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Systematic identification and prioritization of communities impacted by residential woodsmoke in British Columbia, Canada

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Abstract

Residential woodsmoke is an underregulated source of fine particulate matter ($PM_{2.5}$), often surpassing mobile and industrial emissions in rural communities in North America and elsewhere. In the province of British Columbia (BC), Canada, many municipalities are hesitant to adopt stricter regulations for residential wood burning without empirical evidence that smoke is affecting local air quality. The objective of this study was to develop a retrospective algorithm that uses 1-h $PM_{2.5}$ concentrations and daily temperature data to identify smoky days in order to prioritise communities by smoke impacts. Levoglucosan measurements from one of the smokiest communities were used to establish the most informative values for three algorithmic parameters: the daily standard deviation of 1-h $PM_{2.5}$ measurements; the daily mean temperature; and the daytime-to-nighttime ratio of $PM_{2.5}$ concentrations. Alternate parameterizations were tested in 45 sensitivity analyses. Using the most informative parameter values on the most recent two years of data for each community, the number of smoky days ranged from 5 to 277. Heat maps visualizing seasonal and diurnal variation in $PM_{2.5}$ concentrations showed clear differences between the higher- and lower-ranked communities. Some communities were sensitive to one or more of the parameters, but the overall rankings were consistent across the 45 analyses. This information will allow stakeholder agencies to work with local governments on implementing appropriate intervention strategies for the most smoke-impacted communities.

1. Introduction

An estimated 3.2 million deaths per year are attributable to ambient fine particulate matter ($PM_{2.5}$) exposure around the world. Of these, approximately 2.1 million could be avoided if all countries achieved the World Health Organization (WHO) guideline of 10 μg/m^3 for annual average $PM_{2.5}$ concentrations [1]. Further reductions in $PM_{2.5}$ pollution would continue to diminish these figures, as evidence to date has not identified a risk-free level of exposure [2]. In fact, further reducing $PM_{2.5}$ emissions in comparatively clean regions of North America and Europe could still lead to sizeable reductions in mortality due to the log-linear nature of the exposure-response relationship [1]. Therefore, even high-income countries should strive for continuous reductions in anthropogenic $PM_{2.5}$ emissions from all sources, including fossil fuel combustion, industrial processes, and residential heating [3].

Currently, $PM_{2.5}$ emissions from mobile and industrial sources are generally well-characterized and effectively regulated. However, residential wood burning is an equally important source of $PM_{2.5}$ emissions in many areas, but it remains poorly-characterized and comparatively unregulated. For example, 34% of total $PM_{2.5}$ emissions in the United Kingdom have been attributed to domestic wood burning, which was 2.4 times the total $PM_{2.5}$ emissions attributed to road transport [4]. A similar phenomenon occurred in British Columbia (BC), Canada, where 41% of $PM_{2.5}$ emissions in populated areas originated from residential wood burning, whereas industrial and mobile emissions accounted for 33% and 21% of emissions, respectively [5]. This is unsurprising given that a single wood heater was estimated to emit more $PM_{2.5}$ per year than 700 cars [6,7].

Although residential woodsmoke is often perceived to be less harmful than mobile and industrial air pollution, its human health impacts are comparable [8]. These include acute outcomes such as exacerbations of asthma [9], middle ear infections [10], and myocardial infarctions [11], as well as chronic outcomes such as heart disease [12] and lung cancer [13]. However, a few studies have shown that reducing residential woodsmoke exposures can improve health outcomes for individuals and communities. In Smithers, BC, filtration of smoky air was associated with decreased systematic inflammation and improved endothelial function, both of which are predictors for cardiovascular morbidity [14]. In Launceston, Australia, the Wood Heater Replacement Program was associated with an 11.4% reduction in overall mortality for men in winter [15]. Finally, a wood stove exchange program in Libby, Montana, was associated with a gradual decrease in childhood wheeze and sore throat, and in reports of bronchitis and influenza [16].

Managing ambient concentrations of $PM_{2.5}$ is an important environmental and public health priority in North America, but there is no simple method to control emissions from residential wood burning. One approach has been to ban the sale of wood stoves that do not meet the emission standards set by the US Environmental Protection Agency [17], but this does not remove inefficient stoves that are currently in use. In the Canadian province of BC, the Provincial Wood Stove Exchange Program subsidizes homeowners who opt to upgrade from conventional wood stoves to certified low emission stoves [18]. However, this is not an optimal solution because municipal by-laws are the main mechanism by which to mandate the adoption of newer technology, and most small BC municipalities lack the resources to fund such a transition. Another approach has been community education, especially around the benefits of burning properly dried wood for improved efficiency and reduced emissions [19].

Because wood is a reliable, affordable, and traditional source of renewable heat in BC communities, many municipalities have been hesitant to address the local air quality impacts of residential wood burning. Furthermore, woodsmoke is not always perceived by the public as an air quality concern. In order to improve communications about woodsmoke with community stakeholders, environmental and public health authorities need specific and reliable information about its local impacts. One method to characterize woodsmoke is to measure ambient concentrations of levoglucosan [20,21,22], which is a primary product of cellulose combustion [23]. However, levoglucosan concentrations are not routinely measured by most air quality monitoring networks because samples are time-consuming to collect and costly to analyse.

It would be ideal if woodsmoke impacts could be characterized using readily-available data, such as $PM_{2.5}$ concentrations. Indeed, levoglucosan concentrations have been strongly correlated with particulate matter concentrations ($R^2 > 0.7$) in smoky communities such as Libby, Montana [24] and Launceston, Tasmania [25]. Here we develop an algorithm that uses this relationship to separate smoky days from non-smoky days based on properties of the 1-h $PM_{2.5}$ concentrations and the daily temperatures. The algorithm includes three parameters: (1) sufficiently high diurnal variation in $PM_{2.5}$ to indicate possible woodsmoke impacts; (2) sufficiently low daily temperature to warrant residential heating; and (3) sufficiently low daytime-to-nighttime $PM_{2.5}$ ratio to match known patterns in wood burning behaviour. We applied the algorithm retrospectively to estimate the number of smoky days in multiple communities over the most recent two years of data, which allowed us to rank the communities by woodsmoke impacts. Environmental and public health authorities can use the results to empirically evaluate woodsmoke impacts within their jurisdictions, which can motivate the adoption of new emissions reductions strategies in the smokiest communities.

2. Methods

2.1 Study area

This study was conducted in the province of BC, on the west coast of Canada. The province is divided into five Regional Health Authorities for the purposes of health administration, which include the Interior, Fraser, Vancouver Coastal, Vancouver Island, and Northern Health Authorities (Fig. 1). Wood burning for residential heating is a significant source of $PM_{2.5}$ in BC, regularly surpassing emissions from the industrial and transportation sectors [5]. This study was limited to communities outside of greater Vancouver, where the impacts of residential woodsmoke have been previously described and contextualized relative to the more dominant mobile sources [10,26].

A 2012 survey estimated that 30% of homes outside greater Vancouver relied on fireplaces, wood stoves, or other wood burning appliances to meet some or all of their residential heating needs [27]. The highest wood burning rates were in the Bulkley Valley, including the study communities of Burns Lake, Houston, and Smithers (Table 1). The lowest rates were in the more urban study communities of Kamloops and Kelowna. The most common woods burned were Douglas Fir (59%), Pine (40%), Alder (28%), Spruce (25%), and Birch (24%). On average, participants reported burning wood five days per week in the winter months, two days per week in the spring and fall, and less than one day per week in the summer. On winter days when these appliances were in use, they were most likely to be burning wood in the evenings (90%), followed by mornings (59%), afternoons (59%), and overnight (44%).

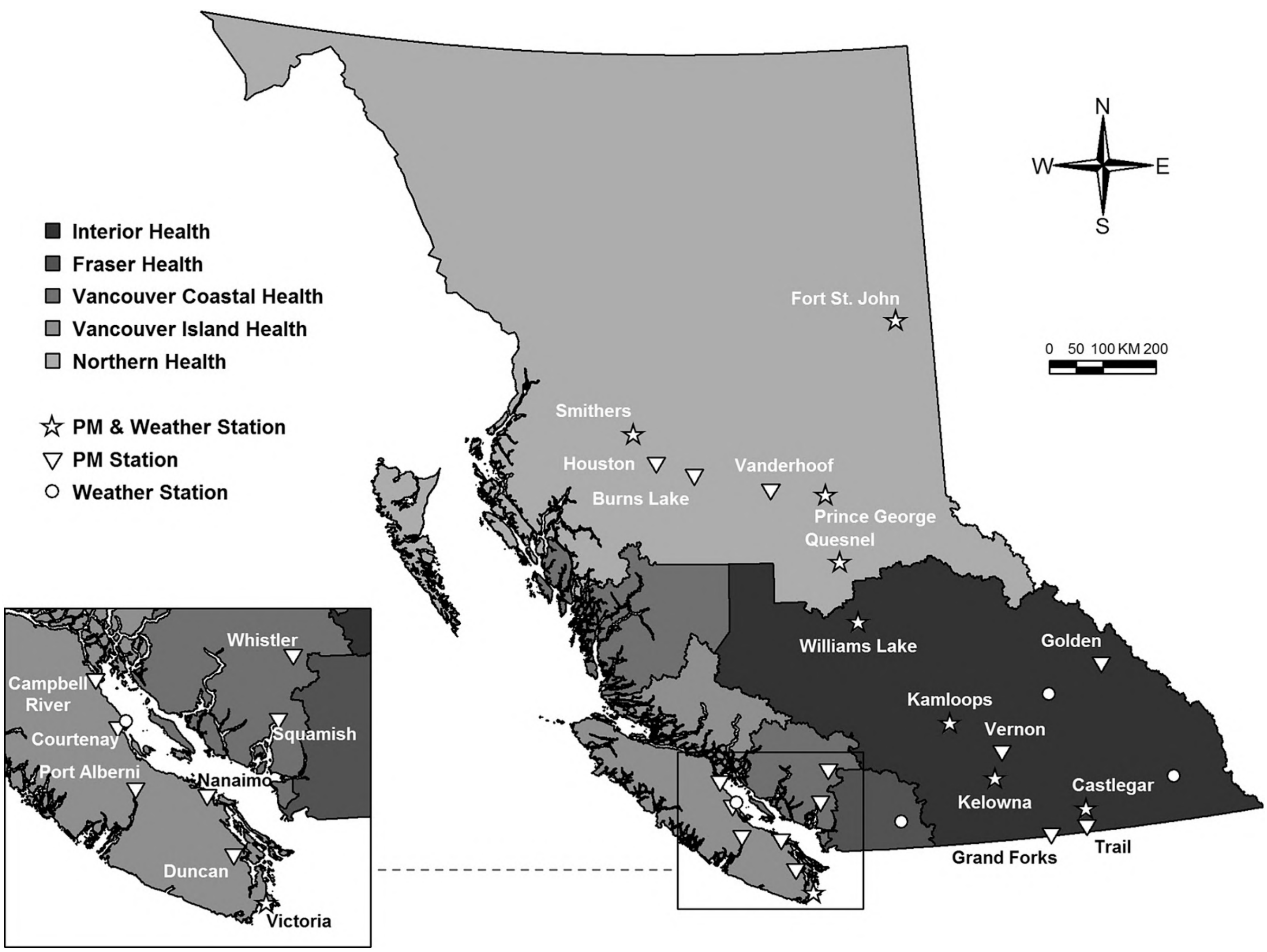

Fig. 1. The locations of the particulate matter (PM) and temperature monitoring stations used in the analyses, as well as the boundaries of the Regional Health Authorities in the province of British Columbia, Canada.

2.2 Air quality and temperature data

The BC Ministry of Environment (MOE) collects all data from the multi-agency air quality monitoring network throughout BC. Many stations in the network continuously monitor ambient concentrations of $PM_{2.5}$ using tapered element oscillating microbalances, beta attenuation monitors, or hybrid light-scattering/beta attentuation monitors. Data on 1-h $PM_{2.5}$ concentrations were obtained from the BC MOE for 48 stations corresponding to 25 unique communities spanning the period of January 1998 to October 2015. As per the BC MOE data cleaning protocol, all negative or zero concentrations were replaced with the last valid measurement within the past 24 h, or set to missing if no valid measurement was available.

Communities were considered eligible for the study if they had a $PM_{2.5}$ station with two or more consecutive years of continuous measurements. For communities with more than one $PM_{2.5}$ station, the station closest to the residential areas was selected. In total, there were 23 eligible communities within four Regional Health Authorities, including eight in Interior Health, two in Vancouver Coastal Health, six in Vancouver Island Health, and seven in Northern Health (Fig. 1). These communities had 2011 populations ranging from 2029 to 117,312 (Table 1), with an average population of 28,758 [28]. The two most recent years of data for each community were included in the analyses (Fig. 2).

We also used data from 13 Environment Canada weather stations that had complete hourly records of temperatures spanning the analysis period for each community (Fig. 2). Each of the 23 communities was matched with one of the 13 weather stations based on Euclidean distance (Fig. 1), with a maximum distance of 135 km.

2.3 Levoglucosan data

We obtained daily mean concentrations of ambient levoglucosan for the study communities of Courtenay (N = 306), Kamloops (N = 418), and Prince George (N = 374) between January 2014 and March 2015 (Fig. 2). These data were collected for a

Table 1. The 23 communities included in the analyses with 2011 census populations and the percentage of households that burn wood estimated by the wood burning survey [27].

Location	2011 Population	Estimated Wood Burning
Burns Lake	2029	54%
Campbell River	31,186	21%
Castlegar	7816	—
Courtenay	24,099	20%
Duncan	4932	36%
Fort St. John	18,609	—
Golden	3701	50%
Grand Forks	3985	36%
Houston	3147	54%
Kamloops	85,678	8%
Kelowna	117,312	10%
Nanaimo	83,810	18%
Port Alberni	17,743	25%
Prince George	71,974	15%
Quesnel	10,007	35%
Smithers	5404	54%
Squamish	17,158	42%
Trail	7681	—
Vanderhoof	4480	—
Vernon	40,000	—
Victoria	80,017	33%
Whistler	9824	42%
Williams Lake	10,832	36%

different project that is described in detail elsewhere [11]. In brief, $PM_{2.5}$ samples were collected using Thermo Partisol 2025i monitors, and the filters were subsequently analyzed for levoglucosan by ion chromatography. We used these data to calculate the daily levoglucosan-to-$PM_{2.5}$ ratio, which reflects the relative contribution of woodsmoke to ambient $PM_{2.5}$. However, this ratio does not strictly reflect the proportion of woodsmoke in ambient $PM_{2.5}$ because levoglucosan is not the sole constituent of woodsmoke particulate matter [29]. Furthermore, the proportion of levoglucosan emitted varies depending on combustion conditions such as fuel type, moisture content, and wood burning appliance [30].

2.4 Algorithm to detect smoky days

We developed a simple algorithm to identify smoky days in each of the 23 communities using 1-h $PM_{2.5}$ concentrations and the mean daily

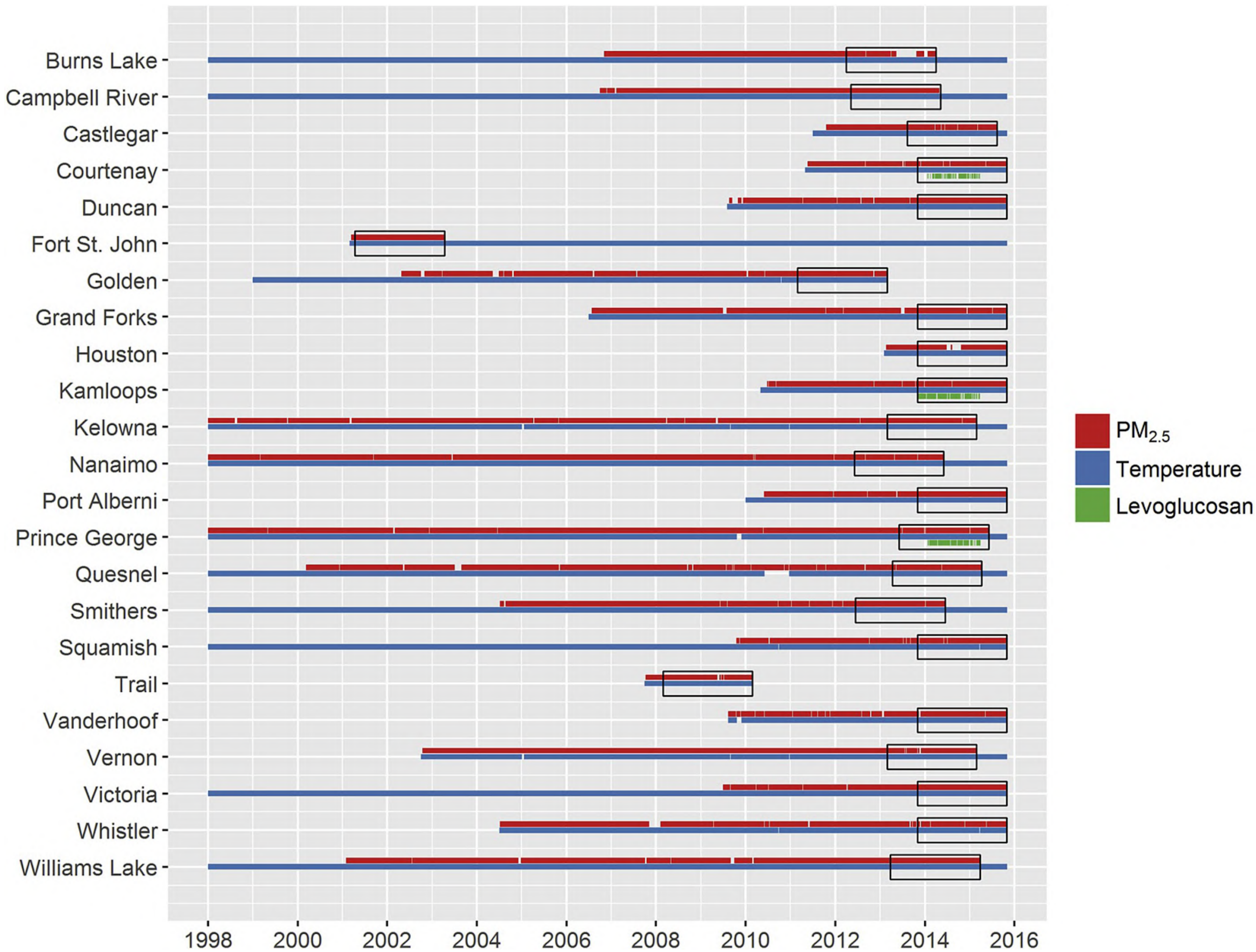

Fig. 2. Fine particulate matter ($PM_{2.5}$), temperature, and levoglucosan data availability for the 23 communities included in the analyses. The black boxes indicate the most recent two years of data used for each community.

temperatures. The algorithm was applied to the most recent two years of available data for each community (Fig. 2). Three parameters were established to classify days as smoky: (1) the daily 1-h $PM_{2.5}$ concentrations were required to meet some minimum variability, as defined by the standard deviation (SD) of the values; (2) the mean daily temperature was required to fall below some threshold that would warrant the use of wood stoves for heating; and (3) the mean daytime (09:00–18:00) to mean nighttime (00:00–09:00 + 18:00–00:00) $PM_{2.5}$ ratio (DNR) was required to fall below some threshold. The DNR was established on the basis that nighttime $PM_{2.5}$ concentrations regularly exceed daytime $PM_{2.5}$ concentrations on smoky days due to a combination of lower temperatures, more people at home, and temperature inversions that trap residential woodsmoke and other pollutants in the surface air [31].

After establishing these parameters, the next step was to systematically identify their most informative values. To do this, we used the Thermo Partisol 2025i $PM_{2.5}$ and levoglucosan data from Courtney, which was the smokiest of the three communities measured by Weichenthal et al. (2016) for their previous study. Based on the distribution of the levoglucosan-to-$PM_{2.5}$ ratio, we chose a cut-off value of 1% levoglucosan to classify days in the Weichenthal et al. (2016) data as woodsmoke impacted (Fig. 3). This cut point corresponded to the 30th percentile in Courtenay, the 74th in Kamloops, and the 68th in Prince George (Fig. 3). We then compared the distributions of daily SD for the 1-h $PM_{2.5}$ measurements, mean temperature, and DNR in

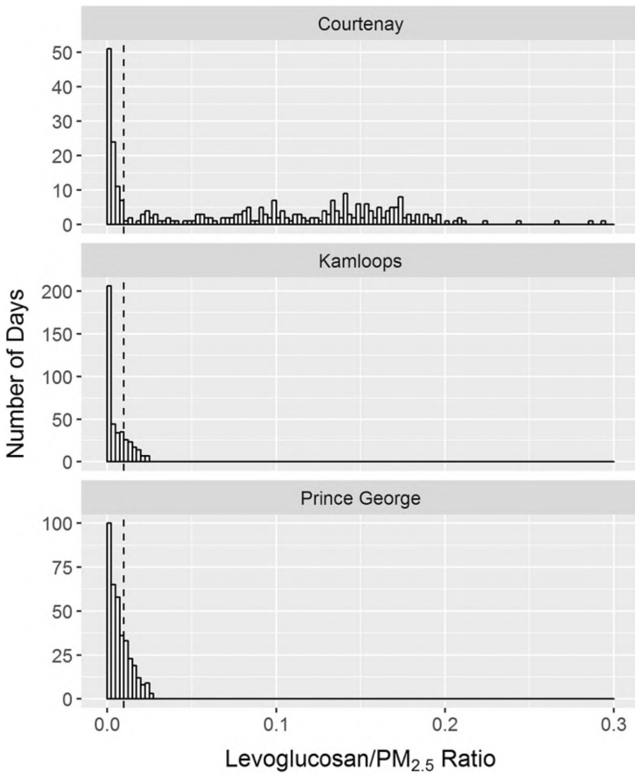

Fig. 3. Histograms showing the distribution of the daily levoglucosan-to-$PM_{2.5}$ ratios in Courtenay, Kamloops, and Prince George. The dashed line indicates the cut-off used to separate high levoglucosan days from low levoglucosan days in Courtenay.

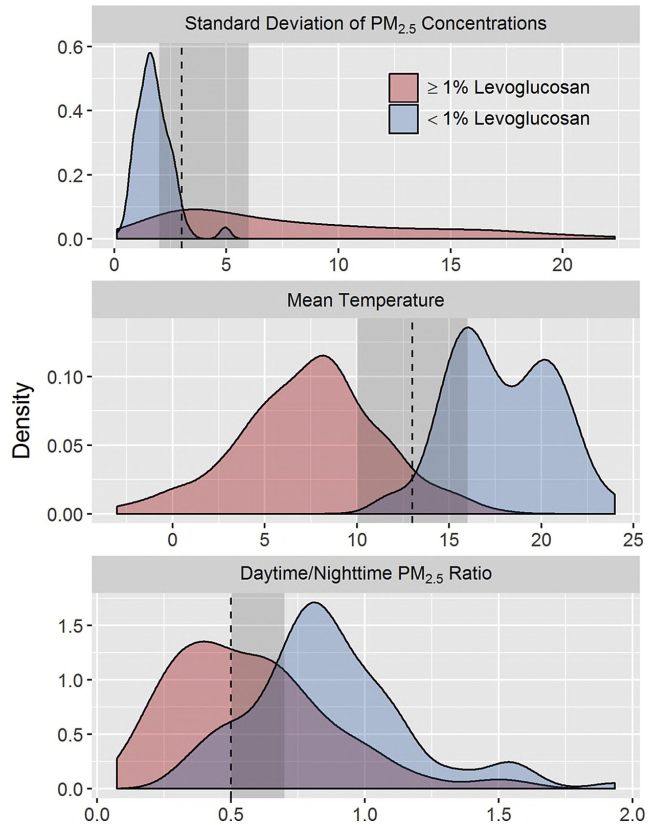

Fig. 4. Density curves for the daily standard deviation of $PM_{2.5}$ concentrations, daily mean temperature, and daytime-to-nighttime $PM_{2.5}$ ratio in the community of Courtenay, separated into high levoglucosan days (red) and low levoglucosan days (blue). The dotted lines indicate the most informative parameter values, at which the inclusion of high levoglucosan days was maximized and the inclusion of low levo- glucosan days was minimized. The gray boxes indicate the range of tested values for the sensitivity analyses.

Courtney on days above and below the 1% threshold using paired density curves (Fig. 4). We chose parameter values that maximized the area under the ≥1% levoglucosan curve and minimized the area under the <1% levoglucosan curve, which was calculated by the trapezoidal rule. The SD and mean temperature thresholds were rounded to the nearest integer values of 3 μg/m^3 and 13 °C, respectively. The DNR threshold was rounded to 0.5, which was the nearest tenth (Fig. 4).

After establishing the most informative parameter values, the algorithm was applied to all 23 communities. Days that satisfied all three of the criteria were classified as smoky, and communities were ranked by their number smoky days in the most recent two years of data. Heat maps were plotted to visualize the seasonal and diurnal variation of $PM_{2.5}$ concentrations in each community, and these were used to further evaluate the utility of the algorithm. The a priori expectation was that the smokiest communities would clearly demonstrate high morning and evening $PM_{2.5}$ concentrations during the heating seasons.

2.5 Sensitivity analyses

We tested a range of parameter values around the most informative values to evaluate resulting sensitivity in the community rankings. The ranges were: 2–6 for the daily SD of the 1-h $PM_{2.5}$ concentrations; 10–16 °C for the daily mean temperature; and 0.5–0.7 for the DNR. The algorithm was run with the 45 unique parameterizations and another heat map was used to compare the community rankings generated by each combination. Ideally, small changes in the parameter values would not significantly alter the final ranking results. The development of the woodsmoke identification and prioritization algorithm and all other analyses were conducted in the R statistical programming environment [32].

3. Results

3.1 Data summary

The median and interquartile range of the daily mean $PM_{2.5}$ concentrations for the 23 communities ranged from 3.2 to 7.7 µg/m^3 and 2.5–10.1 µg/m^3, respectively. For daily mean temperature, these values ranged from 3.6 to 11.2 °C and 8.4–18.0 °C, respectively (Fig. 5). The correlation (R^2) between the Thermo Partisol 2025i $PM_{2.5}$ and levoglucosan concentrations was 0.84 in Courtenay, 0.51 in Kamloops, and 0.58 in Prince George. The number of days included in the analyses for each community ranged from 516 to 730. There were periods of missing data for Burns Lake and Houston (Fig. 2), but all occurred during summer months when residential wood burning is minimal.

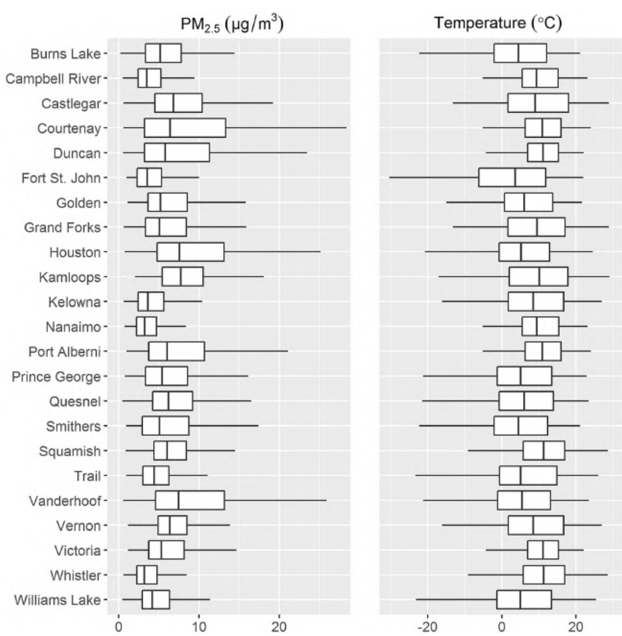

Fig. 5. Boxplots showing the distributions of daily average fine particulate matter ($PM_{2.5}$) and mean daily temperature for each of the 23 communities included in the analyses. The white box indicates the interquartile range (IQR), the black line indicates the median, and the whiskers indicate the most extreme measurement that is no more than 1.5 times the IQR away from the white box in both directions.

3.2 Identification of smoky days

The number of smoky days in the two most recent years of data ranged from 5 to 277 (Table 2) across all 23 communities. The algorithm identified Houston, Courtenay, Port Alberni, Vanderhoof, Whistler, Castlegar, and Golden as the seven smokiest communities in the study, each exceeding 15% smoky days. Houston and Vanderhoof are located in the Northern Health Authority, Courtenay and Port Alberni are located in the Vancouver Island Health Authority, Whistler is located in the Vancouver Coastal Health Authority, and Castlegar and Golden are located in the Interior Health Authority (Fig. 1). Heat maps of average monthly diurnal $PM_{2.5}$ concentrations for the 23 communities showed elevated $PM_{2.5}$ concentrations during the nighttime starting in the fall, peaking in the winter,

Table 2. The 23 communities included in the analyses with 2011 census populations and the percentage of households that burn wood estimated by the wood burning survey [27].

Location	# Smoky Days	# Days with Data (730 max)	% Smoky Days
Houston	277	623*	0.445
Courtenay	211	716	0.295
Port Alberni	143	729	0.196
Vanderhoof	136	712	0.191
Whistler	125	705	0.177
Castlegar	124	710	0.175
Golden	116	722	0.161
Smithers	107	721	0.148
Campbell River	102	720	0.142
Victoria	97	730	0.133
Duncan	91	727	0.125
Burns Lake	89	514*	0.173
Quesnel	80	714	0.112
Grand Forks	58	711	0.082
Prince George	52	706	0.074
Williams Lake	41	729	0.056
Kelowna	25	720	0.035
Trail	17	705	0.024
Vernon	17	698	0.024
Squamish	16	702	0.023
Fort St. John	12	728	0.016
Nanaimo	8	717	0.011
Kamloops	5	711	0.007

* Data were missing during summer months, so the percentage of smoky days will be higher than if data were missing at random.

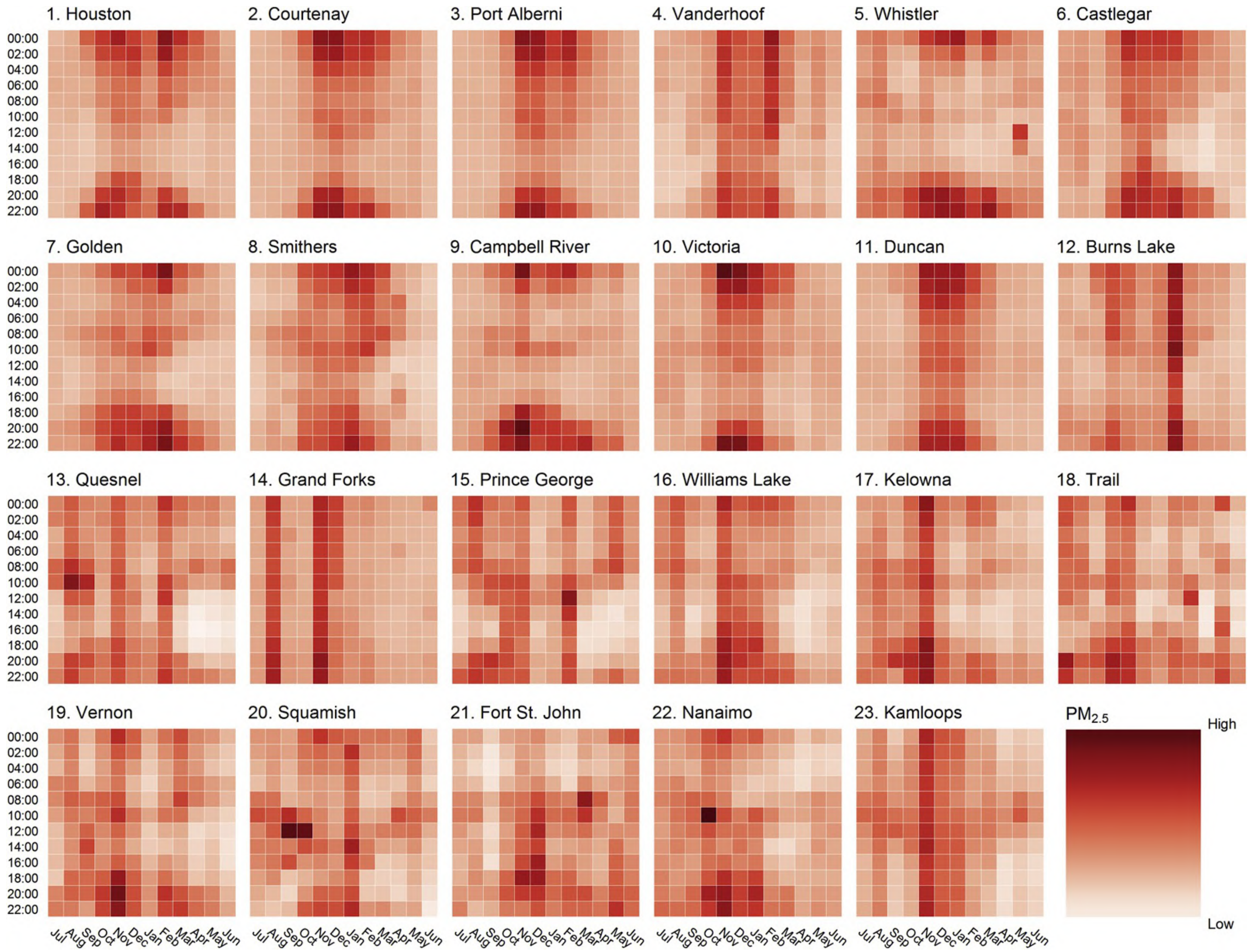

Fig. 6. Heat maps visualizing the average seasonal and diurnal fine particulate matter ($PM_{2.5}$) concentrations for the 23 communities included in the analysis. The x-axis shows months of the year, arranged such that the winter months are in the middle and the summer months are at the edges. Forest fire smoke events during the summer months have been omitted. The communities are ordered by the smokiness rankings using the most informative parameter values.

and ending in the spring for the top ranked communities, which is consistent with typical wood burning behaviour and meteorological influences during the heating seasons. These patterns were not evident in the less smoky communities (Fig. 6).

3.3 Sensitivity analyses

The parameter values tested were all combinations of SD = {2, 3, 4, 5, 6}, temperature = {10, 13, 16}, and DNR = {0.5, 0.6, 0.7}. The overall ranking of the 45 combinations identified Houston, Courtenay, Vanderhoof, Castlegar, Golden, Duncan, and Smithers as the seven smokiest communities in the study (Fig. 7). These results were quite consistent with the original parameterization (SD = 3, temperature = 13, and DNR = 0.5), especially within the high- and low-ranking communities. Houston and Courtenay were ranked #1 and #2 by all 45 combinations, while Kamloops was ranked #20–23. The variation in rankings was higher among the other 20 communities. The average difference between the within-community rankings was five positions, with a maximum difference of nine positions in Duncan. Greater variability in the within-community rankings suggests greater sensitivity to the SD, temperature, and/or DNR thresholds. For example, Williams Lake was sensitive to the SD threshold, as evidenced by its continuous decrease in ranking as the SD threshold increased. On the other hand, Quesnel was sensitive to the temperature threshold, as evidenced by its continuous increase in ranking as the temperature threshold increased. Lastly, Duncan was sensitive to the DNR threshold, evidenced by its increase in ranking as the DNR threshold increased.

3.4 Communities with levoglucosan data

For the community of Courtney there were 306 days with levoglucosan, $PM_{2.5}$, and temperature data. The algorithm identified 96 days of 214 days that exceeded the 1% levoglucosan threshold as smoky, and the other 118 as non-smoky. Furthermore, the algorithm identified none of the 92 days under the 1% levoglucosan threshold as smoky. The mean levoglucosan contribution on the smoky days was 14.6%, compared with 12.5% on the non-smoky days. There were 418 and 374 days with similar data in Kamloops and Prince George, respectively. In Kamloops 106 of the days exceeded the 1% levoglucosan threshold, but only two were identified by the algorithm as smoky. The levoglucosan contribution on the smoky days was 2.5%, compared with 1.7% on the non-smoky days. Similarly, in Prince George, 117 of the days exceeded the 1% levoglucosan threshold, but only nine were identified as smoky. The levoglucosan contribution on the smoky days was 1.6%, compared with 1.7% on the non-smoky days.

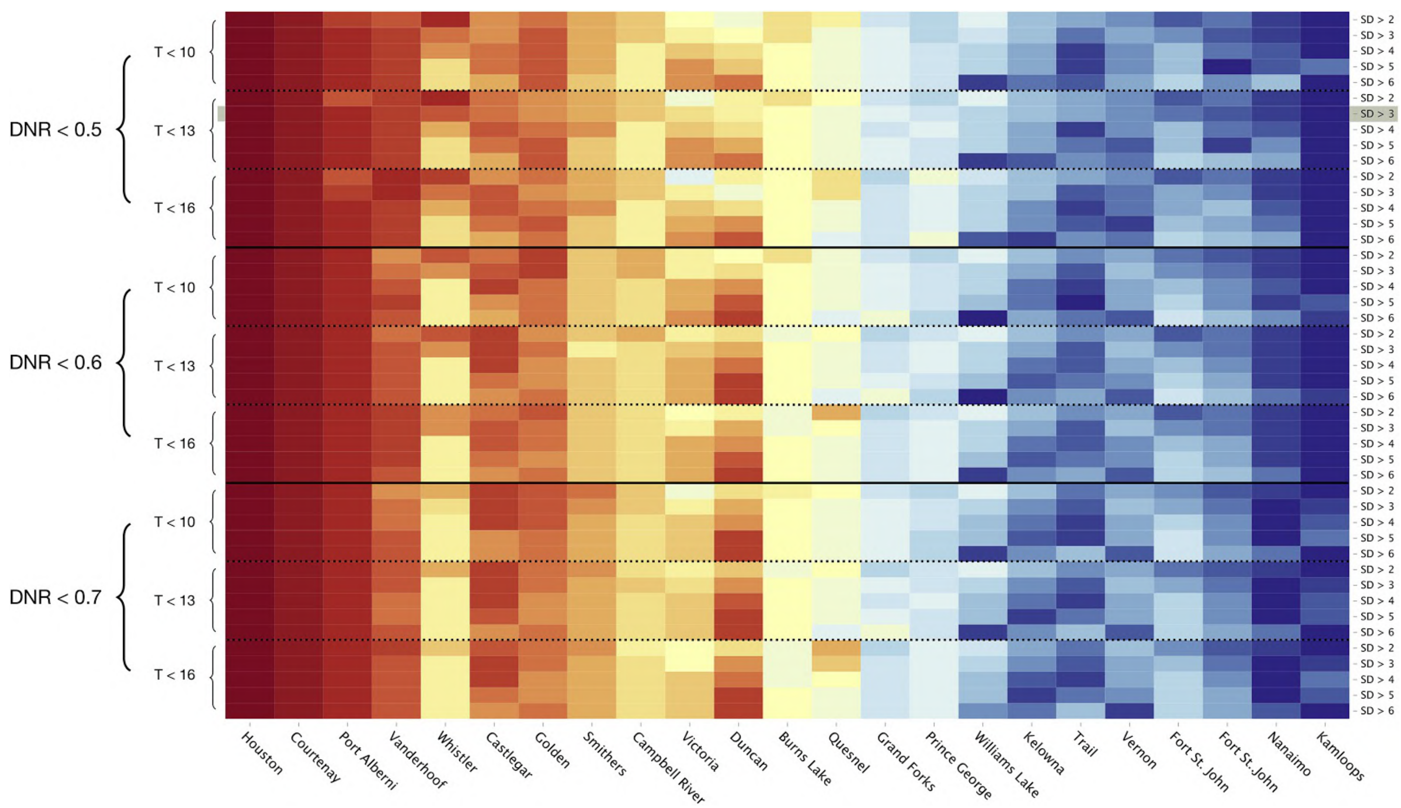

Fig. 7. Heat map of the smokiness rankings assigned by 45 different parameter combinations tested in the sensitivity analyses. The temperature (T) and daytime-to-nighttime ratio (DNR) values are shown on the left, and the daily standard deviation (SD) of fine particulate matter concentrations ($PM_{2.5}$) is shown on the right. The communities are ordered by the smokiness rankings using the most informative parameter values, as indicated by the gray highlight (seventh from the top). Darker colours on the left (red) indicate more smokiness while darker colours on the right (blue) indicate less smokiness.

4. Discussion

We developed an algorithm that uses routine $PM_{2.5}$ and temperature measurements to retrospectively identify smoky days in order to rank communities by woodsmoke impacts. Our objective was to provide a systematic and empirical tool that stakeholder agencies can use to identify and prioritise communities as targets for $PM_{2.5}$ mitigation strategies using readily-available data. We established three parameters that, when combined, may be able to detect smoke-impacted days: (1) the daily standard deviation of 1-h $PM_{2.5}$ concentrations; (2) the daily mean temperature; and (3) the daytime-to-nighttime ratio of $PM_{2.5}$ concentrations. The most informative values for these parameters were identified using 306 days of levoglucosan data measured for another study in Courtenay, which is one of the smokiest communities in BC. In brief, we found the parameter values that maximized the number of days with ≥1% levoglucosan, while minimizing the number of days with <1% levoglucosan (Fig. 4). We then tested a range of parameter values in 45 unique combinations to evaluate the sensitivity of the rankings.

The most informative parameterization identified communities throughout the province as smoky, suggesting that the parameterization was not biased towards any geographic region. Most of the higher-ranking communities are situated in mountain valleys or on the coast, where diurnal variation in meteorological conditions can be strong. The sensitivity analyses demonstrated consistency in the highest ranked communities, with more variation among the central- and lower-ranked communities. Overall, there was little variation in the rankings, with an average within-community difference of five positions across the 45 combinations. While small changes in the parameterization had limited effect on the relative community rankings, they had more effect on the number of days identified as smoky in each community. Furthermore, some communities were particularly sensitive to changes in one or more of the parameters, and all of these results might shift if the most informative parameterization was chosen based on levoglucosan data from a different smoky community. Our future work will focus on more complete woodsmoke characterization in some of the other communities using levoglucosan measurements along with fixed and mobile multi-wavelength aethalometers [33].

The heat maps of the average seasonal and diurnal $PM_{2.5}$ patterns (Fig. 6) showed elevated nighttime $PM_{2.5}$ concentrations during the heating season for the smokiest communities. These elevated concentrations coincide with hours of increased wood burning [27,34] and overnight temperature inversions that can trap woodsmoke in the surface air. In contrast, the less smoky communities showed no clear seasonal or diurnal patterns in $PM_{2.5}$ concentrations, suggesting less wood burning, fewer temperature inversions, or both. Although data from the survey are limited, the range of wood burning households between the higher- and lower-ranked communities was similar (Table 1 and Table 2), which may indicate that rankings are driven more by meteorological conditions. Another important consideration is the locations of the fixed monitoring stations relative to the wood burning population (see supplemental KML file), because some stations simply may not capture the impacts.

Although residential woodsmoke is a known concern in BC, many of the communities in this study have other important sources of $PM_{2.5}$, including large industrial facilities that have their air emissions permitted by the Ministry of Environment. The National Pollutant Release Inventory (NPRI) for 2014 [35] lists major $PM_{2.5}$ emitters (tonnes/year) in Quesnel (467), Prince George (423), Nanaimo (341), Houston (109), Kamloops (102), Trail (85), Castlegar (79), and Williams Lake (50). Only Houston and Castlegar were in the top ten smokiest communities, according to our rankings. Another important source of $PM_{2.5}$ includes pile burning of biomass residue from logging and development. These burns typically occur in the spring and fall, which is evident in the community heat maps (Fig. 6).

The most informative parameter values chosen using the levoglucosan data from Courtney were SD =

3, mean temperature = 13, and DNR = 0.5. In Courtney, this parameterization successfully identified 45% of days exceeding the 1% levoglucosan threshold as smoky, and 100% of days below the 1% levoglucosan threshold as non-smoky. However, 55% of the days over the 1% levoglucosan threshold were classified as non-smoky, and the parameterization did not distinguish between days under and over the 1% levoglucosan threshold in Kamloops and Prince George. Poor performance in the other communities was not surprising given the generally low levoglucosan contributions (Fig. 3) and near complete overlap between the <1% and ≥1% levoglucosan days in all three of the parameter distribution curves (analogous to Fig. 4, not shown). Overall, we suggest that this approach may be more useful for identifying and prioritizing affected communities than it is for accurately classifying smoky days.

The primary strength of this approach is its dependence on readily-available $PM_{2.5}$ and temperature data, rather than more complex source apportionment or speciation methods. Additionally, the algorithm could be adjusted to accommodate additional parameters such as PM_{10}, wind speed, humidity, and precipitation, which all have an association with local $PM_{2.5}$ concentrations. An important limitation is that the algorithm will not detect smoky days with consistently elevated $PM_{2.5}$ concentrations, given its dependence on the standard deviation and the daytime-to-nighttime $PM_{2.5}$ ratio. Such conditions can occur under prolonged temperature inversions, when smoke is trapped in the surface layers. Another important limitation is the uncertainty behind the absolute number of smoky days identified in each community. However, the relative ranking of communities is more important in selecting priority candidates for woodsmoke intervention methods.

Currently, the most common interventions for residential woodsmoke pollution are banning the sales of uncertified wood burning appliances, wood stove exchange programs, and community education programs [15,16,17,18,19,36]. Banning the sale of noncertified wood stoves is effective for switching to cleaner and more efficient technologies, but it does not remove the inefficient stoves that remain in use. Wood stove exchange programs can also be effective in reducing woodsmoke impacts on pollution and human health [15,16], but positive impacts are inconsistent [37]. Community education may be effective for reducing woodsmoke emissions, but it requires public commitment that cannot be guaranteed. Ultimately, however, the best way to reduce woodsmoke pollution and to improve public health is to use cleaner forms of residential heating such as pellet stoves, natural gas, or electricity [38].

5. Conclusion

Residential woodsmoke is an important source of $PM_{2.5}$ exposures in BC and elsewhere, and it is more challenging to regulate than mobile and industrial sources. We have developed a simple algorithm to empirically identify smoke-impacted communities so that stakeholder agencies can focus limited resources in the priority areas, with the caveat that many unmeasured communities may also be impacted. Although data for validation were limited, heat maps of the seasonal and diurnal $PM_{2.5}$ concentrations showed clear differences between the higher- and lower-ranked communities. Many other parts of the world face similar challenges with respect to residential woodsmoke, including the United States [39], Europe [40], Australia [41], and New Zealand [42], where this approach may be useful.

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