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Evidence Review:

Health surveillance for wildfire smoke events

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Key points

- The data sources that could be used to measure the public health impact of wildfire smoke include a range of healthcare utilization and other data, such as pharmaceutical dispensations, physician visits, emergency department visits, hospitalizations, and all-cause mortality.
- Respiratory data sources are well suited for surveillance and real-time monitoring of the health impacts that occur during fire events, based on strength of association, accessibility, and timeliness.
- As new research emerges on the sensitivity of health surveillance systems, cardiovascular outcomes may be valuable to assess immediate health response to fire smoke exposure.
- Mild to moderate measures of health effect, such as dispensations of asthma medications and respiratory-related physician visits, may provide the timeliest measurement of an effect, and show the greatest effect, allowing for easier detection using surveillance methods.
- Ad hoc surveillance systems may be suitable for rare events, but regions that experience seasonal wildfires should establish ongoing surveillance systems using validated methods. An established surveillance system could provide useful information in real-time as well as information for evaluation of interventions and potentially facilitate research on the long-term health effects of chronic seasonal smoke exposure.
- Baseline (historic) data and demographic characteristics of regions will provide important information for model-building and assessing regional vulnerability to smoke exposure.
- Improved ways of measuring and forecasting air pollution concentration may boost the performance of models used for public health surveillance of forest fire smoke.
- More research is needed to define clear objectives and develop best practices, including use of suitable data, syndrome definitions, and methods development and validation.

Evidence Gaps

- More development and evaluation of surveillance systems in this area, including acquisition of suitable data, is needed in all areas strongly affected by wildfire smoke exposure. More sophisticated methods may be required to link the exposure and health data, simultaneously model health outcomes, and incorporate baseline and vulnerability data. Technical expertise will be useful in collaboration with those working in public health, to develop useful, feasible systems capable of accurate surveillance and potentially forecasting.
- While we can make some assumptions around the relative utility of potential data sources with respect to their acuity and sensitivity or specificity, exploration of real surveillance data will be necessary and it may differ by setting, given potential differences in population characteristics and exposure patterns.
- If more sophisticated integrated surveillance systems are desired, then more advanced methods may need to be proposed and evaluated. Proposal and evaluation of potential methods are needed in order to link the exposure data to the health outcome data, to integrate multiple data streams simultaneously, and to incorporate measures of vulnerability at various spatial scales.
- It is not yet clear how to best approach surveillance in settings with limited data. Environmental monitoring or exposure predictions may be used to predict health effects based on known

demographic characteristics. Such systems could be validated using manual chart review in regions with frequent fires.

- Surveillance systems could potentially be used for intervention evaluation, and this goal should be considered while developing systems. More research is needed to determine how this could proceed.
- Surveillance systems could also potentially collect data to aid in research on long-term exposure to investigate relationships with chronic health outcomes. Likely this would be particularly valuable in regions with regular exposure and potentially even prescribed burns. Research in this area may become increasingly important if wildfire seasons continue to increase in severity and length due to climate and land use changes.
- Forecasting is a key objective of many surveillance systems. Forecasting health effects of smoke exposure could provide key information for estimating health care utilization needs and planning response interventions. However, development of forecast models that accurately predict health effects based on environmental forecasts and historical outcomes will require focused effort and resources to develop, test and evaluate.
- Ad hoc systems can be useful in the absence of established surveillance systems. The most useful methods of just-in-time health surveillance have not been established. However, some methods of ad hoc surveillance are likely to be more effective than others. Recording and sharing lessons from development of ad hoc smoke health effects surveillance is one way to improve future systems.

1. Introduction

Wildfires occur throughout the world and have direct and indirect impacts among human populations. Wildfire smoke can travel far from the original source, causing adverse respiratory and other health effects over broad geographic areas. Effects are especially strong in individuals with pre-existing co-morbidities, such as asthma or other chronic lung diseases. Scientists have shown that climate change and land use changes are leading to an increase in the frequency and severity of wildfires (1). While there is a substantial amount of research showing the negative acute health effects of smoke[1], as well as a growing amount suggesting long-term effects, few public health bodies engage in regular surveillance of smoke-related health effects. There is a need for a better understanding of the measures of health outcomes that could be used during smoke events to monitor population-level health impacts and guide interventions and emergency response.

1.1 Objective

The objective of this report is to determine, through a thorough literature review, which measures of health impact are most useful for real-time surveillance of the health effects from wildfire smoke. The relevant measures will be summarized and discussed in terms of their availability, timeliness, cost, and the strength of the association.

2. Methodology

There is a strong body of literature estimating the epidemiological health effects of wildfire smoke, generally using surveillance type data sources such as emergency department (ED) visits or all-cause mortality, but surveillance systems using these data for surveillance of these health effects in real-time have not been documented in the literature. Therefore, in order to identify and discuss the measures most likely to be informative for surveillance, we (1) reviewed the relevant epidemiological literature thoroughly and (2) identified smoke-related health surveillance in order to report on their systems, by contacting authors and discussing details of their current surveillance systems and future plans. We reviewed studies that used health outcomes data, from dispensations of asthma medications to all-cause mortality, to estimate the magnitude of the effect on the population during smoke events, and we considered the utility of these measures in monitoring and informing emergency response. Further details on the methods and results of this literature search can be found in Appendix A, including inclusion and exclusion criteria. We focused on studies from Canada, the United States, Europe, and Australia as these regions have data and healthcare infrastructure that are fairly similar to those available in Canadian public health settings. Studies from Europe and Asia generally show comparable results, although the exposure severity has been higher in parts of Asia than is routine in North America and Australia (2).

[1] Throughout this document, the word *smoke* is used to refer to smoke produced from wildfires

3. Results

This section will summarize the main findings from the literature search, starting with a discussion on the types of data typically used in these epidemiological papers, and the potential sources for these health data. We classify the commonly used types of data into those measuring mild, moderate, or severe health outcomes and discuss their relative utility in terms of timeliness, cost, availability, and the strength of the association between smoke and the measured health outcome. Finally, we discuss the potential for using these data for burden estimation and forecasting, which are important aspects of public health surveillance, as well as how measures of population susceptibility from other data sources may enhance the potential surveillance models using these health data.

This literature search revealed that wildfire smoke is known to have a range of health effects from eye irritation to an increase in all-cause mortality, and that respiratory health effects are often the focus of epidemiological studies. The respiratory health outcomes often show the strongest effects, particularly those related to asthma and chronic lung disease (3) and therefore are an important focus for public health response. Studies showing that population exposures to particulate matter (PM) from urban sources (such as traffic) are correlated with cardiovascular outcomes (such as myocardial infarction). However, many studies investigating cardiovascular outcomes and wildfire smoke exposure report a weak and often insignificant association (4–7). More detailed information on the acute and chronic health impacts of wildfire smoke can be found in review on *Health Effects of Smoke.*

The objective of surveillance is to provide information in (near) real-time to inform public health decisions. Surveillance requires suitable input data, appropriate methods for data analysis, expert knowledge to interpret the analysis and use it for information to guide decision making. Each surveillance application area may have a different focus; for example, infectious disease surveillance is often primarily concerned with aberration detection – alerting when the incidence of a given disease (or proxy measure for incidence of a disease) passes an established (statistical or substantive) threshold. In the context of public health surveillance for wildfire smoke exposure, outbreak detection is not the primary goal as the precipitating event (a wildfire) is known to occur or not occur. A surveillance system here would be useful to estimate the magnitude of the health effects of smoke on populations, provide situational awareness in real time and inform public health intervention. Once a system exists that regularly collects exposure data (e.g., particulate matter concentrations in the air) and links it to health outcomes data (e.g., respiratory physician visits), these data could be used retrospectively for intervention evaluation. For example, the magnitude of the health effect preceding and following an intervention could be compared to help assess whether the action had a positive impact on public health. The objectives of a surveillance system in this relatively unique application area will be emphasized throughout this report while summarizing the potential measures of health impact that could be used to develop such a system and inform emergency response.

3.1 Data sources

Surveillance data for real-time assessment of health impacts during wildfire smoke events may be obtained from primary data collection, existing surveillance systems, or repurposing of data collected for other functions. In much of the literature examining health effects from wildfire smoke, particularly that which is more than ten years old, primary data collection through the manual abstraction of medical records was used to evaluate health outcomes. More recently, electronic administrative data are used. Manual primary data collection is not generally a sustainable or economically realistic way to do surveillance, as it would be costly and time-consuming, lack baseline information, and is subject to quality concerns and human error. However, if no other data are readily available during an acute event, manual collection may be necessary. If data are already collected by a government agency for vital statistics or billings, it is more efficient to repurpose these data through a data sharing agreement with the agency. These types of data are referred to as *syndromic surveillance* data, because they provide timely information on the syndromes associated with a condition without measuring that condition explicitly (8). Because these data are not directly measuring the health effects of interest, but rather are acting as a proxy measure, they will contain more random variation and extraneous trends. For example, ED records have been reviewed in some studies to identify respiratory or cardiovascular visits according to International Classification of Disease (ICD) code (9). Electronic administrative data of ED records have been used more frequently in recent years, as this does not require the labor associated with manual chart abstraction. In some jurisdictions, medical billings collected by public medical plans are available and can be used by public health departments for the purposes of surveillance.

There are now a wide range of administrative data used for the purpose of surveillance, that vary from measuring relatively mild health effects to relatively severe health effects. Examples, in order of increasing severity, include phone logs to nurse help lines, pharmaceutical dispensation data, physician visits, ambulance call out records, ED visits, hospital admissions, and mortality. General data, such as hospitalizations or mortality, can be classified by chief complaint or cause of death, narrowing the focus from all-cause to more specific measures like respiratory hospitalization or cardiovascular mortality. Using an all-cause definition will provide a larger dataset and potentially more statistical power for an analysis, but using a specific definition (e.g., respiratory) should provide a more focused measure of the health effect of interest.

Systems developed prior to fire smoke events have the advantage of validated data streams, historical baselines and method. Lead time allows for more sophisticated estimation of excursions, established reporting mechanisms, and evaluation.

For example, scientists at BCCDC Environmental Health Services established the British Columbia Asthma Medication Surveillance (BCAMS) in 2012 (10). BCAMS provides near real-time surveillance of exposure and health outcomes to local health authorities to provide situational awareness for public health and emergency management decision-making. This system uses three exposure estimates: measured $PM_{2.5}$ (particulate matter less than 2.5 μm in aerodynamic diameter) from 85 monitoring stations distributed throughout the province, estimated $PM_{2.5}$ from an empirical model that covers all populated areas of BC (11) and forecasted PM from the BlueSky Western Canada Wildfire Smoke Forecasting System (12). Currently the health outcome reported is daily dispensations of salbutamol sulfate from 89 local health areas. Salbutamol is a medication used to alleviate exacerbations of obstructive lung disease and dispensations have been shown to increase rapidly and significantly during fire smoke episodes in British Columbia (13). Excursions from the expected number of daily dispensations are identified by Public Health Intelligence for Disease Outbreaks (PHIDO) using an algorithm adapted from one originally developed for infectious diseases. PHIDO uses iterative regression to identify excursions beyond the 95th (unusual), 99th (rare) and 99.5th (very rare) percentiles of the expected daily distributions. Physician visits have also been shown to be associated with fire smoke episodes in BC (14) and are currently being integrated into the BCAMS system. An evaluation of an earlier iteration of BCAMS found it to be acceptable and useful for medical health officers responding to minor fire smoke events (15)(Elliott, unpublished data). The current BCAMS incorporating PHIDO algorithm, empirical PM estimates and BlueSky forecasting remains to be tested in an active fire season.

If a smoke surveillance system is not established then a pre-existing surveillance system could be used during a smoke episode. For example, two studies by the same primary author in North Carolina, USA used existing public health surveillance data on respiratory ED visits to perform epidemiological studies on the health effects of wildfire smoke. Data from any other surveillance system monitoring relevant health outcomes could feasibly be used to establish situational awareness of smoke health effects (16, 17). Because health outcomes responsive to smoke include respiratory syndromes, and potentially cardiovascular ones, existing surveillance systems that obtain data for other purposes, such as influenza could be shared for these purposes, provided that there is legal authority to do so. While most states or provinces do not currently have a pre-existing surveillance system in place for wildfire smoke health effects, public health departments could plausibly rapidly establish data sharing agreements during smoke events.

3.2 Data attributes

In order for data to be suitable for ongoing surveillance, they need to be available at a high temporal resolution (e.g., daily counts), they should be reasonably sensitive and specific, and suitable methods for their analysis should be proposed and evaluated using historical data. In a surveillance context, sensitivity refers to a measure revealing a health effect when in fact one exists, and specificity refers to a measure not revealing a health effect when one does not exist (i.e., a low rate of false positives and false negatives). Wildfire smoke health surveillance is a challenging research area methodologically because (i) it benefits from exposure data linked to health outcomes data, and (ii) it may have a small individual effect but a large public health impact because entire populations are exposed during fire events. It can be difficult to disentangle the health effect from random variation in the data. There is a relationship between the severity of an effect and the anticipated signal strength. For example, in specific-cause mortality data, all individuals in the data represent the measure of interest (mortality), although the cause of death may or may not be related to the exposure (18). In contrast, when relying on less severe measures of effect such as asthma medication dispensations, some individuals are experiencing an acute health effect necessitating refill of their prescription, while others may be refilling for other reasons, such as prior to a vacation. Therefore, less severe measures are expected to have a stronger signal (more individuals will refill a prescription due to an acute respiratory response to smoke exposure than will pass away due to smoke exposure), but less severe measures are also expected to contain more extraneous variation (noise). However, while this is expected theoretically, it is worth noting that each dataset is unique and this may not always be the case with any true data stream. These are issues to assess when selecting and evaluating measures for surveillance.

3.3 Data accessibility and cost

Cost and timely availability of data are important considerations for assessing health effects in real time during wildfires smoke events. In Table 1, the final column (data access method) describes how data were obtained, either by manual abstraction (e.g., from medical records), through administrative data (e.g., collected by a third party and made available to researchers), or through a pre-existing surveillance system where data sharing agreements are already in place. Manual data abstraction has proven useful for research, but it has several limitations for ongoing surveillance. The cost could be prohibitive, the timeliness would likely be poor (it may take days or even longer before data were available for analysis), and there could be concerns about maintaining consistent quality over time. Most epidemiological studies on smoke and health, particularly those in the last decade, have used secondary data collected by a government body such as a federal, state, or provincial statistical agency or a via a public or private health care system such as a public health insurance system. Repurposing existing secondary data into a real-time surveillance and monitoring system is much more cost-effective and efficient than primary data collection. Provided that such databases exist, the barrier is establishing an agreement with the appropriate government bodies to share data at a timely rate. This has proven possible, for example, with dispensation and physician visit data in BC. Once a system is established, further data sharing agreements can be negotiated to evaluate new health data streams.

In this report, the focus was on acute measures of health impact that are useful to inform emergency response. However, there are peripherally related research areas that study the chronic effect of PM exposure. For example: any-cause PM associations with health, including traffic and residential wood burning (19); particular sub-populations of interest, such as respiratory cancer rates in wildland firefighter cohorts (20–27); risk of low birth weight among pregnant women exposed to wildfire smoke (28); and impact of wildfire smoke on children (29). These measures are not useful for short-term surveillance, but measurement of chronic exposure is an important public health issue. Wildfires are increasing in frequency and severity due to climate change. Some parts of the world are affected by wildfires not only occasionally, but in fact the exposure is essentially chronic with longer, more severe fire seasons each year in fire prone regions (1). A surveillance system developed to monitor health effects in the short-term may also provide some useful data for studying the longer-term effects of repeated or chronic exposure to smoke on populations.

3.4 Measures of mild health effects

Measures of mild health effects are useful for real-time health surveillance during wildfire smoke events because such effects tend to exhibit relatively quick onset and, although not severe in terms of outcome, they affect a larger proportion of the population than some more severe or chronic outcomes. Health effects that may be considered mild include dispensations of over-the-counter or prescription pharmaceuticals, calls to nurse health help lines, and online web searches. The mild health effect used most often in this research area is pharmaceutical dispensations of medications such as salbutamol sulphate, which is used to treat acute respiratory distress common among people with asthma and other obstructive lung diseases (10, 13). Dispensation data have been shown to be strongly associated with health outcomes during wildfire events (10, 13), and reveal a relatively minor (but common) health effect. Mild but acute health effects are likely to appear sooner after exposure than the more severe health outcomes such as hospitalizations or death. In any surveillance system, timeliness of effect detection is important. The limitation of dispensation data is that they may contain a great deal of random variation and noise, as people with asthma and related diseases likely refill asthma medications for many reasons, often preemptively, and in fact may opt to refill their prescriptions based on public health warnings before and during wildfires. This reverse-causation is also an issue in modeling the smoke-health relationship if analysts are using these input data to provide forecasts.

3.5 Measures of moderate and severe health effects

Moderate measures of health effect include physician and ED visits, either all-cause visits or those specific to relevant outcomes including respiratory, cardiovascular, ocular, and psychological. These visits are generally identified through ICD codes, though there are limitations to relying on these codes as there is variation in disease classification practices. Alternative approaches, such as free text searches of presenting complaints across a range of symptoms, may be preferable, although this may also require additional data preparation steps. The most commonly used moderate and severe outcomes are related to respiratory conditions such as respiratory-related medical visits or admissions (17, 30–38). Measuring ocular or psychological symptoms is less common (3, 39). While mild measures of health effect occur faster and more frequently during a wildfire event, the moderate and especially severe measures of health effect may provide a more precise measurement of the impact that the smoke is having on populations. For example, individuals visiting an emergency department for asthma exacerbation are likely in distress, and therefore ED visits may provide a more precise estimate as compared to prescription dispensations.

Severe measures of health effect may be more precise than moderate measures, revealing the most serious potential implications of acute exposure to high levels of PM in the air, such as hospitalizations and deaths. These measures only occur when there is some precipitating reason for a severe respiratory or cardiovascular health event, and therefore an otherwise unexplained spike in severe outcomes could be more easily attributed to wildfire smoke exposure during fire events, assuming confounding variables are taken into account. Some data may specify the actual cause of death or cause of the health event, such as respiratory hospital admissions or respiratory related mortality versus all-cause admissions or mortality. These data may provide a more precise measure specific to smoke exposure. The relative precision and timeliness of the different measures has not been well established in the literature, and it is important that the proposed data and methods be compared and evaluated before assuming these possible trends will hold. As well, there are temporal patterns that can confound these relationships; for example, heat waves often occur concurrently with wildfire season, and can independently cause respiratory health effects (17, 40) and death (41, 42). Using syndromic surveillance data, analysts and public health officials can never be entirely certain that observed patterns are due to any one specific cause, but can use models to control for known confounding variables and make probabilistic predictions. Exploring more sophisticated methodological approaches may also facilitate better surveillance; this will be discussed further in sections 3.7 and 4.0.

3.6 Burden estimation and forecasting

The mild, moderate, and severe measures of health effect differ in their utility for surveillance. Measures of mild effects would likely provide a more timely and widespread effect. Measures of more severe outcomes could contain less random variation and noise, although this would need to be investigated for each real surveillance dataset. The most severe outcomes may not have sufficient signal, due to low absolute numbers of events, to be detected (43). Moreover, it may be difficult to separate the small increase in mortality risk from the confounded relationship with heat-related mortality.

There are also other important considerations for the use of these data in informing emergency response. In the epidemiological studies reviewed for this report, the goal of each study was essentially to measure the magnitude of the association between exposure and one or more health outcomes. Burden estimation is a useful component of surveillance, where public health officials may be interested in the magnitude of the impact that the smoke is having on the population in real time. However, estimating the causal effect that an exposure (wildfire smoke) has on a health outcome is a complex epidemiological problem that is beyond the scope of routine surveillance. It requires careful consideration of exposure measurement, control for confounding variables, selection of individuals or population into the study, and exploration of variables that modify the effect measure between the exposure and the outcome, as all of these could affect the validity of the results. Exploring these issues in-depth are beyond the scope of this report but are routinely considered in epidemiological studies that aim to measure this effect (31, 44). For example, as mentioned earlier, temperature is a common confounder in time-series analyses, as heat waves can also cause respiratory effects and can frequently coincide with wildfire season (45). In some places, flu season can overlap with wildfire season, and flu season notably increases respiratory healthcare utilizations.

Measuring smoke exposure is a very complex task, as it is costly and impractical to directly measure individual level exposure across a population, and therefore some ecological measure is generally used as a proxy (11). This has inherent limitations because it increases the risk of misclassification, and many studies use a combination of exposure measurements, such as air quality monitors and satellite imagery, to increase the accuracy of the exposure measurement (6). A comprehensive review of smoke exposure measures can be found in another review in this series (refer to review on *Smoke Surveillance*). Some studies have investigated effect modifiers such as pre-existing comorbidities, finding that individuals with asthma and other lung diseases are more susceptible to the effects of wildfire smoke on their health; in other words, the increased risk of a negative outcome given an increase in smoke exposure is higher in these individuals than in the general population (16). Which measures of health effect are best suited for burden estimation depends on the focus of the public health department and, to some degree, on the characteristics of the population (see section on population susceptibility). In general, less severe outcomes may provide more timely detection whereas more severe may be a more precise measure of the health effect of smoke exposure.

Forecasting health outcomes is another very relevant issue for informing emergency response. In the context of wildfire smoke, short-term forecasting of health effects (e.g., 24 or 48 hours) could provide a reasonable picture of the anticipated burden, given the existing levels of exposure in the population. Health officials are often interested in forecasting as part of a surveillance system, as it allows them to plan interventions in advance. In the case of wildfire smoke exposure, health officials may issue public health warnings, encouraging individuals with certain medical conditions to limit activity and reduce their risk of a negative outcome, and they may develop evacuation plans in case the exposure becomes very high. Having a sense of what is likely to come in the following days is very useful in this context.

Forecasting the health effects of smoke exposure could be performed based on modeling the historic trends in the relationship between environmental data and health outcomes, both during periods of smoke exposure (smoke events) and periods of no exposure (to provide baseline data). The choice of which health measure to forecast will again relate to the focus of the public health setting, although respiratory health effects are likely a plausible choice, given that they show the strongest health effects and may be the most timely as well (3, 46). It may be useful to have a range of severity of health effects (low, moderate, high) so that estimated effects across various severity levels can be approximated. Sophisticated methods may be required to obtain sufficiently accurate forecasts in this area; partly because there are no gold standard health outcome data (no equivalent to laboratory-confirmed cases used in validation of infectious disease surveillance systems). The healthcare utilization data typically used as a proxy measure of health effects caused by wildfire smoke exposure contains extraneous noise and variation that must be carefully modeled, in addition to the temporal and spatial correlation. If forecasts of the exposure are available (e.g., particulate matter measurements, temperature), these could be used to potentially increase forecast accuracy and precision. Details on modeling and forecasting exposures are addressed in more detail in the review on *Smoke Surveillance*.

3.7 Surveillance process and methods

Building a surveillance system using syndromic surveillance data often requires use of more sophisticated methods to disentangle the health effect of interest (the signal) from the extraneous effects depicted by the data (the noise). The general process of surveillance in the context of an acute environmental exposure goes from data collection to analysis to interpretation to public health action. Each stage has necessary inputs and required expertise. As previously mentioned, data collection for surveillance can be done via automated abstraction from various data systems facilitated with data sharing agreements or mandatory reporting. Analysis requires expert knowledge from methodologists with expertise in statistics, epidemiology, and informatics; historical data are necessary to build and evaluate proposed methods, prior to putting a system online for use in real-time monitoring. Interpretation also requires technical expertise and expert knowledge on the nature of the exposure and health outcomes. Existing surveillance systems, such as regular surveillance of respiratory health effects or air quality and health monitoring, can further contextualize the interpretation (47).

Stakeholders such as decision makers in public health settings will need access to the output from surveillance systems, and in turn can provide insight and context. It is desirable to have standard training and protocols for use of these systems at different sites across a region. For example, having minimum data standards and comparable data elements will allow stakeholders to compare system performance and possibly collect data on the effectiveness of interventions. This could eventually lead to intervention evaluation – to determine what public health actions, and when, result in the best public health outcomes, which could be a next step after the development of well-evaluated surveillance systems. These systems could also facilitate monitoring of long-term effects of repeated acute exposures, collecting consistent data over years or decades.

3.8 Population susceptibility and vulnerability

Another component of real-time surveillance and emergency response is the impact of population characteristics. Refer to the review on *Health Effects of Smoke* for more details on vulnerability. In a surveillance context, it may be of interest to obtain some measures of population-level susceptibility to the health effects of smoke, including baseline health and demographic data. For example, Cal Fire has identified vulnerable communities based on a measure of risk for the occurrence of nearby wildfires, as well as distance from the flames (48). Those with asthma or other lung diseases have been shown to be more strongly affected by smoke than those without these conditions (16, 32, 34, 49). The prevalence of asthma and chronic obstructive pulmonary disease (COPD) in the population may provide additional information, and could potentially explain geographic patterns in the effect of smoke if some areas have a greater burden of disease than others. However, this data is often difficult to obtain at small spatial units. Age has been shown to modify the effect of smoke on health, with older adults more likely to experience a negative health effect, although this could also be influenced by the prevalence of disease, as older adults also more commonly are afflicted with conditions such as COPD (5, 17, 50). Basic demographic data like age and sex distributions are often obtainable from government agencies. The more relevant population characteristics available, the more variation in health effects across space and time can be explained. It would likely be straightforward in most public health settings to obtain characteristics of populations, such as disease prevalence and age distributions per geographic unit. Historical data on exposure and health outcomes will also provide important context to the specific public health setting.

4. Gaps

The surveillance framework is a clear gap in this literature – there are many epidemiological studies demonstrating the health effects of smoke in various capacities, and researchers and those working in public health have called for research into surveillance system development (10, 13, 30, 51). Several communities are currently exploring descriptive surveillance, following measures of healthcare utilization over time during fire seasons and making comparisons to measures of exposure. For example, the San Diego County Public Health Services has retrospectively investigated ED visits during the 2007 wildfire season using the pre-existing BioSense Surveillance system (52). BCAMS provides on-going monitoring of both exposure and health outcomes (salbutamol dispensations).No implementation of a real-time monitoring and forecasting system that links exposure and health outcomes data has been proposed in the literature, although there is ongoing work in BC towards better exposure assessment and development of forecasting systems.

There are also methodological gaps in using surveillance to inform public health response during smoke events. While some sites have access to suitable data available to provide real-time surveillance and forecasting, and there is established epidemiological evidence that wildfire smoke is a harmful public health exposure, suitable, well-validated methods do not yet exist. This is a challenging surveillance application area for several reasons. The exposure is a large-scale environmental phenomenon that varies rapidly over space and time and is affected by many factors, such as meteorological variables (temperature, wind). Estimating individual-level exposure for epidemiological purposes is not straightforward, and there currently are no gold standards for exposure measurement. The exposure data also need to be linked to the health outcomes data, and the most straightforward surveillance and forecasting models do not readily allow modeling the relationship between covariate data and outcome data (e.g., autoregressive integrated moving average (ARIMA) models), although more sophisticated extensions could facilitate this. The relative health effect of interest is likely quite small, in spite of the absolute public health effect being large, necessitating more sophisticated methods to disentangle the health effect from the random or extraneous variation. For example, simultaneously modeling the multiple health outcomes could provide more information than modeling each data stream separately, but multivariate time-series methods are not trivial to implement. There is a great deal of correlation structure (temporal, spatial, and multivariate) inherent in these data, and harnessing this correlation to provide additional information may be necessary to accurately monitor and forecast.

Computational issues are also important to surveillance methodology. Complex models require fast computation so that results are available at a high temporal resolution. Serious consideration to parameter estimation approaches, such as Markov-Chain Monte-Carlo methods implemented in a hierarchical Bayesian framework, where correlation between data streams and over time can be more easily modeled. There is also a need for development and thorough evaluation (validation) of suitable methods, potentially with the aid of simulation studies, so that characteristics of the data and model specifications can be evaluated across a range of plausible scenarios. This will likely require considerable technical expertise from those trained in epidemiology, statistics, and informatics.

5. Summary and Conclusions

This paper has summarized the measures of health effect that are available for use in a public health setting for real-time surveillance, and discussed each measure with consideration of relative timeliness, precision, availability, and cost. Burden estimation and the utility of these measures for forecasting are also relevant considerations discussed, and are elaborated in the other evidence reviews. Wildfire smoke has been shown in numerous epidemiological papers, many of which have been reviewed here, to have negative acute health effects on human populations. These effects have been found across a wide range of study designs and in drastically different settings from North America to Asia. The respiratory effects appear to be more prevalent relative to other effects such as cardiovascular.

Mild health effects may allow public health officials to detect a health effect faster, assuming the lag period between exposure and outcome is shorter on average in, for example, asthma attacks versus mortality. However, these mild health effects data may contain a great deal of random variation and noise, posing a methodological challenge in modeling. Having historic data to provide baseline measures during periods of exposure and periods of no exposure to build and validate models will be very important. In order to inform emergency response, timeliness is crucial. In order to develop surveillance models for these data, knowing that the absolute increase in risk is relatively small and that the data will contain a lot of noise, complex methods may be needed. For example, time-series methods that allow for inclusion of covariates to remove confounding variables and account for temporal correlation via random effects (e.g., generalized linear mixed models). Hierarchical methods that combine multiple data streams to simultaneously model the health outcomes as arising from common covariates (multivariate models) may allow for faster, more accurate detection and forecasting, although these methods are sophisticated and will require considerable statistical expertise and computational resources (53). This is an ongoing research area in wildfire smoke and health surveillance.

Each measure of health outcome discussed in this report reveals a different angle of the overall health impact that wildfire smoke has on human populations, and each measure has benefits and limitations. When it comes to monitoring acute public health impacts and informing emergency response, timeliness is crucial. Therefore, data that are readily available in (near) real-time are likely the best candidates for this task. Repurposed data collected by government agencies on pharmaceutical dispensations, physician and emergency room visits, and all- and specific-cause mortality are likely some of the best indicators of the effect of wildfire smoke on public health.

A first step towards developing a surveillance system in this area is data access, and it will be useful for public health agencies to develop data sharing agreements with government and industry, where new data are available in real-time or at least provided on a daily basis. It will be useful as well to gather relevant baseline health data, such as prevalence of diseases such as asthma and COPD at a reasonable spatial resolution (e.g., local health areas in BC), and demographic information such as age and sex distributions, and any other relevant vulnerable groups. These data should be fairly straightforward to obtain as compared to the real-time health data, as demographic and population prevalence health data do not generally change rapidly over time; annual averages should be sufficient. Finally, while the data are a crucial resource in the development of a surveillance system, the modeling of these data is unlikely to be trivial, and simplistic models will likely not provide enough information or precision to really guide intervention strategies. It will be important for researchers to work alongside public health officers in the design, development, and evaluation of these models.

5.1 Summary points for public health decision making

- Epidemiological studies have shown a clear public health impact from exposure to wildfire smoke, and those working in public health have acknowledged a need for the development of surveillance systems for monitoring and forecasting these health impacts in near real-time.
- Surveillance using descriptive epidemiology of exposure and health outcomes data is already performed in some areas, including BC and California. Current best practices in public health and smoke surveillance include near real time simultaneous daily reporting of health outcomes and environmental exposures. Excursions from expected outcome counts are identified using statistical analysis of deviations from predictive models based on historical trends.
- It is critical to have historical baseline data for building and validating surveillance models in this area, such as year-round exposure and health outcome data, to properly model seasonality and identify excursions from established trends.
- Public health surveillance of health effects associated with an environmental exposure is inherently different from that of infectious disease, but some ideas and tools from infectious disease surveillance may facilitate further development of surveillance systems in this area; for example, time-series methods from traditional (e.g., ARIMA models) to newer approaches (e.g., machine

learning methods such as neural networks; hierarchical modeling, potentially using Bayesian methods to ease the computational burden of parameter estimation).

5.2 Recommendations for public health decision making

- Standard guidelines are not currently developed for surveillance of health effects of wildfire smoke. Development of best practices could aid in system evaluation and collaboration between public health settings. Further consideration is needed to: (1) define clear surveillance objectives, (2) define syndromes, (3) develop health and environmental data streams, (4) develop models to identify meaningful excursions from baseline, and (5) facilitate forecasting of the health outcomes.
- While surveillance will increase situational awareness for communities that experience fires, the role and effectiveness of surveillance for informing public health action will need to be evaluated. Trigger points (ranges) for public health actions should be set, tested and evaluated. The surveillance data could play a role in surveillance system evaluation retrospectively (e.g., pre-post analyses to determine if health outcomes appeared to improve after the intervention as compared to before). Further understanding of the relationship between duration and intensity of exposures and magnitude and character of excursions in health outcomes data will be required to inform trigger points for action.
- Ad hoc systems of surveillance are useful when established systems are not available, and may be most appropriate for situations which occur infrequently. Because wildfires occur with seasonal regularity in many regions, developing an established surveillance system and validating the efficacy of the system over time could provide faster, more accurate information in real-time, provide useful forecasting of the health effects, and facilitate system and intervention evaluations.

Table 1. Summary of key papers, sorted by primary author[2]

Source	Location	Study design / approach	Health outcomes measured	Exposure measure	Outcome data source	Strength of associations	Data access method
Analitis, Georgiadis & Katsouyanni 2012 (50)	Athens, Greece	Ecologic, time-series	Mortality – all natural causes (non-accidental), cardiovascular causes, respiratory causes	Black smoke; number/size/duration of fires	Provided by Hellenic Statistical Authority	Increase in all-cause, cardiovascular, and respiratory mortality, respectively, for large fires: 49.7% (95% CI: 37.2, 63.4) 60.6% (95% CI: 43.1, 80.3) 92.0% (95% CI: 47.5, 150.0)	Administrative database
Chen, Verrall & Tong, 2006 (35)	Brisbane, Australia	Ecologic, time-series	Respiratory hospital admissions	PM_{10} monitoring stations	Routinely collected data provided by Queensland Department of Health (ICD-9 and ICD-10)	RR range: 1.11–1.16	Administrative database
Crabbe 2012 (4)	Darwin, Australia	Ecologic, time-series	Respiratory hospital admissions	PM_{10} monitoring stations, 1 day lag	Routinely collected, provided by Northern Territory Government's Department of Health and Community Services	RR=1.025 (CI: 1.000, 1.051)	Administrative database

[2] Not exhaustive of all papers reviewed and included in report. See references for full list of all relevant papers included. Reference list is separated by key epidemiology study papers and supplemental references.

Source	Location	Study design / approach	Health outcomes measured	Exposure measure	Outcome data source	Strength of associations	Data access method
Delfino 2009 (5)	California, USA	Aggregate time-series	Respiratory hospital admissions (asthma, acute bronchitis, COPD, pneumonia)	$PM_{2.5}$ monitoring stations, remote sensing	California State Office of Statewide Health Planning and Development	Respiratory RR=1.03 (CI: 1.01, 1.05), Asthma RR=1.05 (CI: 1.02, 1.08)	Administrative database
Duclos, Sanderson & Lipsett 1997 (30)	California, USA	Pre-post study with individual covariates	ED visits for respiratory illness including infectious; eye irritation; anxiety and panic reactions	Exposed was defined as during a 2.5 week fire event period, and unexposed was defined as other time periods prior to and after these events	Emergency room records were abstracted over a 2 ½ week period during a severe fire period, and two reference periods	Risk ratio = 1.4, 1.3 for visits related to asthma and COPD respectively	Manual abstraction
Elliott, Henderson & Wan, 2013 (13)	British Columbia, Canada	Time-series, meta-regression	Pharmaceutical asthma reliever dispensations	Per 10 $\mu g/m^3$ in $PM_{2.5}$ during fire season	Routinely collected data by the BC Ministry of Health via their PharmaNet program for prescription pharmaceuticals	Fire season RR=1.06 (CI: 1.04, 1.07)	Administrative database
Hänninen et al. 2008 (18)	Finland	Ecologic, time-series	All-cause mortality	Eight $PM_{2.5}$ and PM_{10} monitoring stations, estimated background PM removed	Additional mortality estimated based on WHO reported increases in risk associated with PM	Relative risk for daily mortality (RR) varied between 0.8% and 2.1% per additional 10 mg/m^3 of $PM_{2.5}$ exposure in the various regression model calculated	Publicly available mortality data

Source	Location	Study design / approach	Health outcomes measured	Exposure measure	Outcome data source	Strength of associations	Data access method
Hanigan, Johnston, & Morgan 2008 (36)	Darwin, Australia	Ecologic, time-series	Respiratory hospital admission	Increase of 10 μg/m^3 in same-day estimated PM_{10}	Routinely collected, provided by Northern Territory Government's Department of Health and Community Services (ICD-9 & ICD-10)	4.81% (CI: -1.04, -11.01) increase in all respiratory admissions	Administrative database
Henderson et al. 2011 (6)	British Columbia, Canada	Population-based cohort,	Respiratory physician visits and hospital admissions	Per 30 μg/m^3 PM_{10} monitoring stations, dispersion model, remote sensing	Routinely collected data provided by the provincial health services plan (Medical Services Plan MSP via BC Ministry of Health)	Physician OR=1.05 (95% CI: 1.03, 1.06) Hospital OR=1.15 (95% CI: 1.00, 1.29)	Administrative database
Johnston et al. 2002 (44)	Darwin, Australia	Ecologic	Asthma ED visits	Per 10 μg/m^3 PM_{10}	Data extracted from hospital records using ICD-9 codes	Rate ratios: Overall: 1.20; 95% CI: 1.09, 1.34 When PM_{10}>40 μg/m^3: 2.39; 95% CI: 1.46, 3.90	Manual abstraction
Johnston et al. 2007 (49)	Darwin, Australia	Case-crossover	Respiratory hospital admission	Per 10 μg/m^3 PM_{10} monitoring stations	Data collected and provided by Royal Darwin Hospital using ICD-10	OR=1.08 (CI: 0.98, 1.18)	Manual abstraction
Johnston et al. 2011 (45)	Sydney, Australia	Time-stratified case-crossover design	Non-accidental mortality	PM_{10}>99 percentile=smoke event, 1 day lag	Routinely collected Australian Bureau of Statistics ICD-9 & ICD-10	Smoke events associated with 5% increase in non-accidental mortality at a lag of 1 day OR=1.05 (CI: 1.00–1.10)	Administrative database

Source	Location	Study design / approach	Health outcomes measured	Exposure measure	Outcome data source	Strength of associations	Data access method
Martin et al. 2013 (37)	Sydney, Newcastle and Wollongong, Australia	Time-stratified case-crossover	Respiratory hospital admissions (total, COPD, asthma)	PM_{10} > 99 percentile = smoke event	Department of Health in NSW, ICD-9 & ICD-10	OR total=1.06 (CI: 1.02, 1.09) OR COPD=1.13 (CI: 1.05, 1.22) OR Asthma=1.12 (CI: 1.05, 1.19)	Administrative database
Moore et al. 2006 (39)	British Columbia, Canada	Ecologic	Respiratory physician visits (acute)	Exposed during 3-week fire period	Routinely collected data provided by the provincial health services plan (Medical Services Plan MSP via BC Ministry of Health) ICD-9	Increases between 46%–78% above 10-year mean rates	Administrative database
Morgan et al. 2010 (38)	Sydney, Australia	Time-series, individual-level covariates	Respiratory hospital admission (total, asthma, COPD)	Per 10 $\mu g/m^3$ PM_{10}	New South Wales Department of Health provided data on hospital admissions, ICD-9 & ICD-10	Asthma increased 5.02% (CI: 1.77, 8.37), COPD 3.80% (CI: 1.60, 6.26) All respiratory 1.24% (CI: 0.22, 2.27)	Administrative database
Mott et al. 2002 (7)	Hoopa, California USA	Pre-post ecologic study	Medical visits at a medical centre for respiratory health	During fire episodes (exposed) vs. same time previous year (unexposed) in the same region	Retrospective abstraction of medical records from a local medical center, ICD-9	"During the weeks of the wildfire, medical visits for respiratory illnesses increased by 217 visits (from 417 to 634 visits, or by 52%) over the previous year."	Manual abstraction

Source	Location	Study design / approach	Health outcomes measured	Exposure measure	Outcome data source	Strength of associations	Data access method
Rappold et al. 2011 (17)	North Carolina, USA	Ecologic, time-series	ED visits (asthma, COPD, pneumonia/ acute bronchitis)	Exposed/unexposed counties, remote sensing	NC Disease Event Tracking and Epidemiologic Collection Tool, a statewide, public health surveillance system: NCDETECT, ICD-9	RR for asthma=1.65 (CI: 1.25, 2.1); COPD=1.73 (CI: 1.06, 2.83), pneumonia=1.59 (CI: 1.07, 2.34)	Pre-existing surveillance system
Smith et al. 1996 (34)	Western Sidney, Australia	Pre-post ecologic study and ecologic time-series	ED visits for asthma	PM_{10} monitoring stations	Retrospective abstracting of medical records	Proportion of all ED visits due to asthma during fire period vs. control period=0.0067 (95% CI: -0.0007, 0.0141)	Manual abstraction
Tham et al. 2009 (51)	Victoria, Australia	Ecologic, time-series	Respiratory hospital admissions and ED visits	PM_{10} monitoring stations & Airborne Particle Index (API)	Daily hospital data from the Victorian Department of Human Services ED visits (the Victorian Emergency Minimum Dataset); admitted to a public or private hospital (the Victorian Admitted Episodes Dataset) with a discharge. ICD-10	PM_{10} and daily respiratory ED attendances in Melbourne RR=1.018, 95% CI: 1.004, 1.033	Administrative database
Rappold et al. 2012 (16)	North Carolina, USA	Ecologic	Asthma ED visits	Per 100 $\mu g/m^3$ $PPM_{2.5}$ smoke forecasting model	NC Disease Event Tracking and Epidemiologic Collection Tool, a statewide, public health surveillance system: NCDETECT, ICD-9	Excess RR=66% (CI: 28, 117)	Administrative database

Source	Location	Study design / approach	Health outcomes measured	Exposure measure	Outcome data source	Strength of associations	Data access method
Vedal & Dutton 2006 (43)	Denver, Colorado (and neighboring counties as control group)	Ecologic, time-series	All-cause mortality (non-accidental)	Residence (during fire vs. control period/location)	Data were obtained from the Colorado Health Information Data set, compiled by the Health Statistics Section of the Colorado Department of Public Health and Environment. ICD-10	No effect found or reported	Administrative database
Yao et al. 2013 (10)	British Columbia, Canada	Ecologic, time-series	Salbutamol dispensations, asthma related physician visits	30µg/m^3 increase in $PM_{2.5}$ monitoring stations, forecast model, remote sensing	Routinely collected data by the BC Ministry of Health, Medical Services Plan and prescription pharmaceuticals plan (PharmaNet) ICD-9	Salbutamol dispensations: 8% increase Physician visits: 5% increase	Administrative database

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Appendix A: Details of search strategy for obtaining relevant literature

Inclusion criteria

- Epidemiologic studies that investigate the health outcomes of wildfire smoke exposure
- Case studies from jurisdictions that have used health surveillance data (e.g., Australia)
- All study designs will be included: most are ecological-level time-series studies; there is one cohort study and a small number of other designs such as case-crossover
- Some measure of health impact must be used
- Should cover the entire population and not be based on specific groups (e.g., wildland firefighter cohort studies will be excluded because they focus on chronic exposure and long-term health outcomes like cancer rates, not suitable for acute effect surveillance)
- Must focus on wildfire or wildfire smoke exposure

Exclusion criteria

- Special-topics will be excluded (e.g., firefighter cohorts; perinatal outcomes will be excluded as they are not useful for measuring acute effect in real-time)
- Papers discussing only measures of exposure (smoke) and not health outcomes (studies focusing on exposure measurement but still including a health outcome will be included)
- Review papers will be used to identify additional relevant papers but will not be explicitly included
- Papers studying particulate matter (PM) exposure that is not specific to wildfires will be excluded
- Papers investigating the effect of wildfire smoke on air quality without measure of health effect will be excluded

Databases

PubMed, Google Scholar, Cinahl, and several specific journals in environmental health (Environmental Health, EcoHealth, Environmental Health Perspectives, Int J of Environmental Health Research, International Journal of Environmental Research and Public Health)

Search terms

Wild fire smoke OR wildfire smoke OR bushfire smoke OR wildland/wild land fire smoke OR landscape fire smoke AND health OR respiratory OR cardiovascular OR ocular

Quality Assessment

Papers were assessed for quality under the following considerations:

- Published in peer-reviewed journals
- Epidemiological studies with exposure measurement (smoke exposure) and outcome measurement (health outcomes) explicitly explained
- Some measure of health effect is provided (e.g., risk ratio, odds ratio)
- Study design is explicitly or implicitly provided
- Confounders (individual or ecological, e.g., temperature) are mentioned or discussed

Most studies in this area are ecological-level time-series analyses, which means they do not have individual-level covariates measures. There are few individual-level covariates which truly are confounders, as most (e.g., individual-level smoking status) are not associated with the exposure; however, they could be effect modifiers. All studies in this area measure the exposure ecologically. At least some discussion of residual confounding and measurement error is expected.