OPEN

Journal of Exposure Science and Environmental Epidemiology (2016) 26, 233–240

www.nature.com/jes

ORIGINAL ARTICLE

Evaluation of a spatially resolved forest fire smoke model for population-based epidemiologic exposure assessment

Jiayun Yao[1], Jeff Eyamie[2] and Sarah B. Henderson[1,3]

Exposure to forest fire smoke (FFS) is associated with multiple adverse health effects, mostly respiratory. Findings for cardiovascular effects have been inconsistent, possibly related to the limitations of conventional methods to assess FFS exposure. In previous work, we developed an empirical model to estimate smoke-related fine particulate matter ($PM_{2.5}$) for all populated areas in British Columbia (BC), Canada. Here, we evaluate the utility of our model by comparing epidemiologic associations between modeled and measured $PM_{2.5}$. For each local health area (LHA), we used Poisson regression to estimate the effects of $PM_{2.5}$ estimates and measurements on counts of medication dispensations and outpatient physician visits. We then used meta-regression to estimate the overall effects. A 10 $\mu g/m^3$ increase in modeled $PM_{2.5}$ was associated with increased sabutamol dispensations (RR = 1.04, 95% CI 1.03–1.06), and physician visits for asthma (1.06, 1.04–1.08), COPD (1.02, 1.00–1.03), lower respiratory infections (1.03, 1.00–1.05), and otitis media (1.05, 1.03–1.07), all comparable to measured $PM_{2.5}$. Effects on cardiovascular outcomes were only significant using model estimates in all LHAs during extreme fire days. This suggests that the exposure model is a promising tool for increasing the power of epidemiologic studies to detect the health effects of FFS via improved spatial coverage and resolution.

Journal of Exposure Science and Environmental Epidemiology (2016) **26,** 233–240; doi:10.1038/jes.2014.67; published online 8 October 2014

Keywords: forest fire smoke; particulate matter; respiratory effects; cardiovascular effects; modeling; epidemiology

INTRODUCTION

Forest fires are increasing in frequency and intensity as the global climate changes,[1] and they can be responsible for periods of extremely poor air quality. Exposure to fine particulate matter ($PM_{2.5}$) from forest fire smoke (FFS) has been associated with a range of adverse health effects, from decreased birth weight to premature mortality.[2–4] However, the clearest evidence is from studies of acute respiratory effects,[5–7] with inconsistent and inconclusive results for cardiovascular effects[6,8–10] and cause-specific mortality.[4,11–14] These inconsistencies are unexpected, given that daily $PM_{2.5}$ has been associated with cardiovascular effects[15,16] and cause-specific mortality[17–19] in urban environments. It is unclear whether the discrepancies between smoke-related and urban $PM_{2.5}$ are because of differences in the constituents of the particulate matter, or limited power to detect the effects of FFS, or both.

FFS events are typically acute, and they often affect rural populations that do not provide the statistical power necessary to detect relatively small increases in health outcomes. In addition, conventional exposure assessment methods that use existing $PM_{2.5}$ monitoring networks are limited because the instruments are spatially sparse compared with the smoke that can cover vast geographic areas. Many novel exposure assessment methods are incorporating satellite data and modeling to address these spatial limitations,[8,9,20,21] but epidemiologic comparisons between conventional and novel methods have been rare.[6,22] New methods have the potential to improve fire smoke epidemiology by better characterizing population variability in exposures, and by allowing inclusion of heavily affected rural areas in population-based analyses. Epidemiologic studies with more accurate exposure assessment and larger populations will have more power to detect small increases in health outcomes because of FFS if they actually exist. It is therefore important to evaluate how new exposure assessment methods compare with conventional methods whenever possible.

Recently the British Columbia Centre for Disease Control (BCCDC) in the province of British Columbia (BC), Canada, developed a spatially resolved model of $PM_{2.5}$ exposure for use in its BC Asthma Medication Surveillance (BCAMS) system.[23] The model was optimized to capture FFS events because evidence suggests that asthmatics are a particularly susceptible subpopulation.[7] The BCCDC model combines daily $PM_{2.5}$ measurements, aerosol optical depth from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments, fire radiative power from MODIS, manual tracings of FFS plumes from the US National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System, and meteorological forecasts of atmospheric venting conditions. Daily estimates are made for all populated areas of the province. Although the model was developed to support real-time public health surveillance, it has the potential to be useful for epidemiologic exposure assessment. The BC context provides a unique opportunity to evaluate that potential by comparing modeled with measured $PM_{2.5}$ across the many areas where both metrics are available, and then to extend analyses using modeled $PM_{2.5}$ to the entire province. Here we evaluate the effects of $PM_{2.5}$ on pharmaceutical dispensations and outpatient physician visits for a range of respiratory and cardiovascular outcomes.

[1]Environmental Health Services, British Columbia Centre for Disease Control, Vancouver, British Columbia, Canada; [2]Health Canada, Winnipeg, Manitoba, Canada and [3]School of Population and Public Health, The University of British Columbia Vancouver, British Columbia, Canada. Correspondence: Jiayun Yao, Environmental Health Services, British Columbia Centre for Disease Control, LL0073, 655 W 12th Avenue, Vancouver, BC V5Z 4R4, Canada.
Tel.: +1 604 707 2400; ext. 2932. Fax: +1 604 707 2441.
E-mail: Jiayun.Yao@bccdc.ca
Received 9 April 2014; revised 16 July 2014; accepted 17 July 2014; published online 8 October 2014

METHODS

Study Area and Period

BC is located on the west coast of Canada, with an area of 944,735 km^2 and a population of 4,243,580 in the census year of 2006. The province is divided into 89 local health areas (LHAs) for the purposes of health administration, and their 2006 populations ranged from 542 to 352,783 individuals. The study period covers the forest fire seasons (1 April to 30 September) of 2003 through 2010, during which the annual area burned averaged 1608 km^2 and ranged from 132 to 3371 km^2. The central and southern interior areas are most prone to forest fires, especially following damage done by an extensive infestation of the mountain pine beetle.[24] The province has a dense air quality monitoring network relative to the size of its population (Figure 1).

Exposure Assessment

Measured $PM_{2.5}$. The air quality monitoring network is maintained by the BC Ministry of Environment. Particulate matter was continuously measured during the study period in 29 of the 89 LHAs using $PM_{2.5}$ and/or PM_{10} tapered element oscillating microbalances (Figure 1). All data were converted to $PM_{2.5}$ equivalent concentrations as described elsewhere.[5] Daily average concentrations measured at the monitoring sites were used to represent the exposure of the entire population of the LHA in which the monitor was located. Despite the large geographic areas covered by some rural LHAs, monitors were typically located in the largest community.

Modeled $PM_{2.5}$. The BCCDC has developed an empirical FFS exposure model for public health surveillance, as described elsewhere.[23] Briefly, the model estimates daily average $PM_{2.5}$ at a spatial resolution of 5×5 km for all populated areas of the province by combining measured concentrations with remote sensing data and meteorological forecasts. The remote sensing data include: aerosol optical depth from MODIS, which is a measure of the total aerosol in any atmospheric column unobstructed by cloud;[25] the local sum of fire radiative power (FRP) from hot spots detected by MODIS, which is proportional to their aerosol emissions;[26] and smoke plumes hand drawn by NOAA analysts, which integrate images from seven different satellites for the Hazard Mapping System.[27] The meteorological forecasts are summarized using the BC Ministry of Environment venting index that describes overall mixing in the atmosphere.[28] We assigned daily average, population-weighted $PM_{2.5}$ estimates to the entire populations of all LHAs. The model estimates were weighted using population data from the 2006 census dissemination areas (DAs) that typically have populations ranging from 400 to 700 individuals.[29] Model estimates were assigned to the DA centroids, and their populations were used to calculate the overall population-weighted averages for each LHA. This resulted in two different exposure metrics for the 29 LHAs with air quality monitoring stations, and only the modeled metric for the other 60 LHAs.

Extreme Fire Days

Although the exposure model has inputs specific to FFS, it reflects $PM_{2.5}$ from all sources because it includes measurements from the air quality network and aerosol optical depth as two of its important covariates. To further evaluate the effect of $PM_{2.5}$ specifically from FFS, we used the FRP from MODIS to identify extreme fire days in BC. All thermal anomalies detected by MODIS include this measure of energy output by the detected fire. We calculated the daily sum FRP for all fires in BC for each day of the study period, and we defined days with summed FRP values above 90th percentile as extreme fire days. The assumption is that during these extreme fire days, fire smoke is more likely to be the dominant source of $PM_{2.5}$ in the province.

Administrative Health Data

Daily counts of pharmaceutical dispensations for each LHA were retrieved from the BC PharmaNet database. We assessed the effect of daily $PM_{2.5}$ on dispensations of salbutamol sulfate and fast-acting nitroglycerin. Salbutamol sulfate is commonly used to relieve acute exacerbations of asthma, chronic obstructive pulmonary disease (COPD), and other obstructive lung diseases. Previous studies in BC have found that increased FFS exposure is associated with increased salbutamol sulfate dispensations.[22,30] Fast-acting nitroglycerin is commonly used to relieve acute exacerbations of angina. One previous study has suggested an association between exposure to smoke from a peat fire and emergency department visits for angina.[8]

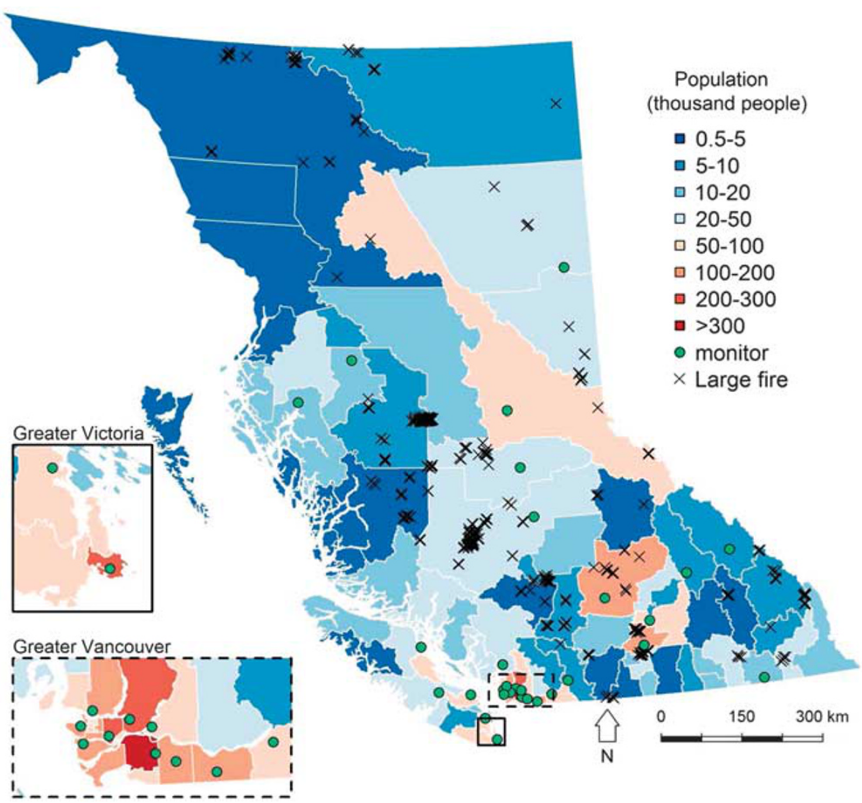

Figure 1. Map of local health areas (LHAs) in British Columbia, Canada. Background is color coded according to LHA population. Green dots indicate monitoring stations and crosses indicate large fires with fire radiative power of >1500 MW during the study period.

Daily counts of cause-specific outpatient physician visits were retrieved from the BC Medical Services Plan billings database. Data were extracted by the International Classifications of Diseases, 9th revision (ICD-9) codes for asthma (493), COPD (490–492, 494–496), upper respiratory infections (460–466), lower respiratory infections (480–486), otitis media (381–382), and all cardiovascular diseases combined (390–459). No previous studies have evaluated the association between FFS and otitis media, but evidence from urban environments indicates a relationship with $PM_{2.5}$ from vehicular sources[31] and residential woodsmoke.[32]

Statistical Analyses

For each LHA, we used a generalized linear Poisson regression model to estimate the effect of $PM_{2.5}$ on the rates of pharmaceutical dispensations and outpatient physician visits. Measured and modeled $PM_{2.5}$ values were used for the 29 LHAs where both were available, and modeled values were used for all 89 LHAs. Individual models were run for all days and for extreme fire days only. All models were adjusted for temperature using a natural cubic spline of daily maximum apparent temperature with 3 d.f. Short- and long-term temporal trends were controlled using a factor variable that indicated the year, month, and day of week. A fixed lag of 0–1 days was chosen for all analyses, meaning that $PM_{2.5}$ on the day before the pharmaceutical dispensation or physician visit was averaged with $PM_{2.5}$ on the day of the event. This lag was chosen because it produced the best-fitted models in previous studies on FFS exposure in BC.[9,30] The rate ratios (RRs) associated with modeled $PM_{2.5}$ estimates were mapped for individual LHAs on extreme fire days to qualitatively evaluate the spatial relationships between the locations of large fires and affected populations. All RRs were calculated for a 10 $\mu g/m^3$ increase in measured or modeled $PM_{2.5}$.

After fitting models to the individual LHAs, we conducted a random effects meta-regression using the inverse variance method to estimate the overall effects for: (1) measured $PM_{2.5}$ in the 29 LHAs with monitoring stations; (2) modeled $PM_{2.5}$ in the 29 LHAs with monitoring stations; (3) modeled $PM_{2.5}$ in the 60 LHAs without monitoring stations; and (4) modeled $PM_{2.5}$ in all 89 LHAs. Meta-regressions were conducted for all days and for extreme fire days. When restricting the analyses to extreme fire days, models for some of the 60 LHAs without monitoring stations did not converge or the variance of the estimates was extremely large (SE >0.5), mostly because of their small populations. These LHAs were excluded from the meta-analyses, and excluded LHAs were indicated in the maps of RR estimates for individual LHAs. From herein meta-regression estimates for modeled $PM_{2.5}$ in the 60 LHAs without monitors and in all 89 LHAs refer to results calculated with a varying number (between 2 and 12) of LHAs excluded.

RESULTS

Descriptive Statistics

Daily rates of pharmaceutical dispensations and physician visits were comparable for the 29 LHAs with monitoring stations and the 60 LHAs without. Similarly, the measured $PM_{2.5}$ was comparable with the modeled $PM_{2.5}$ in both cases (Table 1). Both measured and modeled exposure estimates were higher for the extreme fire days. In the 29 LHAs with monitors, the mean correlation coefficient between measured and modeled exposure within each LHA was 0.70 (ranging from 0.25 to 0.91) for all days, and 0.72 (ranging from 0.29 to 0.95) for extreme fire days. Correlations tended to be higher in heavily fire-affected LHAs and lower in LHAs where populations were distributed farther away from the monitors. In addition, more large fires occurred in the 60 LHAs without monitors.

Pharmaceutical Dispensations

For the 29 LHAs with air quality monitoring stations, a 10 $\mu g/m^3$ increase in measured $PM_{2.5}$ was associated with a 4% increase (RR = 1.04; 95% CI = 1.03–1.06) in the meta-regression estimate for salbutamol dispensations during all fire season days. The same increase was observed for the modeled $PM_{2.5}$ estimates in the same 29 LHAs, the 60 LHAs without monitors, and in all 89 LHAs. When restricted to the most extreme fire days, the estimates increased for all exposure groups (Figure 2). Individual LHA estimates for modeled $PM_{2.5}$ on the most extreme fire days showed that rates were elevated in areas affected by large fires (Figure 3).

Table 1. Summary statistics for total population, daily local health area (LHA) pharmaceutical dispensation and physician visit rates, measured and modeled $PM_{2.5}$ exposure levels, and number of large fires in the 29 LHAs with monitors and 60 LHAs without monitors.

	29 LHAs with monitors	*60 LHAs without monitors*
Total population (2006)	2,681,840	1,561,740
Mean (± SD) daily pharmaceutical dispensation rates (per 100,000 individuals)		
Salbutamol	40 ± 23	36 ± 32
Nitroglycerin	14 ± 14	16 ± 22
Mean (± SD) daily physician visit rates (per 100,000 individuals)		
Asthma	13 ± 10	11 ± 15
COPD	11 ± 10	12 ± 16
Lower respiratory infections	6 ± 5	6 ± 11
Upper respiratory infections	62 ± 37	55 ± 54
Otitis media	9 ± 8	7 ± 12
Cardiovascular	111 ± 73	117 ± 95
Mean (± SD) daily $PM_{2.5}$ ($\mu g/m^3$)		
Measured		
All days	5.9 ± 5.2	NA
Extreme fire days[a]	10.2 ± 11.1	NA
Modeled		
All days	6.0 ± 5.4	5.6 ± 5.1
Extreme fire days[a]	10.3 ± 9.9	10.1 ± 9.5
Total large fires[b]	136	252

[a]Extreme fire days defined as those when the provincial sum of fire radiative power (FRP) was in the 90th percentile of the distribution. [b]Large fires defined as those with FRP >1500 megawatts.

Dispensations of fast-acting nitroglycerin showed a different pattern. There was no significant effect of measured or modeled $PM_{2.5}$ during all fire season days, but the effects were significantly elevated for modeled $PM_{2.5}$ on extreme fire days. A 10 $\mu g/m^3$ increase was associated with a 3% increase (RR = 1.03; 95% CI = 1.01–1.05) in the meta-regression estimate for nitroglycerin dispensations across all 89 LHAs (Figure 2). Once again, results for the individual LHAs show elevated rates in areas affected by large fires on the most extreme fire days (Figure 3).

Physician Visits

There was generally good agreement between meta-regression estimates for measured and modeled $PM_{2.5}$ across the 29 LHAs with monitoring stations for all types of physician visits. One exception was a significant effect of measured $PM_{2.5}$ on upper respiratory infections on all fire season days (RR = 1.03; 95% CI = 1.02–1.05), with no similar effect observed with the modeled estimates. Both measured and modeled $PM_{2.5}$ were consistently associated with increased physician visits for asthma, lower respiratory infections, and otitis media on extreme fire days, and not associated with increased visits for upper respiratory infections. The consistency of the associations for COPD and cardiovascular visits was less clear. For COPD, the effects of measured $PM_{2.5}$ were the same on all days and extreme fire days, whereas the effects of modeled $PM_{2.5}$ were elevated on the extreme fire days. The effects of $PM_{2.5}$ were small for cardiovascular visits, and significantly protective for measured $PM_{2.5}$ in the

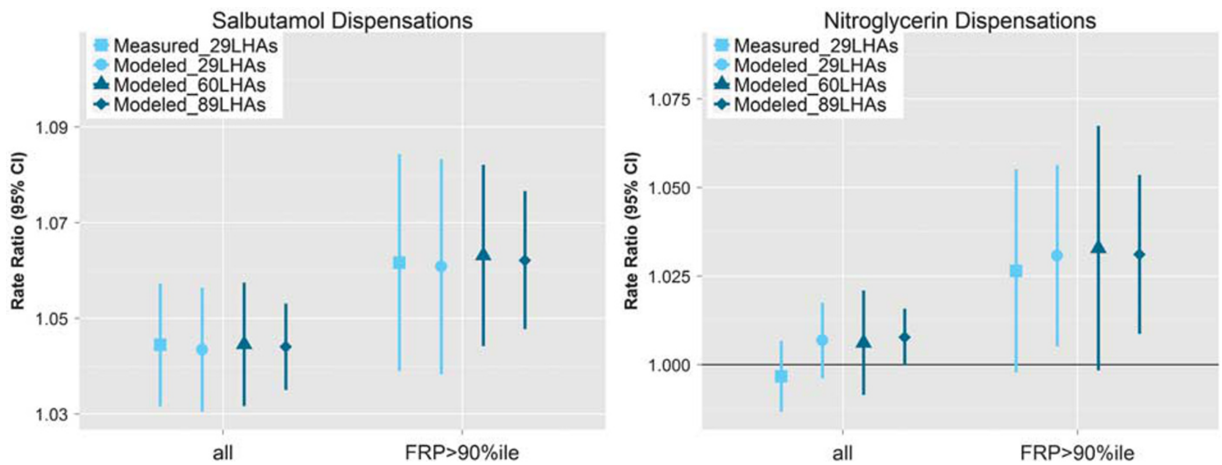

Figure 2. Meta-regression results for the associations between pharmaceutical dispensations and measured and modeled $PM_{2.5}$ in the 29 LHAs with monitors, modeled $PM_{2.5}$ in 60 LHAs without monitors, and all 89 LHAs, for all days of fire seasons and extreme fire days. Varying numbers (indicated in Figure 3) of LHAs were excluded from the analyses for 60 LHAs and all 89 LHAs in extreme fire days.

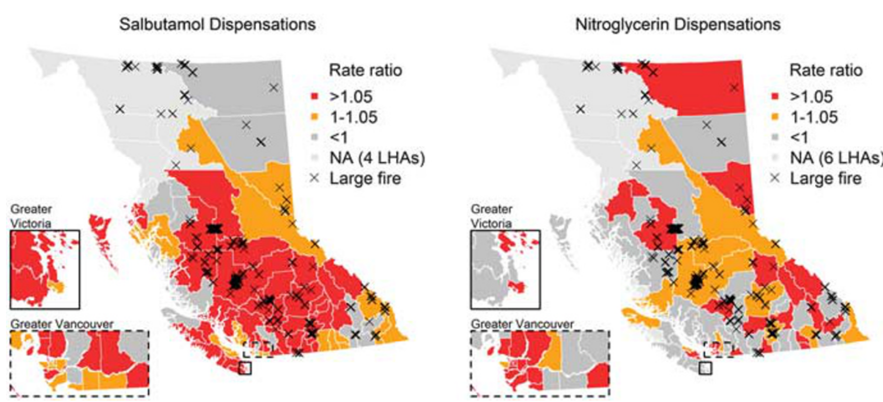

Figure 3. Maps of point estimates for the association between a 10 $\mu g/m^3$ increase in modeled $PM_{2.5}$ and pharmaceutical dispensations for LHAs during extreme fire days. The background color is coded by the values of point estimates, and the insets show the major urban areas of Greater Vancouver and Victoria.

29 LHAs on all fire season days. Effects were slightly greater for modeled $PM_{2.5}$ in those LHAs, and greater still for modeled $PM_{2.5}$ in the 60 LHAs without monitors, and in all 89 LHAs (Figure 4). Effects of modeled $PM_{2.5}$ were small but marginally significant on the most extreme fire days (RR = 1.01; 95% CI = 1.00–1.02) for all 89 LHAs.

Mapping results from the modeled $PM_{2.5}$ estimates for all 89 LHAs on the most extreme fire days showed spatial overlap between affected areas and large fires for asthma, COPD, and otitis media. The overlap was less consistent for respiratory infections and cardiovascular disease. There were also strong associations for otitis media throughout the urban areas of Greater Vancouver and Victoria that are far removed from fires but still affected by smoke on extreme fire days (Figure 5). For example, Keane[33] found that the Greater Vancouver area was affected by FFS in 30% of the summer days during the intense fire season in 2009, with an average $PM_{2.5}$ increase of 5 $\mu g/m^3$ on smoke-affected days.

DISCUSSION

We found consistent associations between measured and modeled $PM_{2.5}$ in 29 LHAs for salbutamol dispensations, and physician visits for asthma, lower respiratory infections, and otitis media. For every 10 $\mu g/m^3$ increase in both measured and modeled $PM_{2.5}$ on all fire season days, there was a 4% increase in salbutamol dispensations, a 6% increase in asthma visits, a 3% increase in lower respiratory infection visits, and a 5% increase in otitis media visits. These results are consistent with other studies on similar health outcomes. Elliott et al.[30] reported that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with a 6% increase in salbutomol dispensations in fire-affected populations in BC during the same fire seasons. Yao et al.[22] reported that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with a 4% increase in salbutomol dispensations and a 3% increase in asthma physician visits, respectively, during the 2010 fire season in BC. Similarly, Henderson et al.[34] reported a 6% increase in odds of asthma physician visits during the 2003 fire season in BC. Null results for upper respiratory infections were also reported in previous studies that examined this outcome.[34,35] These internal and external consistencies provide confidence in the $PM_{2.5}$ estimates from the BCCDC exposure model, and therefore confidence in the effect estimates derived using health data from all 89 LHAs, including those 60 LHAs with no $PM_{2.5}$ measurements available.

There were some outcomes that indicated discordance between the measured and modeled $PM_{2.5}$ estimates for the 29 LHAs. These included nitroglycerin dispensations, COPD, and upper respiratory infections on all fire season days. These

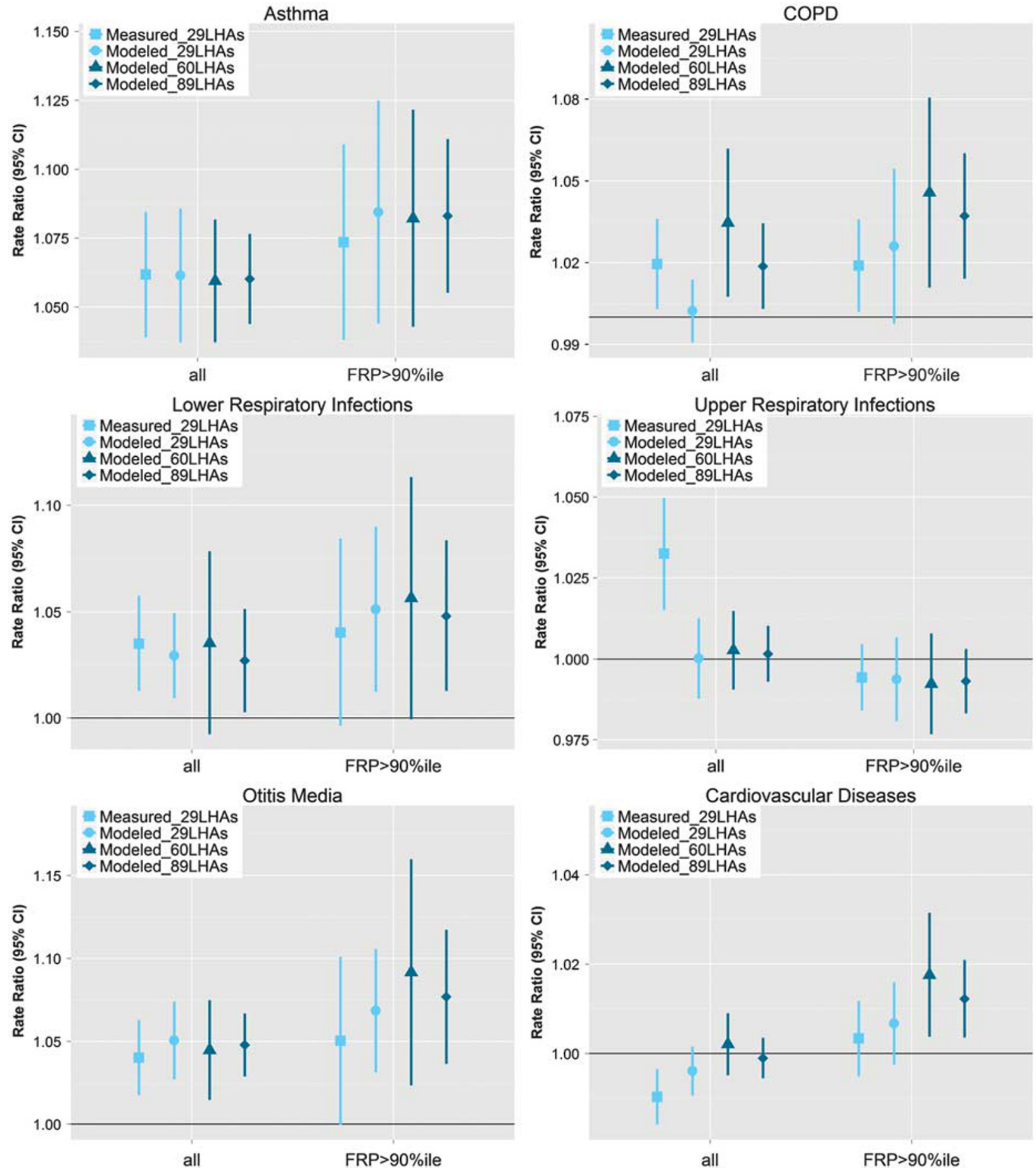

Figure 4. Meta-regression results for the associations between physician visits and measured and modeled $PM_{2.5}$ in the 29 LHAs with monitors, modeled $PM_{2.5}$ in 60 LHAs without monitors, and all 89 LHAs, for all days of fire seasons and extreme fire days. Varying numbers (indicated in Figure 5) of LHAs were excluded from the analyses for 60 LHAs and all LHAs in extreme fire days.

differences are likely because of differences in the exposure assignment for the two metrics. For measured values, the $PM_{2.5}$ concentration recorded by the monitoring station or the $PM_{2.5}$ equivalent of its PM_{10} measurement[30] was applied to the entire population of the LHA. On the other hand, only the available $PM_{2.5}$ measurements were used in the $PM_{2.5}$ model on any given day, the estimates in each 5 × 5 km grid cell were population weighted, and then applied to the entire population of the LHA. For geographically large LHAs with dispersed populations, the modeled exposure can be quite different from the measured exposure, even though the measured exposure is one of many variables included in the modeled exposure. The population-weighted average distance to a monitoring station ranged from 2 to 32 km for the 29 LHAs, with a mean of 10 km. The LHA with the smallest correlation between measured and modeled values (LHA60, $r = 0.25$) had a population-weighted average distance of 20 km from the monitoring station within the LHA.

To the best of our knowledge, this is the first study to examine the effects of FFS on otitis media. However, previous studies have found increased risk of childhood otitis media associated with exposure to environmental tobacco smoke, traffic-related air pollution, and residential wood smoke.[31,32,36–38] Our study

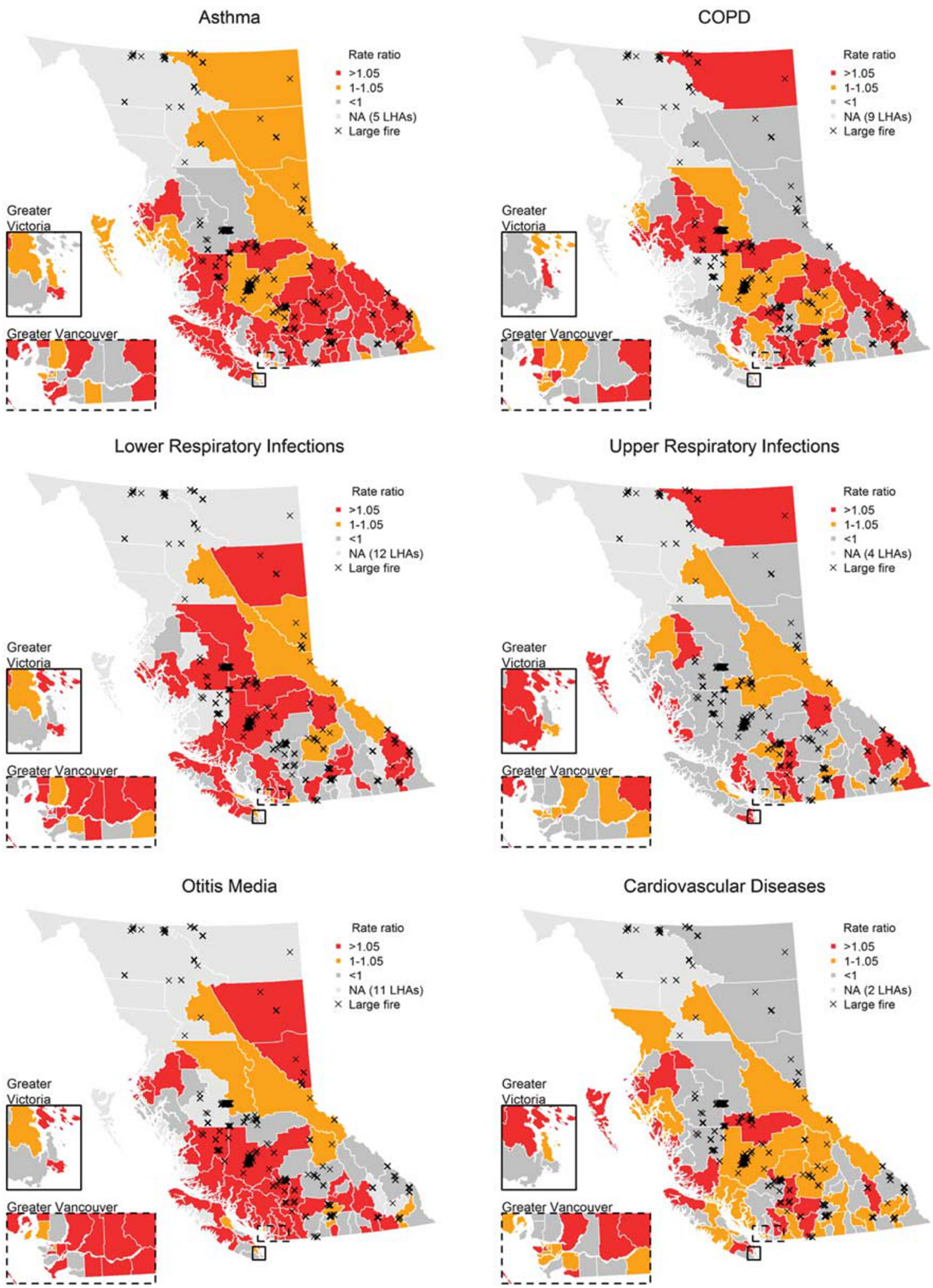

Figure 5. Maps of point estimates for association between a 10 $\mu g/m^3$ increase in modeled $PM_{2.5}$ and physician visits for LHAs during extreme fire days. The background color is coded by the values of point estimates and the insets show the major urban areas of Greater Vancouver and Victoria.

demonstrated a 5% increase in otitis media visits for population of all ages. Among all the otitis media visits, approximately half of them were visits by children under the age of 10 years. Restricting the analyses to this age group yielded the same point estimate (RR = 1.05, 95% CI = 1.03–1.08).

The meta-regression estimates for nitroglycerin dispensations and physician visits for cardiovascular diseases were null in most cases, but the associations with modeled $PM_{2.5}$ in all 89 LHAs became statistically significant when restricting the data to extreme fire days. On fire days with the provincial sum of FRP in the 90th percentile, a 10 μg/m^3 increase in modeled $PM_{2.5}$ was associated with a 3% increase in nitroglycerin dispensations and a 1% increase in all cardiovascular physician visits. These effects were not significant for measured or modeled $PM_{2.5}$ in the 29 LHAs with monitoring stations. One possible explanation is that the effects of FFS exposure on cardiovascular diseases are more prominent in rural areas where monitors are not available, and where access to care may be limited. This may also explain the null findings in many previous studies, mostly conducted using monitoring measurements in urban or densely populated areas.[9,34,39–41] Another possible explanation is that inclusion of an entire population over an unprecedentedly long time series provides enough power to detect differences that have gone undetected by other studies. Only two other studies have found statistically significant effects on cardiovascular health outcomes from FFS, both by comparing outcomes in an area or time period affected by fires with outcomes in the same area or time period when it was not affected by fire.[11,35]

In this study, we evaluated the application of the FFS exposure model in epidemiologic studies by comparing the health effects related to the modeled $PM_{2.5}$ with those related to measured $PM_{2.5}$. The comparable effects observed for most respiratory health outcomes give us confidence in the model performance and utility. Modeled $PM_{2.5}$ in all 89 LHAs was associated with cardiovascular outcomes during extreme fire days, but measured and modeled $PM_{2.5}$ in the 29 LHAs was not. This suggests that the improved spatial coverage of the model may improve our ability to capture the population health effects of FFS exposure that may be more prominent in rural areas without air quality monitoring stations. The generally larger point estimates from modeled $PM_{2.5}$ in the 29 LHAs compared with measured $PM_{2.5}$ on extreme fire days suggested that the model might detect effects specific to FFS more sensitively, with the addition of smoke-specific information and the finer spatial resolution of estimates for exposure assignment.

There are several limitations in this study. First, the approach was ecologic and the entire population of an LHA, some with very large geographic areas, was assigned the same daily exposure level. Although the use of population-weighted average model estimates has improved the representativeness of the exposure assignment compared with using single monitors, misclassification is still likely to exist. Further studies on exposure and health responses at the individual level are needed to address this limitation. Second, the statistical approach we used was not able to estimate the effects in LHAs with very small populations (<5000) with small daily heath outcome counts (<10), and thus not able to include their effects in the overall meta-analysis. This could be an important limitation, especially if these remote and small communities responded to FFS exposure differently from the rest of the province, possibly because of their differences in population composition, access to health care, or social economic status.

In conclusion, we find consistent associations between measured and modeled $PM_{2.5}$ for multiple cardiopulmonary health outcomes. The effects for modeled estimates are comparable with the effects for measured estimates on respiratory outcomes, and the effects of modeled estimates are generally stronger than the effects of measured estimates on cardiovascular outcomes. This suggests that the exposure model is a promising tool for increasing the power of epidemiologic studies to detect the health effects of FFS via improved spatial coverage and possibly via improved spatial resolution compared with conventional approaches.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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