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Evidence Review: Exposure measures for wildfire smoke surveillance

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Key points

- Wildfire smoke exposure is challenging to evaluate because it is complex and sporadic.
- Tools for assessing wildfire smoke exposure include air quality monitors, remote sensing products, retrospective and forecasting modeling, and fire smoke proxies.
- All of these tools have strengths and limitations, and there is no clear gold standard.
- Air quality monitoring is the most widely used tool in both epidemiologic studies and public health surveillance. It is reliable and easy to interpret, but the limited spatial coverage restricts its use to communities with monitors in place.
- Visibility range is a good proxy for smoke levels and it requires minimal expertise and resources to measure, thus recommended in existing public health guidelines for communities without monitors. However, its accuracy can be influenced by other environmental factors and it depends on the availability of landmarks at known distance.
- Forecasting model can provide prospective information, which is a desirable source of information for public health decision making. It should be used more qualitatively than quantitatively due to the uncertainties in model performance.
- Remote sensing and retrospective modeling have been developed and used in recent epidemiologic studies but not as much in public health surveillance. With their unique features, they have great potential for specific purposes, such as for monitoring smoke from long-ranged transportation and improving the spatial resolution of existing monitoring networks.
- Public health decisions should utilize information from multiple exposure assessment tools, with priorities in their suitability for the purpose.
- Exposure levels should not be the singular base for decision making but coupled with knowledge and expertise from other relevant local parties.

1. Introduction

Wildfires have become an increasing hazard around the world as climate change favors increasingly extreme weather events. In addition to the direct threat fire poses to life and property, wildfire smoke has caused large-scale air quality degradation and impacted large populations (1-3). Wildfire smoke exposure has been associated with adverse health effects such as cardiopulmonary responses, low birth weight, and increased mortality (4-7).

Wildfire smoke is challenging to evaluate from an epidemiologic and public health protection perspective. It is usually sporadic and short-lived with highly variable concentrations. In addition, its greatest impact is often in non-urban areas that do not have regulatory monitoring networks in place.

This evidence review aims to summarize the tools available to help public health authorities understand wildfire smoke exposures in their jurisdictions, and to support public actions that protect against those exposures.

2. Objective

The objective of this review is to summarize how different tools have been used for assessing population exposure to wildfire smoke, and to evaluate how these tools can be used to inform public health actions.

3. Methods

We used PubMed and Web of Science to search for peer-reviewed literature. We also used Google to search for government documents concerning population exposure to wildfire smoke.

We identified potentially relevant articles with a set of key words (Table 1) and then manually selected by their abstracts according to the following exclusion criteria:

- Non-English articles;
- Letters, commentaries, editorials and review articles;
- Studies not related to wildfire smoke exposure or without measures of exposure;
- Studies not performed on humans;
- Studies of tools not practical for assessing population exposures for time-constrained public health decision making, for example, filter-based sampling for chemical analysis, personal monitoring, and biomonitoring;
- Studies published before the year 2000.

We used another set of key words (Table 1) to search for existing public health guidelines, and included those with descriptions of exposure assessment methods. The references found were reviewed by experts in the field.

We summarized the use of different exposure assessment tools in the health studies identified by the literature search, and discussed the articles without health study component in the result sections if relevant. We did not describe any individual study in detail, but provided an overall summary of the approaches used in these studies.

Table 1. Key words for literature search

Key words for search in PubMed and Web of Science	Key words for Google search
Forest fire smoke, wildfire smoke, wild fire smoke, bushfire smoke, bush fire smoke, vegetation smoke	Forest fire/ wildfire/wild fire/bushfire/bush fire/vegetation smoke + guideline

4. Results

The results section is divided into five sub-sections, describing five categories of exposure assessment tools. Each sub-section starts with a general introduction to the tools, followed by a description of how the tools have been applied in epidemiologic studies, their strengths and limitations, and finally their current and potential application in public health surveillance.

Thirty five epidemiologic studies, with details on assessing and assigning exposure to populations and the association between exposure and health outcomes, and were selected for detailed review in this result section. Table 2 summarizes the exposure assessment methods in these studies and whether they have association with "mild" or "severe" health outcomes, classified by Henderson and Johnston (4). Details of health outcomes and strengths of association are described in evidence review *Health Effects of Smoke* and *Health Surveillance.*

Other articles or documents involving wildfire smoke exposure but without any health component will be used to provide supplementary information for our discussion in this section. These remaining literatures apply exposure assessment methods to 1) quantify the impacts of wildfire smoke on air quality on local, regional or global scale, 2) estimate emission inventories attributable to wildfire smoke, or 3) support epidemiologic studies or public health action.

4.1 Routine air quality monitoring

4.1.1 Introduction

Air quality monitoring stations are set up to measure a range of atmospheric pollutants. These data are valuable for tracking changes in air quality and supporting air quality regulations. They are also widely used by epidemiologic researchers and public health practitioners. Fine particulate matter ($PM_{2.5}$[1]) is considered the most useful indicator of wildfire smoke impacts because it is the most elevated of the routinely-measured pollutants during smoke episodes (8), and it has been consistently associated with adverse public health impacts (8). The measurement of coarse particulate matter (PM_{10}[2]) has also been used when $PM_{2.5}$ is not available because $PM_{2.5}$ is the major fraction of PM_{10} in wildfire smoke (9, 10).

There are two types of monitoring methods: filter-based and continuous instrumental. Filter-based method measures the PM mass collected on a pre-weighed filter exposed to known volume of air. This method is the most accurate way to measure PM mass concentrations and used to determine air quality compliance in many jurisdictions. However, the whole process of sampling and weighing usually takes weeks. On the other hand, continuous instrumental method can provide real time reporting of PM concentrations. Its timely and continuous feature makes it more suitable for health studies and surveillance. Instruments commonly used to continuously measure PM include the tapered element oscillating microbalance (TEOM), the Beta Attenuation Monitor (BAM), the Synchronized Hybrid

[1] $PM_{2.5}$: particulate matter with an aerodynamic diameter smaller than 2.5 micrometer

[2] PM_{10}: particulate matter with an aerodynamic diameter smaller than 10 micrometer

Ambient Real-time Particulate Monitor (SHARP), and the Partisol Air Sampler. Only continuous instrumental monitoring methods have been used in the selected epidemiologic studies. In the following discussion, monitoring measurements refers to continuous instrumental monitoring only.

4.1.2 Application in epidemiologic studies

Three approaches used in epidemiologic studies are summarized in the Table 2:

1. The first used time-series measurements to identify smoke-impacted time periods and compared health outcomes within those periods with health outcomes outside of those periods. Baseline PM concentrations were derived from long-term historical data (9, 11) or measurements taken before and after the event (12-14). This approach had limited power to detect changes in severe health outcomes, such as emergency room visits and mortality.
2. The second approach directly associated PM measurements with counts of specific health outcomes within a population assumed to be affected by the exposure. This method had consistently detected effects on a wide range of health outcomes and in different study settings. Most of these studies were conducted in relatively small urban areas or in regions with dense monitoring networks.
3. The third approach defined high pollution days as those when PM measurements exceed certain percentile (e.g. 99th percentile) of the entire time-series of historical data, and verified the attribution of fire smoke on these days from media, government reports, and other sources (15, 16). The PM values on high pollution days during fire smoke events were then associated with health outcomes. This approach provided information more specific to fire smoke pollution, and had detected severe outcomes such as respiratory mortality. This was a useful method for regions where wildfire smoke was the major cause of extreme air pollution events.

4.1.3 Strengths and limitations

The use of monitoring measurements is generally simple and provides robust and quantitative information representative of population exposure. It is the most reliable measures currently available and serves as an important reference for developing and validating new tools such as remote sensing and modeling. However, it is not an ideal gold-standard method for smoke exposure due to the following limitations. First, the monitoring network is spatially scarce, so its use is restricted to geographical areas where monitors are available. For example, Elliott et al. 2013 (17) reported that only 29 of 89 local health areas had PM monitoring measurements available for the 10-year study. Even in regions with monitors, they may not adequately represent the smoke impact if they are not positioned downwind of the smoke plumes. Temporary portable measuring devices may provide important supplemental information under these circumstances, but their availability is resource-dependent and their use has been limited. Second, extremely high PM concentrations common during wildfire smoke events can overload instruments or cause monitors to malfunction (10, 13). Third, PM monitoring measurements are not source-specific. It is difficult to use these measurements to quantify health effects specifically with wildfire smoke, especially in regions with significant amounts of PM from other sources.

4.2 Remote sensing

4.2.1 Introduction

Satellite remote sensing has been applied in atmospheric aerosol observation over the past 30 years (18). Satellite sensors can detect sun radiation reflected from the ground. These reflectance signals are determined by the ground surfaces, as well as the gases and aerosols in the atmosphere. By decomposing these signals, we can retrieve information about the properties of the atmospheric pollutants (18).

Several different types of remote sensing products have been used for wildfire smoke exposure assessment. The simplest products use information directly available from satellite detection with minimal post-processing by the data provider, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) true color images provided by the US National Aeronautic and Space Administration (NASA). These photo-like images use signals from three visible bands (red, blue and green) of the sensor, and they can provide visual and qualitative information about smoke plume coverage. More sophisticated products require that the raw data be processed using complex algorithms that are continually refined and updated to provide standardized and quantitative information. One widely used product is the aerosol optical depth (AOD), an index of the amount of aerosol in the total atmospheric column. Satellite sensors with AOD measurements include the Total Ozone Mapping Spectrometer (TOMS), Geostationary Operational Environmental Satellite (GOES), and MODIS. Many of these products are manually combined by analysts into an ensemble product within the US National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System (HMS), to produce smoke plume outlines over North America. Another useful product is the MODIS fire radiative power (FRP) measurement. MODIS can detect fire by identifying thermal anomalies on the surface of the earth and measure FRP indicating the intensity of the fire. FRP has been found proportional to smoke emissions from the detected fires (19).

4.2.2 Application in epidemiologic studies

The true color images have only been used in one health study, to visually identify the occurrence of smoke events (6). The use may be extended with statistical methods developed to systematically identify smoke plumes from these images.(20) Although AOD is a quantitative measure and HMS have recently been changed from strictly qualitative to semi-quantitative, most studies have used them only to qualitatively classify smoke impacted areas or periods with two approaches summarized in Table 2.

1. A binary exposure variable was created to indicate whether a location was covered by smoke plume and the variable was associated with health outcomes. Smoke plume was defined using smoke plume outlines specified in the product, such as smoke plume outlines in HMS (21, 22). It could also be defined using certain threshold of the AOD (21, 22). For example, Frankenberg et al. (23) classified smoke plume as area with TOMS AOD (an index ranging from 0 to 4) exceeding 1.5 and Rappold et al. (7) used a threshold of 1.25 for GOES AOD (an index ranging from 0 to 2). Health outcomes can then be compared between populations covered and not covered by smoke plumes.
2. Areas or periods impacted by smoke were identified using remote sensing products and PM monitor measurements in these areas/periods were associated with health outcomes (17, 24). Elliott et al. (17) classified the health regions in the study area to fire-affected and non-fire-affected by the FRP sum of all fires detected within the 100km radius circle around the monitoring station in the health region. They also identified extreme fire days as days with FRP sum of fires detected within and

around the study area above the 80th, 90th or 95th percentiles of the entire study period. By limiting the analyses in fire-affected areas and on extreme fire days, the study was able to associate the health effects with PM measured by monitors, specifically from wildfire smoke.

AOD, HMS and FRP have also been used to develop models to quantitatively estimate ground-level PM concentrations. This will be discussed more in Section 5.3.

4.2.3 Strengths and limitations

Remote sensing has unique advantages for wildfire smoke exposure assessment. It can cover very large geographical areas, including regions where monitoring networks are not available (23). Remote sensing data can also capture the trajectory of the smoke plumes, which routine monitoring data cannot. Most of these products are publicly available online or upon request. However, remote sensing tools also have some limitations. They measure air pollutants in the total column of the atmosphere rather than the ground level concentrations of most concern to public health. There has been research on algorithms to convert columnar measurements to its ground level fraction (25), but they are usually complex and location-specific. In addition, satellite images can be influenced by cloud, resulting in large amount of missing data. During intense wildfire events, the thick smoke can be falsely identified as cloud by the regular data retrieval algorithms. Efforts have been made to address this issue by relaxing the criteria of cloud identification (25, 26).

4.3 Retrospective modeling

4.3.1 Introduction

Air quality modeling has been used in air quality management by different jurisdictions. There are two major types of air quality modeling: mechanistic models and empirical models. Mechanistic models simulate the process whereby the pollutants are emitted, transported and, transformed in the atmosphere. For wildfire smoke, the models are run with emission estimates from fires, meteorological conditions, and the assumptions and equations based on our understanding of the behavior of fire and smoke. Empirical models, on the other hand, are derived solely from observational data. They are constructed by fitting a statistical model with smoke-related variables to achieve the best predictions of smoke concentrations.

4.3.2 Application in epidemiologic studies

1. Mechanistic air quality models have been developed in different regions and some of them have been used for wildfire smoke. Henderson et al.(21, 27) used satellite-detected fire emissions as input to the CALPUFF atmospheric dispersion model to estimate smoke-specific PM10 concentrations and associated the concentrations with cardiopulmonary physician visits and hospital admissions. Thelen et al. (28) used a fire emission model coupled with the HYSPLIT dispersion model to estimate PM from fires. They then combined fire-related PM with modeled anthropogenic PM, and used the resulted PM concentrations to predict emergency room visits. Johnston et al. (29) used GEOS-Chem 3-D chemical transport model to estimate global exposure to landscape fire smoke, and to assess the attributable annual global mortality. Other mechanistic models such as the chemistry transport model CHIMERE developed in Europe have also been used to estimate air quality impacts from wildfires (30, 31), but few of them have been used in health studies.
2. Empirical models have been built using regressions with visibility, meteorological data, monitoring measurements, and remote sensing data, to estimate PM concentrations during wildfire smoke

events. Delfino et al. (32) used an empirical model coupled with spatial interpolation to estimate daily $PM_{2.5}$ concentrations at the postal code level in a fire season. Hanigan et al. (33) constructed an empirical model with data from three dry seasons to estimate daily PM_{10} concentrations for ten seasons. Similar models have also been developed in two cities in Australia (34) and all populated areas in British Columbia, Canada (35) for public health surveillance and epidemiologic study.

4.3.3 Strengths and limitations

Modeling can provide smoke estimates in fine spatial and temporal resolutions and both types of models have their strengths and limitations. Mechanistic models can provide source specific information with good temporal resolution, but they are computationally expensive, data intensive, and they take specialized expertise to parameterize and run. Their performance may depend on the quality of the input data for each module, as well the agreement between model assumptions and reality. In addition, it is challenging to validate these mechanistic models without any gold-standard approach for measuring smoke-specific PM. On the other hand, most empirical models have simple structures and are easy to implement under time constrained settings. However, it requires large volumes of historical data at the model training stage to develop a robust model. This can be problematic for regions without sophisticated monitoring network and historical measurements of variables relevant to wildfire smoke. Investment in sampling campaign or temporary monitoring sites may be essential in such cases in order to develop the model.

4.4 Forecasting Modeling

4.4.1 Introduction

From the perspective of public health protection, it is desirable to have prospective information on wildfire smoke exposures. Forecasts may allow extra time for plans and actions before the hazardous events. Operational wildfire smoke forecasting systems have been developed in the US, Canada, and Europe (36-38). These systems are mechanistic models with the capability to forecast, usually composed of two major parts: an estimate of future fire emissions, and a simulation of air dispersion. Future fire emissions can be estimated based on current trend of fire behavior, either from the fire intensity measured by remote sensing or computations from an emissions production model using fuel types, fuel loads, and emission factors. The dispersion of the fire emissions can be simulated by air dispersion models with the emission estimates and meteorological forecasts as inputs.

4.4.2 Application

Forecasts from some of these systems are publicly available online. Although most of them only agree modestly with observations from monitors or remote sensing (22, 36, 38, 39), their utility for public health is promising because forecasts have been associated with health outcomes. Yao et al. (22) evaluated the smoke forecasting system in western Canada by associating its forecasts with respiratory health outcomes and found consistent effects comparable to those estimated using observed data from the air quality monitoring network and remote sensing instruments. Rappold et al. (40) found excess relative risk in cardio-pulmonary emergency room visits associated with increased $PM_{2.5}$ forecasted by a system developed by the US National Oceanic and Atmospheric Administration (NOAA).

4.4.3 Strengths and limitations

Wildfire smoke forecasting systems provide prospective information for ground level smoke concentrations in high spatial and temporal resolutions. These features are among the most desirable for supporting public health decision making. Similar to retrospective models, the biggest limitation for these forecasting models is the uncertainty in their performance. Assumptions are made in the model to simulate the behavior of fire and smoke, which can lead to uncertainty in how well these assumptions agree with reality. The degree of uncertainty may be greater than that for retrospective models because many inputs to the model are predictions from other models, with their own uncertainty embedded. Model validation is also challenging in the absence of accepted gold standard measurements. In addition, they are computationally demanding, especially during intense fire seasons. When there are more fire hotspots, it will take significantly longer time for the models to process and compute smoke emission and dispersion from these fires.

4.5 Smoke proxies

4.5.1 Introduction

Some information about wildfires has been used as a proxy for smoke exposure, including the number of fires or the area they have burned. The underlining assumption is that more fires and larger fires will result in more smoke emission and exposure. Visibility range has also been recommended by different public health agencies to approximate ambient PM concentrations and air quality indices during wildfire smoke events. Visibility range can be impaired by the light scattering and absorption effects due to PM and gases in the atmosphere. For a given distribution of PM sizes and compositions, this impairment is strictly proportional to the ambient PM concentrations (41). Thus, a relationship can be established between visibility ranges and PM levels.

4.5.2 Application in epidemiologic studies

Caamano-Isorna et al. (42) classified municipalities in the study area into no exposure, medium exposure, and high exposure categories based on the monthly total number of fires within the municipalities and associate the exposure categories with drug consumption for obstructive airway diseases. Analitis et al. (43) categorized the study period into small, medium, and large fire days based on the daily total area burnt in the study area and evaluated if the fire categories related to mortality. The categorizations of exposure days/areas are usually based on the distribution of fire numbers or burnt areas in the entire time-series.

Visibility range is measured by determining whether or not reference objects at known distances are visible to a human observer (44). Few epidemiologic studies assessed smoke exposure using visibility range only, but some included visibility as a major predictor in their empirical exposure models, together with other variables such as relative humidity, temperature, and remote sensing data (10, 32, 33).

4.5.3 Strengths and limitations

Fire proxies, such as number of fires or burnt area, are relatively easy to obtain and associated with health outcomes in available studies. However, they are more likely to introduce exposure misclassification because the assumption that they be proportional to the smoke emission may not be correct. Differences in fire intensity, burn conditions, and fuels can result in different smoke emission for the same number of fires or burnt area. In addition, these fire proxies do not account for dispersion and transportation of smoke, which can cause error in estimating exposure, especially in places distant to the fires.

While having close relationship with PM measurements, visibility range requires much less expertise and resources to apply. It can be a measure of local exposure in high time resolution. However, it cannot be used at night, dawn or dusk, or when specific landmarks at known distances are not available. The relationship between visibility and PM levels can be greatly influenced by other factors such as relative humidity and aerosol hygroscopicity. The influence is especially pronounced at high humidity and high PM concentrations, increasing the uncertainty in differentiating pollution and health message categories at the high scales. For example, it may be easy to distinguish visibility between good and moderate condition, but it will likely be challenging to precisely differentiate category hazardous from unhealthy or very unhealthy. It may help address this issue to establish region-specific relationship with consideration of relative humidity, such as the one developed by O'Neil et al. (45).

Table 2. Summary of exposure assessment approaches in health studies

Tool	Exposure assessment	Author, year	Study area	Outcome severity, association
Monitor (Section 5.1)	**Use PM_{10} and/or $PM_{2.5}$ monitoring measurements to define smoke event periods in the time series (Section 5.1.2, bullet #1)**	Mott et al. 2002(11)	California, USA	Mild[1]: ↑
		Moore et al. 2006(9)	British Columbia, Canada	Mild: ↑
		Vedal & Dutton 2006(12)	Denver, USA	Severe[2]: -
		Kolbe & Gilchrist 2009(13)	Albury, Australia	Mild: ↑
		Schranz et al. 2010(14)	San Diego, USA	Severe: -
	Directly associate PM_{10} and/or $PM_{2.5}$ monitoring measurements with health outcomes (Section 5.1.2, bullet #2)	Emmanuel et al. 2000(46)	Singapore	Mild: ↑ Severe: -
		Jalaludin et al. 2000(47)	Sydney, Australia	Mild: -
		Tan et al. 2000(48)	Indonesia	Mild: ↑
		Johnston et al. 2002(49)	Darwin, Australia	Severe:↑
		Sastry et al. 2002(50)	Malaysia	Severe:↑
		Kunzli et al. 2006(51)	California, USA	Mild: ↑
		Chen et al. 2006(52)	Brisbane, Australia	Severe:↑
		Viswanathan et al. 2006(53)	San Diego, USA	Severe:↑
		Johnston et al. 2007(54)	Darwin, Australia	Severe:↑
		Hanninen et al. 2009(55)	Finland	Severe: ↑
		Lee et al. 2009(56)	California, USA	Mild: ↑
		Tham et al. 2009(57)	Victoria, Australia	Severe:↑
		Morgan et al. 2010(58)	Sydney, Australia	Severe:↑
		Vora et al. 2011(59)	San Diego, USA	Mild: ↑
		Henderson et al. 2011(21)	British Columbia, Canada	Severe:↑ Mild: ↑
		Crabbe 2012(60)	Darwin, Australia	Severe:↑
		Yao et al. 2013(22)	British Columbia, Canada	Mild: ↑

Tool	Exposure assessment	Author, year	Study area	Outcome severity, association
	Use PM measurements to identify fire days and associate the concentrations with health outcomes (Section 5.1.2, bullet #3)	Johnston et al. 2011(15)	Sydney, Australia	Severe:↑
		Martin et al. 2013(16)	Australia	Severe:↑
Remote sensing (Section 5.2)	**Use remote sensing to define smoke impacted and non-impacted areas or periods (Section 5.2.2, bullet #1)**	Frankenberg et al. 2005 (23)	Indonesia	Mild: ↑
		Henderson et al.2011 (21)	British Columbia, Canada	Severe:↑ Mild: ↑
		Holstius et al. 2012(6)	California, USA	Mild: ↑
		Yao et al. 2013(22)	British Columbia, Canada	Mild: ↑
		Rappold et al. 2011(7)	North Carolina, USA	Severe:↑
	Use remote sensing data to define smoke-impacted areas or periods and associate PM monitoring measurements with health outcomes (Section 5.2.2, bullet #2)	Kochi et al. 2012(24)	California, USA	Severe:↑
		Elliott et al. 2013(17)	British Columbia, Canada	Mild: ↑
Retrospective model (Section 5.3)	**PM estimated by empirical modeling (Section 5.3.2, bullet #1)**	Hanigan et al. 2008(33)	Darwin, Australia	Severe:↑
		Delfino et al. 2009(32)	California, USA	Severe:↑
	PM estimated by mechanical modeling (Section 5.3.2, bullet #2)	Henderson et al. 2011(21)	British Columbia, Canada	Severe:↑ Mild: ↑
		Thelen et al. 2013(28)	California, USA	Severe: ↑
Forecasting model (Section 5.4)	**PM predicted by mathematically modeled smoke forecasting system (Section 5.4.2)**	Rappold et al. 2012(40)	North Carolina, USA	Severe:↑
		Yao et al. 2013(22)	British Columbia, Canada	Mild: ↑
Smoke proxy (Section 5.5)	**Number of fires**	Caamano-Isorna et al. 2011(42)	Spain	Mild: ↑
	Burnt area	Analitis et al. 2012(43)	Athens, Greece	Severe:↑

[1]Mild outcomes: Lower birth weight, self-report cardiopulmonary symptoms, medication dispensations and physician visits

[2]Severe outcomes: Cardiopulmonary hospital admissions, emergency room visits and mortality.

↑: Significant association with at least one health outcome examined

-: No significant association found.

5. Summary and implications for public health

A wide range of approaches has been used to assess wildfire smoke exposure in health studies. Information from multiple tools, if available, should be gathered for a comprehensive assessment of exposure levels and durations for public health surveillance. These different sources of information can be weighted by their suitability for different purposes and under different circumstances, based on their strengths and limitations, as summarized in Table 3. While exposure assessment is an important aspect, it should not be the singular base for public health decision making. In other words, actions should not be invoked simply by the level of exposures, but coupled with knowledge and expertise from other relevant local parties, such as professionals in forest fire management, emergency response and meteorology.

The following subsections describe some examples of the current application of exposure assessment tools for public health surveillance, as well as suggestions on how these tools should be used for public health surveillance.

5.1 Routine monitoring

The fact that it is not possible to monitor air quality in every community limits the use of monitoring in public health surveillance. However, for places where monitors do exist, it is the most reliable tool available. These data are usually freely available in near real time and easy to access. The measurements are quantitative and require little expertise to interpret. With sufficient historical records, we can easily establish an algorithm to detect peaks in measurements, such as approaches described in Section 5.1.2.

Monitoring data has been used in public health surveillance in many jurisdictions. It can be simply presented in time-series and combined with health outcome data, such as in the BC Asthma Surveillance System developed for British Columbia (35). Coinciding peaks in monitoring PM and health outcomes can be an indicator of impacts from smoke. Such environment and health surveillance systems are valuable for situational awareness, and can be combined with other information to trigger interventions. Historical PM-health associations can be used to establish thresholds for action, such as Air Quality Index in the US and Air Quality Health Index in Canada, where certain levels of exposure will suggest certain public health actions(44). With the high time resolution (usually hourly) of the monitoring data, different time intervals for average can be used to account for the effects of exposure duration and the short-term high peaks.

5.2 Remote sensing

So far, remote sensing products have been used as supplementary information for many public health jurisdictions. Although some of the products have quantitative measures, they are difficult to interpret and sometimes not relevant to the ground-level exposure. Missing data due to cloud cover also affects their utility in surveillance, which relies on stable and continuous data feed. Nevertheless, they have been used to qualitatively observe and predict fire and smoke behavior (44), making use of their visual feature and global coverage. For instance, in 2012, satellite images and measures were used widely to monitor the long-range transport of wildfire smoke from Siberia to North America.

For regions where very few monitors are available, remote sensing can be an important source of information. For example, in Southeast Asia, with only 14 monitors available in the entire region, maps of fire hotspots and smoke haze are derived from satellite images, coupled with meteorological information. These maps are the major source of information regarding wildfire smoke in the region (61).

5.3 Retrospective modeling

Mechanistic models have seldom been used in real-time surveillance as they require excessive time, resources and expertise to operate and can rarely operate in near-real-time condition. Mechanistic models are more useful for retrospectively analysis, or to assess the potential impacts in hypothetical scenarios under different fire and meteorological conditions.

Empirical models, on the other hand, are more suitable for surveillance purposes. Once developed and automated, they require minimal resources to maintain and provide a continuous data feed in close to real-time. Currently, the available models are developed and used in regions where there is a monitoring network, which provides sufficient historical data to construct the model. Model estimates are used to improve the spatial coverage and resolution for exposure assessment in these regions. For example, estimates from the empirical model developed for British Columbia have been incorporated into a surveillance system to fill in information for areas where monitors are not in place (35).

5.4 Forecasting modeling

For public health surveillance, it is valuable to assess not only the current smoke exposure levels, but also the future levels. Public health actions can be very different for a few hours of smoke exposure compared with several days of exposure to smoke lingering in the region. As a result, tools that can provide prospective information, such as accurate forecasting models, are highly desirable to facilitate decision making.

Forecasting models have been recommended by different jurisdictions to predict the future development of the smoke events (44, 62). They have also been presented as a supplementary information along with monitoring measurements and retrospective modeling estimates (35). So far, most of these forecasting models are still under development and improvement. Uncertainties in these models are usually large and not well understood. Public health actions should not be based solely on forecasts but coupled with current fire and smoke situations observed by other tools. In addition, because of the uncertainties in model performance, forecasts should be used more qualitatively rather than quantitatively. For example, their predictions can be used to identify regions where PM concentrations may potentially be elevated by upcoming smoke relative to current, but not to determine actions according to the exact predicted concentrations (e.g. to evacuate if the PM prediction is over certain level).

5.5 Smoke proxies

Smoke proxies based on fire information, such as number of fires or burnt area in the region, can be useful to quickly determine whether we should be concern about fire and smoke at all. Daily delivery of fire information such as fire hotspot locations, mostly from satellite detections, is available by email subscription from many organizations. In Southeast Asia, daily fire counts in the sub-divisions across the region are updated daily to monitor the trend of fire activity in the region and cumulative daily hotspot counts of the current year are reported and compared with records in previous years to detect abnormality in seasonal fire activities (61). However, if we rely on fire information in the region alone, we are likely to miss smoke long-range transported from distant fires. In addition, although more fires or larger burnt areas are more likely to produce more smoke, the relationship is not definite. Smoke concentrations can be largely influenced by other factors. As a result, these fire proxies should only be used to initiate a more sophisticated investigation on smoke levels with other tools, or at locations without other tools.

Visibility range has been recommended in public health guidelines for many jurisdictions (44, 62, 63), as a proxy for PM levels in communities where monitors are not available. Different ranges of visibility correspond to different PM levels and health messages. Prior to wildfire season, reference landmarks (such as mountain or building at known distance) should be identified. To more systematically monitor visibility, cameras can be set up at locations where multiple reference landmarks are visible, and continuous real-time photos can be taken to assess visibility range. Such a method provides consistent, timely and intuitive information about the smoke condition at relatively low cost. The US EPA has established a network of visibility cameras across the country, producing real-time images with labels of reference landmarks, publicly available online(64).

Table 3. Summary of strengths and limitations for exposure assessment tools

Tool	Strengths	Limitations
Routine monitoring	Reliable and robust; Representative of ground-level exposure; High time resolution; Easy to access and interpret.	Spatially sparse; Overload or malfunction with high concentrations; Not source-specific.
Remote sensing	Sufficient spatial coverage; Good for seeing the "big picture" of fire and smoke trajectory; Capture long-range transport.	Measure smoke at all altitudes, not always representative of ground-level exposure; Missing data due to cloud cover; Good for qualitative but not quantitative use.
Retrospective modeling - Mechanistic	Source specific; High spatial and temporal resolution; Good for scenario planning and retrospective case studies.	Time and resource intensive, not suitable for real-time operation; Require expertise to run and maintain; Uncertainty in model performance.
Retrospective modeling - Empirical	Simple to operate and maintain in near real-time setting; High spatial and temporal resolution.	Require large volume of historical data to construct the model; Require additional investment if there is no existing monitoring network in the region for model construction.
Forecasting modeling	Provide prospective information; High spatial and temporal resolutions.	Uncertainty in model performance; Require expertise and resource to run; Require longer processing time with more fires burning simultaneously. Good for qualitative but not quantitative use.
Smoke proxy - fire information	Easy to access and interpret; Good for initial examination of area of concern.	Not always proportional to smoke emission; Do not consider smoke dispersion and transportation.
Smoke proxy - Visibility range	Provide localized information in high time resolution; Require minimal expertise to measure. Highly correlated with PM concentrations.	Cannot be used at night, dawn or dusk, or when specific landmarks at known distances are not available; The relationship with PM levels influenced by factors such as relative humidity and aerosol hygroscopicity.

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Appendix A: Access to wildfire smoke exposure assessment tools

1. Routine air quality monitoring

Air quality monitoring networks are usually operated by environment departments of local, regional or national governments. Real-time measurements of criterion pollutants for many regions are publicly available. Below are some examples of the data portals in North America and Australia.

US EPA: http://www.epa.gov/airdata/index.html

British Columbia, Canada: http://envistaweb.env.gov.bc.ca/

Ontario, Canada: http://www.airqualityontario.com/history/summary.php

New South Wales, Australia: http://www.environment.nsw.gov.au/aqms/hourlydata.htm

2. Remote sensing

All the remote sensing products we describe in this review are publicly available online or upon request.

MODIS true color image: http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=aeronet

MODIS aerosol optical depth: http://modis-atmos.gsfc.nasa.gov/MOD04_L2/

GOES aerosol optical depth: http://www.ssd.noaa.gov/PS/FIRE/GASP/gasp.html

Hazard Mapping System: http://www.ospo.noaa.gov/Products/land/hms.html

MODIS fire radiative power: https://earthdata.nasa.gov/data/near-real-time-data/firms/active-fire-data

3. Smoke forecasting system

Some smoke forecasting systems provide publicly available forecasts.

BlueSky Western Canada Wildfire Smoke Forecasting System:
http://www.bcairquality.ca/bluesky/west/index.html

US NOAA Smoke Forecasting System: http://www.arl.noaa.gov/smoke.php

Smoke Model for Europe: http://silam.fmi.fi/fires_forecasts/Fires_introduction.htm

4. Smoke proxies

Smoke proxies related to fire information, such as number of fires or burnt area, can be accessed from wildfire management departments or remote sensing products.

Current fires and burnt area in British Columbia, Canada:
http://bcwildfire.ca/hprScripts/WildfireNews/Fires.asp

Current fires in Ontario, Canada: http://www.affes.mnr.gov.on.ca/Maps/Fire/FireMap.html

Active fire mapping, Canada: http://activefiremaps.fs.fed.us/?extent=canada

Active fire mapping, USA: http://activefiremaps.fs.fed.us/#

MODIS global active fire detection: https://earthdata.nasa.gov/data/near-real-time-data/firms/active-fire-data

Visibility range is a localized measure of air quality that can be easily administered by designated personnel in local communities, or the general public. At the same time, networks of visibility cameras have also been set up to provide near-real-time photos online for more systematic evaluations.

AIRNow Visibility Cameras, US EPA: http://www.airnow.gov/index.cfm?action=airnow.webcams

Lower Mainland, British Columbia, Canada: http://www.clearairbc.ca/Pages/default.aspx