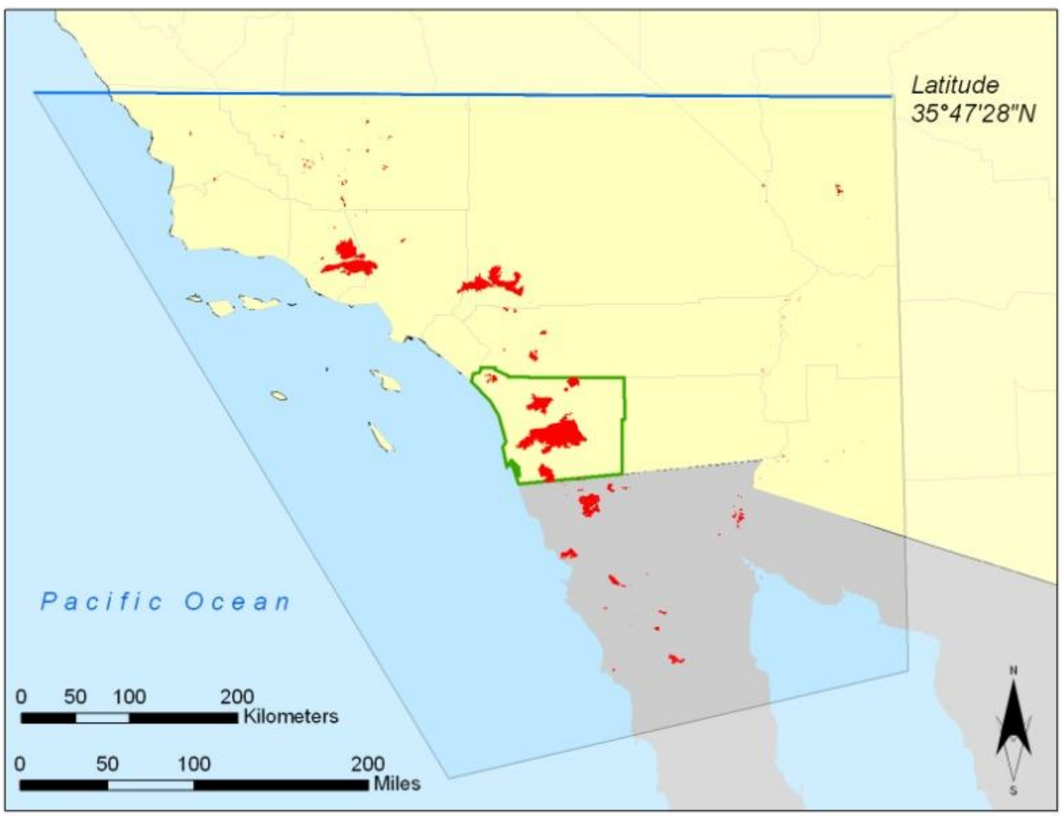

Figure 2. This map shows the project study area. Red features are areas where wildfire burned during the study time period. The green outline shows the San Diego county boundary.

Specific aim #1 – Conduct a geospatial model of fire emission particulate matter (PM) sources

Progress completed

Our activities in the first year of funding included compilation of geospatial data sets needed for the PM emissions estimations. The data sets compiled for the emissions model included detailed maps of burn area for the period of interest (2003 to 2008). We also acquired an improved spatial map of fire fuels (vegetation type and density) provided through the USDA Forest Service (FCCS 30 m maps; http://www.fs.fed.us/pnw/fera/fccs/maps.shtml), comprehensive maps of fire perimeters obtained from USGS and San Diego County government sources (http://www.landfire.org), maps of fire progression derived using thermal satellite data collected twice per day from the NASA-operated MODIS sensors (MOD/MYD14; http://modis-fire.umd.edu/index.html), and fire weather, needed to know fuel moisture at the time of burning, derived from the North American Regional Reanalysis climate products (NARR data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA; www.esrl.noaa.gov/psd/).

In the first year, we developed the model fully for the U.S. portion of the study area and made first-order estimates of PM emissions. In the second year, the comprehensive set of burn area, fuel loading, and fuel moisture data were incorporated into the Wildfire Emissions Information System (WFEIS, wfeis.mtri.org)(*French et al.* 2011) to produce PM emissions estimates on a daily basis at a scale of approximately 30m spatial resolution. The input datasets totaled over 14,000 wildfire burn polygons with a cumulative area of 14,464 km^2 distributed across 1700 dates from 2003-2008. The total output emissions across the entire study area and time period amounted to 188,000 metric tons PM_{10}.

Specific aim #2 – Estimate PM concentrations for downwind regions

Progress completed

The atmospheric transportation/dispersion model was built and tested for use of the emission source data coming from specific aim #1. PM source emissions estimates were ingested into the HYSPLIT dispersion model and PM concentration map results (Figure 3) were evaluated. Air quality data from in situ California Air Resources Board (CARB) sensors was used to calibrate emissions model inputs.

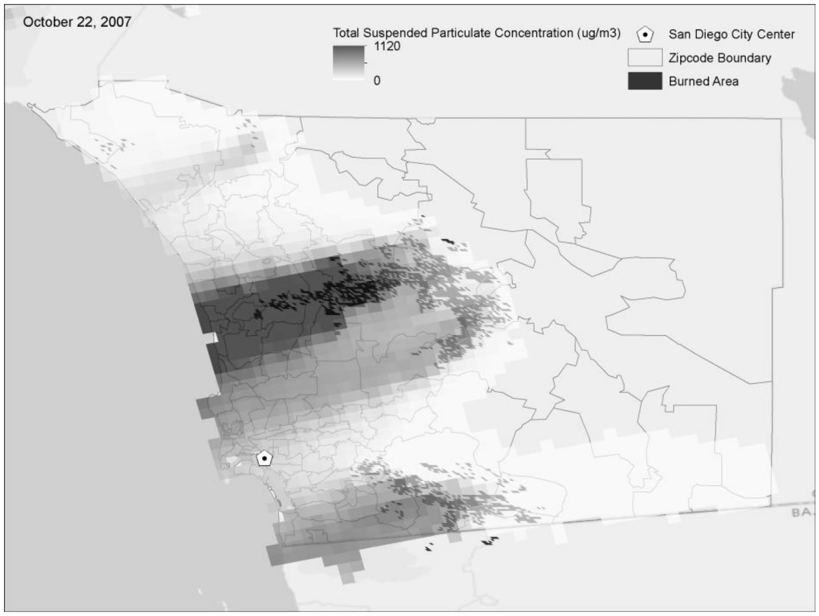

Figure 3. Gridded concentrations of particulate matter from wildfire as output from the HYSPLIT atmospheric transport model for the peak day of burning in the study. Burned areas show where wildfire particulate emissions originated.

Atmospheric transport trajectories of PM from wildfires output from the HYSPLIT model (*Draxler and Hess* 1997; *Draxler and Hess* 1998; *Draxler* 1999) were spatially aggregated to produce daily wildfire emissions concentration values by zip code and sub-regional area (SRA, see Figure 4) within San Diego County. An example result from the atmospheric dispersion model is shown in Figure 3, depicting PM plumes moving west from their wildfire origin towards the Pacific coast on the peak day of wildfire burning during the study time period, October 22, 2007.

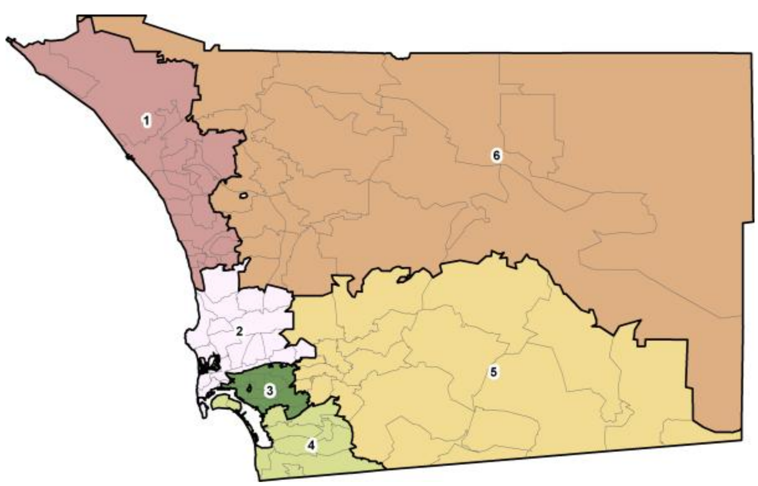

Figure 4. Map of subregional areas used to fit the "Regional" model.

Specific aim #3 – Statistical modeling to link spatial estimates of PM concentrations to respiratory illness using syndromic surveillance data

Progress completed

Syndromic surveillance datasets summarizing the incidence of specific respiratory conditions that were derived from hospital records were collected and provided to MTRI by co-investigators from the San Diego County Health & Human Services Agency. The health officials provided a set of data extracted from the San Diego Aberration Detection and Incident Characterization (SDADIC) syndromic surveillance system in specific formats to allow comparison to the PM concentration data sets.

A statistical modeling approach was developed for estimating the relationships (and approximate error distributions) between PM concentrations and incidence rates of specific respiratory conditions. The response variable took the form of a binomial distribution with the likelihood of seeking emergency care represented by the number of recorded emergency department (ED) visits by day and representative geographic population. When back-transformed, each resulting explanatory variable coefficient represented the relative amount with which they influence the likelihood of seeking ED care.

We utilized a generalized additive model (GAM) with binomial logistic regression (*Wood* 2006), for relating the covariates to the health outcomes; more specifically, we modeled Emergency Department (ED) visit data from any day i and region j, as being binomial with probability p_{ij} and population size n_{ij} (known from demographic data) related to the covariates via the logistic link function:

$$\text{logit}(p_{ij}) = \log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \beta_0 + \sum_{k=1}^{n} \beta_k x_{ij} + \sum_{m=1}^{n} f_m(x_{ij}) \quad , \tag{1}$$

where the first term on the righthand side (β_0) is the offset term, the second term represents the linear portion of the model with coefficients that must be estimated, and the last term represents nonlinear functions, $\{f_m\}$, which must be estimated. For the latter terms, we utilized a spline model incorporating regularization via generalized cross-validation to minimize the effects of overfitting. It is critical to allow for nonlinearity within this model, since it is clear that the effects may not be linear over the range of inputs we expect to encounter. This modeling framework is quite flexible providing considerable capacity for modeling inputs in a realistic nonlinear fashion.

For cumulative particulate matter exposure, we used a Gaussian-type weighting function with a standard deviation of one day. We fit two models: the first a "global" model representing all of San Diego County with static population variables, and the second a "regional" model with data aggregated to six subregional areas (SRAs) within San Diego County that incorporated population and emissions spatial variability.

The overall best fit models ("Global" model shown in Figure 5) were generated via a backward variable elimination procedure – for this, a threshold significance value of 0.05 was nominally used though significant terms were generally far below this level. Significance of the nonlinear model terms was assessed through a combination of approximate chi-square p-values and confidence bands on the functional forms.

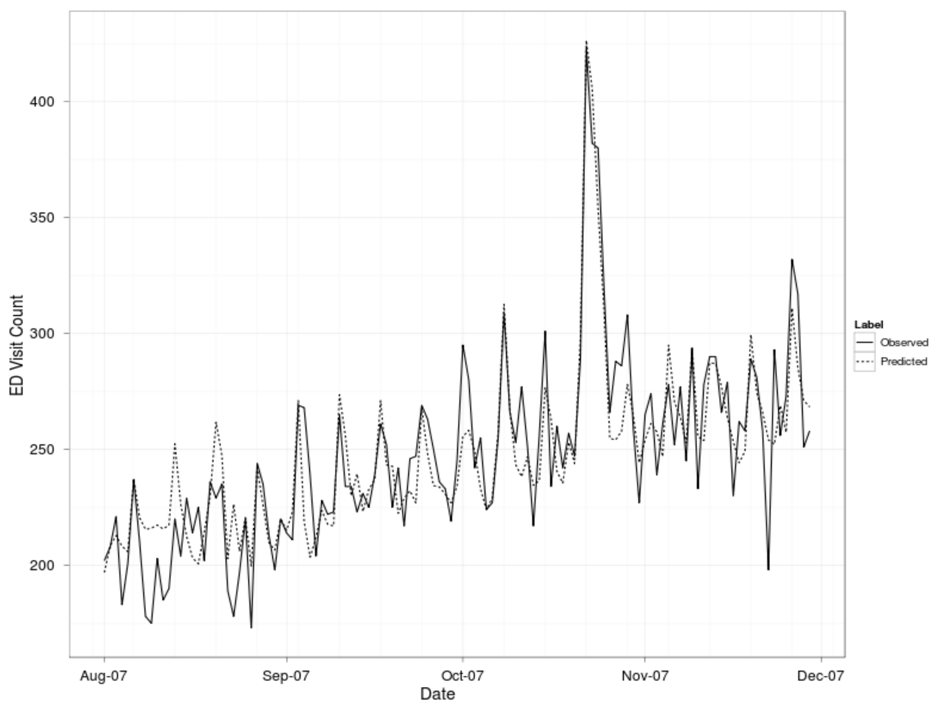

Figure 5. Comparison of emergency department (ED) visits observed versus predicted by the statistical model for the study time period. Data represents the "Global" (all of San Diego County) model. Results for each subregional area are similar.

Of the suite of environmental and demographic variables tested, the final global model was comprised of three linear predictor variables (Is-Monday, Is-Tuesday, and total suspended particulates of wildfire origin) and two non-linear predictors (anthropogenic

$PM_{2.5}$, and a bivariate spline on air temperature and relative humidity). The final regional model included those of the global model as well as four additional linear predictor variables: Is-SRA3, Is-SRA6, proportion of population less than 24 years of age, and proportion of population with annual income greater than $50,000. All predictors were significant at $p < 0.01$.

Model results show that at peak fire particulate concentrations the odds of a person seeking emergency care is increased by approximately 50% compared to non-fire conditions (40% for the generalized case, 70% for a geographically specific case; see Table 1). The resulting model was developed to allow for a geospatial assessment of respiratory health impacts under possible future wildfire conditions in the San Diego region.

Table 1. General Additive Model results for "Global" (San Diego County) and "Regional" (SRA, see Figure) fits. Interpretation of "Estimated Odds Effect Range" values: e.g, for the 'Is Monday' indicator variable (range = 1 – 1.17), on Mondays the odds that a person seeks ED care increases by as much as 17%.

	"Global" Model		**"Regional" Model**	
Term	**Observed Data Range**	**Estimated Odds Effect Range[1]**	**Observed Data Range**	**Estimated Odds Effect Range[1]**
Adj. r-Squared	**0.75**		**0.617**	
% Deviance Explained	**76%**		**75%**	
Intercept	-9.45	7.9e-5	-7.87	3.8e-4
Particulate Matter from Wildfire (ug/m^3)	0 - 412	1 - 1.43	0 - 624	1 - 1.72
Is Monday	0 - 1	1 - 1.17	0 - 1	1 - 1.17
Is Tuesday	0 - 1	1 - 1.07	0 - 1	1 - 1.07
Is SRA3	NA	NA	0 - 1	1 - 0.52
Is SRA6	NA	NA	0 - 1	1 - 1.19
Proportion Income >50k	NA	NA	0.31 - 0.55	0.25 - 0.08
Proportion Age <24	NA	NA	0.32 - 0.41	1.77 - 2.06
f(Anthropogenic $PM_{2.5}$)	0.03 – 1.78	0.91 – 1.07	0.03 - 2.39	0.94 – 1.08
f(Relative Humidity, Min. Temp.)	6 - 79, 28-72	0.80 – 1.40	6 - 84, 25-74	0.90 – 1.40

[1] GAM with binomial distribution and logit link

Specific Aim #4 – Evaluate climate change impacts on future fire regimes

Progress completed

Co-Investigator T. Loboda at the University of Maryland calculated Canadian Fire Weather Index for the study area using weather variables produced by the Regional Climate Model (RegCM v. 4.1) under IPCC future climate scenarios for 2001-2040. At the decadal scales the RegCM produced conditions comparable to those observed during 2001-2010 (Figure 6). Thus, we expect San Diego County will experience approximately two extreme fire seasons each decade by 2040, similar to the present.

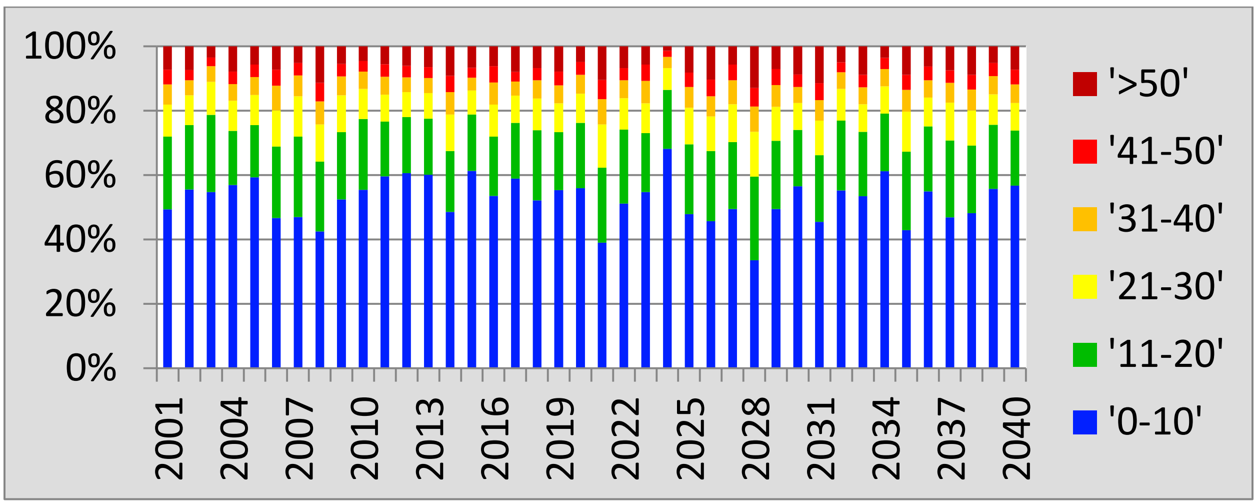

Figure 6. Canadian Fire Weather Index values forecasted according to the Regional Climate Model under IPCC future climate scenarios for the San Diego County study area.

The fire occurrence model (*Loboda* 2009) show the most notable increases in fire danger conditions that overlap with areas with high potential for burning are likely to occur in June. These increases are linked to an increased number of moderate fire danger days rather than necessarily high and extreme fire conditions.

We also explored how predicted climate change effects could influence respiratory symptom counts by scaling the data for the weather variables included in the statistical model according to IPCC climate change forecasts. We plugged in IPCC 2100 forecasts of temperature (-4° C) and relative humidity (-10%) into the 2007 statistical model. Figure 7 shows the results where the peak day and 5-day peak of symptom counts are ~10% greater than 2007 predicted and observed symptom counts.

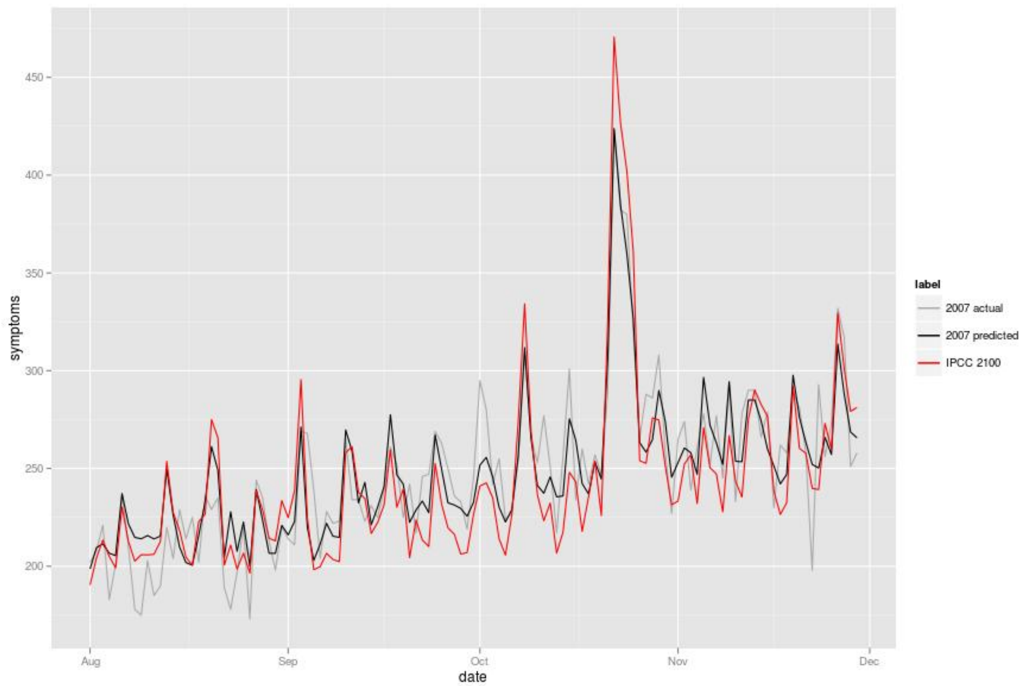

Figure 7. Predicted changes in ED visits with IPCC 2100 climate change forecasts are applied (+4 degrees C, -10% relative humidity).

Summary of results and project outcomes

Predictive model development

The coupled statistical and process-based modeling demonstrates an end-to-end methodology for generating reasonable estimates of wildland fire particulate matter concentrations and health effects at resolutions compatible with syndromic surveillance data. The model performs well at predicting ED visits in most cases by including nine ancillary variables in addition to wildfire smoke concentration. While model coefficients and functional estimates are specific to San Diego County, the method has applicability to other regions and syndromic responses.

The study's technological contribution is this novel combination of a newly available comprehensive data set (respiratory complaints collected through syndromic surveillance) to advanced methods to geospatially model TSP originating from naturally-occurring wildfire. The methods demonstrated show the power of an interdisciplinary approach to employ advanced data sets and modeling methods to a problem of great consequence for human health.

This approach can be used and refined by public health officials and emissions scientists in other regions of the globe wherever appropriate datasets are available. However, the product can most appropriately be considered "under development" as the resulting statistical model is specific to San Diego County.

Application of the predictive model under climate change scenarios

Analysis of future fire occurrence shows San Diego County will experience approximately two extreme fire seasons each decade through 2040. We are in the process of finalizing a manuscript to demonstrate the application of the model connecting wildland fire smoke concentration to health outcomes in years of these extreme fire conditions. Our initial results show that the model formulation can be used to assess the location and impact of elevated PM concentrations from particulate emissions originating from wildfire in and around San Diego county that could be valuable for use by public health officials. In a proposed additional grant activity, we hope to work more closely with public health agencies and first responders to better define the value of applying our model and how products we could generate from this study can be improved for their use.

Highlights of project outcomes and results

- Our interdisciplinary research team developed a coupled statistical and process-based model system that:
  - Demonstrates an end-to-end methodology for generating reasonable estimates of wildland fire particulate matter concentrations and effects on respiratory health,
  - Applicable at resolutions compatible with syndromic surveillance health information,
  - Model coefficients and functional estimates are specific to San Diego County, but the method has applicability to other regions and syndromic responses.
  - Model results show that at peak fire particulate concentrations the odds of a person seeking emergency care is increased by approximately 50% compared to non-fire conditions.
- Future fire occurrence modeling shows San Diego County will experience approximately two extreme fire seasons each decade by 2040, similar to the present.

- We demonstrated the impact of wildfire under climate change on emergency department visits
- We showed the value of syndromic surveillance data, which are rapidly being developed across the US, for post-disaster analytic work.
- The grant helped to expand the San Diego syndromic surveillance capacity by adding several new hospitals to the SDADIC syndromic surveillance network.
- The project activity promoted collaboration between public health and environmental modeling communities to better understand determinants of health during a disaster.

Manuscripts and conference presentations resulting from grant

Here we list conference papers and journal manuscripts that were a result of the grant funding and study. The project has produced eight conference presentations with two additional presentations planned. Five manuscripts have been prepared or are under preparation for submission to peer-reviewed journals. Project outputs and general description of the project can be found at:

http://mtri.org/firehealth.html

Peer-review journal submissions:

NOTE: All listed are in process of being referenced through Pub Med Central (PMC), so do not yet have a PMC reference number.

Billmire, M., N.H.F. French, T. Loboda, R.C. Owen, and M. Tyner. "Santa Ana winds and predictors of wildfire progression in southern California" Submitted to *Fire Ecology*.

French, N.H.F., et al. "Wildfire Particulate Emissions and Respiratory Health: Model application and implications under a changing climate". In preparation for submission to *Environmental Health Perspectives*.

Huang, Y. S. Wu, M.K. Dubey, and N.H.F. French. "Impact of aging mechanism on model simulated carbonaceous aerosols". Submitted for review to *Atmospheric Chemistry & Physics.*

Loboda, T., et al. "Modeling Fire Occurrence as a function of Landscape Characteristics: A case study from San Diego county, California" In preparation for submission to *Journal of Disaster Risk Reduction*.

Thelen, B., N.H.F. French, B. Koziol, R.C. Owen, J. Johnson, M. Billmire, M. Ginsberg, T. Loboda. "Modeling acute respiratory illness during the 2007 San Diego wildland fires using a coupled emissions-transport system and Generalized Additive Modeling". To be submitted 2012 to *J of Environmental Health*.

Presentations:

December 2010: American Geophysical Union (AGU) Fall'10 – San Francisco, CA – Poster presentation by B Koziol. "Modeling PM Plumes from 2007 California Wildland Fires using a Coupled Emissions-Transport System"

April 2011: American Association of Geographers – Seattle, WA – Oral presentation by T. Loboda. "Evaluating impacts of climate-driven change in fire regimes on human and natural systems using a Fire Occurrence Model"

June 2011: National Environmental Health Association (NEHA) – Columbus, OH, – Poster presentation by N. French and B. Koziol. "Respiratory Health Impacts of Wildfire Particulate Emissions under Climate Change Scenarios"

December 2011: AGU Fall'11– San Francisco, CA:

- Oral presentation by M Billmire. "Santa Ana winds and predictors of wildfire progression in southern California"
- Poster presentation by T Loboda. "Modeling fire occurrence as a function of landscape"
- Poster presentation by Y Huang. "Effects of updated aging scheme on the model simulation of global carbonaceous aerosols"

June 2012: NEHA – San Diego, CA – Oral presentation by N. French, R.C. Owen, M. Ginsberg, J. Johnson, M. Billmire. "Wildfire Particulate Emissions and Respiratory Health under Climate Change Scenarios: Project overview and results"

June 2012: NASA Science Meeting, GOFC-GOLD and NEESPI Workshop and Regional Conference – Volga, Russia – Invited talk by T Loboda "The role of satellite observations in assessing impacts of wildfire occurrence on respiratory health of population"

June 2012: ENVIROMIS 2012 – Irutsk, Russia – Invited report by T Loboda "The role of satellite observations in assessing impacts of wildfire occurrence on respiratory health of population".

June 2012: ACCENT-IGAC-GEIA (Global Emissions InitiAtive) Conference – Toulouse, France – Poster presentation by N. French "Respiratory Health Impacts of Wildfire Particulate Emissions under Climate Change Scenarios"

April 2012: IAWF Human Dimensions of Wildland Fire – Seattle, WA – N French poster presentation "Respiratory Health Impacts of Wildfire Particulate Emissions under Climate Change Scenarios"

Planned presentations:

December 2012: International Society for Disease Surveillance (ISDS) Annual Conference – San Diego, CA – Accepted for oral presentation by Jeff Johnson "Use of syndromic surveillance information for expanded assessment of wildfire disaster"

December 2012: American Geophysical Union (AGU) Fall'12 – San Francisco, CA – Oral presentation by T Loboda "Modeling risk of ignition as a function of landscape and human presence using satellite observations"

March 2013: Environmental Health 2013 – Boston, MA – Oral presentation requested by N French "Wildfire Particulate Emissions and Respiratory Health: Model application and implications under a changing climate"

Description and access to project outputs and the Wildfire/Heath predictive model

All project outputs (listed above), interim project reports, and this final report are available for viewing and download at our project web page at MTRI: http://mtri.org/firehealth.html. Final journal articles or manuscripts (if not accepted for publication) will be posted when complete.

Also available is the code for running the statistical General Additive Model resulting from this study. The model exists in the form of R code that will be made accessible via the MTRI web page summarizing the project. R is a free, open-source software environment for statistical computing. Along with this code, we will provide sample data and instructions for applying the model to alternate datasets. Contact Michael Billmire (mgbillmi@mtu.edu) or Nancy French (nhfrench@mtu.edu) for more information. Contacts for accessing these resources are also given and will be maintained on the MTRI web pages.

References

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