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https://doi.org/10.4224/40002655

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Air Treatment Technologies for Shelter-in-Place Scenarios in Response to WUI Fires

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Report No.: A1-015810.1
Report Date: 28 August 2020
Contract No.: A1-015810
Agreement Date: 13 August 2019

National Research Council Canada
Conseil national de recherches Canada

Canada

Sample 1: Used when only one publication format is created.

Cat. No. . NR24-53/2020E-PDF
ISBN 978-0-660-35920-5

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Program: Fire Safety R&D

13 pages

Copy no. 1 of 1

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Table of Contents

List of Figures

List of Tables

Executive Summary

This report discusses the health impact of wildfires smoke on communities situated at the interface between wildland and urban areas, and the use of available air treatment technologies to mitigate this hazard. Wildfire smoke concerns are increasing with the increase of wildfires events frequency, which is partially attributed to climate change. Emissions from wildfires are chemically and physically complex and represent a high health hazard. Most of the health hazards from smoke are caused by the microscopic particles that can trigger heart attacks, breathing problems and other health issues.

In response to wildfires events, communities are either asked to evacuate or seek a shelter-in-place. In order to protect the occupants from the smoke, high Indoor Air Quality (IAQ) should be provided within the shelter. The most commonly used technologies, for air treatment to improve the IAQ, are portable air cleaners and in-duct air filters. However, limited research is conducted to assess the efficiency of these technologies against wildfire smoke. Thus, this report suggests the development of a standard test for assessing air filters against wildfires smoke. Further, the report highly recommends developing guidelines for best practice at homes or community shelters to protect residents from wildfires induced smoke.

The report is structured as follow, first types of shelter-in-place as alternative to population evacuation are presented followed by the discussion of the frequency of wildfires in Canada. Next a detailed discussion of emissions from these fires presented followed by discussing health effects of the exposure to wildfires smoke. Subsequently, current technologies for air treatment are discussed. Finally, international and provincial regulations and guidelines for reducing health risk of wildfires smoke are reported.

1 Introduction

The anthropogenic climate change is increasing the frequency of wildfires and duration of fire season, which is attributed to the high spring and summer temperatures and dry conditions [1]–[3]. Canada has 32.3 million ha of Wildland-Urban interface (WUI), which presents 3.8% of total national land area [4]. Evacuation of large number of people as a consequence of WUI fires is challenging endeavor [5], [6], especially for health care facilities and remote communities. Hence, it is crucial to improve the resiliency of these communities to wildfire disasters.

Recently, the Canadian Forest Service indicated that 60% of First Nations in Canada are located within or intersect with WUI areas. Most of these communities are isolated and, when evacuated, residents are often hosted in unfamiliar towns. An investigation of evacuation actions in Mishkeegogamang Ojibway Nation, Ontario, Canada, showed that more than half of the interviewees did not want to evacuate during Sioux Lookout Fire 35 (SLK 35) wildfire in 2011 [7]. Another study [8] examined the emergency evacuation of Hatchet Lake Denesuline indigenous community in Saskatchewan, Canada, and found that some mothers did not want to evacuate. This might be attributed to several reasons such as, the perception that they were not at risk, the desire to protect home contents and the lack of communication. Other reasons for unsuccessful evacuation might be due to the lack or damage of evacuation routes and the impediment of physical movement.

Evacuation of health care facilities including hospitals, on the other hand, is a complex process as it usually involves patients with impaired mobility and requires highly skilled personnel with special equipment. The decision to evacuate, as such, is often challenging and risky. A recent review of climate change impact on hospitals in California identified the risk of wildfires as the highest concern amongst the effects of climate change on health care facilities [9], [10].

An alternative to evacuation is using shelter-in-place (SIP) strategies. SIP enables the population at risk to stay in their premise of origin or to be relocated to a less vulnerable protected shelter within the threat area until the risks are subsided to an acceptable level. As such, communities subjected to wildfires could seek refuge in either Community Clean Air Shelters (CCAS) or Home Clean Air Shelters (HCAS). Decisions on recommending CCAS versus HCAS require several practical considerations, including:

- The distance that residents may be required to travel to reach CCASs, and their exposures to smoke in transit.
- The mobility of residents, which may be limited for families with small children or elderly residents or who may not be able to walk or drive to a CCAS.
- Added stress to community members who are trying to access CCAS versus remaining at home.
- The benefits of potentially more effective filtration obtained intermittently at CCASs (e.g., malls) versus less effective, but more consistent, filtering obtained in HCAS for extended periods of time.
- How to best encourage community members to go to, and remain in, CCASs if the need is determined; encouraging individuals to remain in CCASs may be a challenge if extended stays are required. If smoke events are expected to persist, HCASs might be a more viable option than encouraging prolonged stays at CCASs. [11]

In all shelter-in-place scenarios, toxic fumes and particulate matter (PM) in the form of smoke serious risk to population should be mitigated. To protect occupants from smoke two possible solutions exist: either a) to completely block the ingress of smoke and products of combustion to the compartment of refuge, or b) to use pressurization to keep the refuge area at a positive pressure to prevent the entry of smoke into the safety compartment. The former approach may be applicable only for purpose-built shelters for a definite period of time due to the consumption of oxygen and increasing carbon dioxide percentage in the air within the shelter. Hence, a continuous flow of oxygen or “clean” air to the shelter will be necessary. For most existing buildings, shutting down the HVAC system could potentially further reduce the indoor air quality. For the latter approach, usually the pressurization needs a make-up air source to keep the compartment effectively pressurized. It is evident that the air that is entering the shelter needs to contain lower levels of pollutants and toxic species.

Various technologies exist and can be used to remove the particulate matter and other combustion products (e.g., carbon monoxide, ozone-forming chemicals, and volatile organic compounds). However, there are no existing specified methods or standards to evaluate air cleaning technologies against wildfire smoke. This presents a significant concern when developing policies and procedures for SIP. Specifically, there is not sufficient information on how effective the prescribed filters are in protecting the indoor air quality (IAQ) in a SIP situation. Moreover, only a few studies have evaluated the use of air filters during wildfire smoke events. Most of the available research has evaluated the use of portable air cleaners in residential settings to reduce $PM_{2.5}$ (Particulate Matter smaller than 2.5 micrometre) related to wood smoke, environmental tobacco smoke and general indoor air pollution.

2 Wildfires in Canada

Several studies have investigated the effect of climate change on wildfires in Canada [12]–[17]. They all predicted an increase of fire events across the country as the climate changes. Boulanger et al. [17] estimated the increase of the annual area burned by 1.5–4 times across the country by the end of the century while Flannigan et al. [18] reported an increase of 1.7–2.2 times over the same period. Fire season length in Canada is also predicted to increase by approximately 30 days over this period [19].

There are about 5000-6000 wildfires in Canada each year which burn on average 2.5 million ha/year [20]. Figure 1 shows the annual number of hectares burned in Canada from 1982-2018 [21]. Generally, the area burned during 2010-2018 is more than that during 2000-2010. This is probably attributed to the impact of climate change.

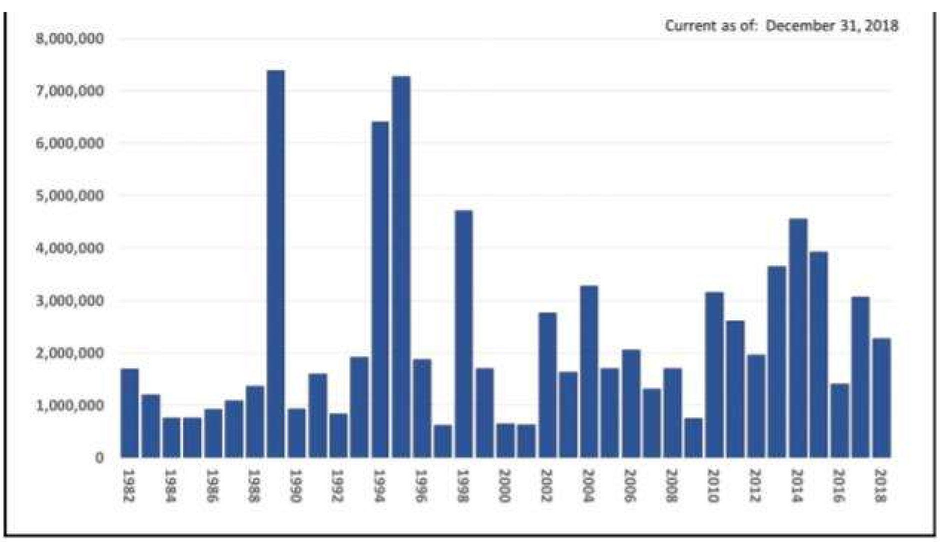

Figure 1. Area burned annually in hectares for Canada from 1982-2018 [21]

Kirchmeier-Young et al. [3] performed an event attribution analysis to investigate the contribution of anthropogenic climate change on the extreme wildfire season in British Columbia (BC) during 2017. They used the decades 2011–2020 and 1961–1970 to represent the current climate and an alternative climate with reduced influence of emissions on population; respectively. Their findings showed a significant anthropogenic contribution to the risk of extreme fire weather, based on multiple metrics and event definitions.

In 2018, The British Columbia wildfire service reported 2,117 fires which consumed 1,354,284 ha of land and affected 2,211 properties. The cost of suppression reached $615 million.

In 2019, wildfires across Canada forced evacuations of communities caught in the path of the flames and heat. The Red Lake 23 wildfire has grown to 719 square kilometres . The Canadian Red Cross reported that residents from First Nation communities in northeastern Manitoba and northwestern Ontario had to evacuate, and special air quality statements for both parts of the provinces were issued during July 2019.

Direct fatalities from wildfires are caused by suffocation, burns or injuries. However, emissions from wildfires can be toxic and travel long distances. They can affect communities that are far from the wildfire event and cause acute and chronic health issues.

3 Emissions of WUI Fires and Their Effect on Air Quality

Wildland fires generate massive emissions into the atmosphere over a short period of time and increase local and distant concentrations of PM. Emissions from wildfires are physically and chemically complex. The main emissions, negatively affecting the air quality, are fine and coarse PM, carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), volatile organic carbon (VOC), in addition to many other air toxins [22]. Emissions also contain a number of trace metals. Moreover, secondary pollutants such as organic aerosols and ozone generated by the photocatalytic reaction of NO_x and VOCs in the atmosphere affect the air quality [23].

3.1 Components of Wildfire Smoke

3.1.1 Particulate Matter (PM)

Particulate matter in smoke is all the suspended solid and liquid particles in the air. They consist of organic and inorganic substances and either directly emitted to the atmosphere (primary PM) or produced through chemical reactions such as combustion into the atmosphere (secondary PM).

PM are usually classified according to their size, which determines their hazardous extent on humans and environment. $PM_{2.5}$ are particles of median diameter less than or equal to 2.5 µm. They can be easily inhaled and reach the lungs, which consequently affect the heart and lungs and cause serious health effects. There is ample evidence that shows that particle pollution exposure causes a variety of problems, including premature death in the population of people with heart or lung disease, nonfatal heart attacks, aggravated asthma, etc. [24]. These effects are non-uniform amongst the population and affect the vulnerable populations such as people with heart diseases, children, and elderly disproportionally. Particle pollution also cause visibility issues [24]. Thus, air quality standards set limits on the concentrations of these PM in the atmosphere and impose regulations to imply these limits.

3.1.2 Carbon dioxide (CO_2), Carbon monoxide (CO) and methane (CH_4)

Carbon dioxide and methane are greenhouse gases. Generally, forests play a predominant role in the carbon cycle through absorption of CO_2, carbon storage and emission of CO_2. Fire is a major driver in the carbon balance in Canada's forests through forest renewal and determination of the age of forests stands [25]. CO_2 is considered as the main culprit of climate change and 8 billion tons of CO_2 per year are estimated to have been emitted from wildfires for the past 20 years, which is around 5-10% of annual global CO_2 emissions each year [26]. This estimation of CO_2 emissions per year takes into account the amount produced during post-fire regrowth.

Methane is almost 30 times more potent than CO_2 as a heat-trapping gas. CH_4 reacts with hydroxyl radical in the troposphere producing water vapor and CO_2. The life time of CH_4 in the atmosphere was estimated to be 9.6 years as of 2001; however, increasing methane emissions over time reduce the concentration of the hydroxyl radical in the atmosphere. It also increases smog.[27]

Carbon monoxide does not directly contribute to climate change, but it affects the concentrations of CO_2 and CH_4. However, CO is toxic and breathing CO can cause headache, dizziness, vomiting, and nausea. If CO levels are high enough, it may lead to unconsciousness or death. Exposure to moderate and high levels of CO over long periods of time has also been linked with increased risk of heart disease.

3.1.3 Volatile Non-Methane Organic Compounds

This includes alkanes, alkenes, aldehydes, ketones, organic acids, furans, dioxins and aromatics. They are considered as ozone precursors through atmospheric photochemical reactions. They also contribute to the formation of secondary aerosols. Finally, some of them are harmful to human health [28].

3.1.4 Nitrogenous Compounds

Biomass combustion takes place at relatively low temperatures (compared to fossil fuel combustion); so atmospheric N_2 doesn’t react and most of the nitrogenous emissions are produced from the fuel nitrogen. NO, NO_2, N_2O, and molecular N_2 are produced during flaming combustion, while NH_3, amines and nitriles are released during smoldering [29]. NO is the most abundant N-species in the emissions, while NO_2 represents around 10% [30], [31]. During smoldering, NH_3 is the dominant nitrogenous emission [30]. Laboratory tests showed that 30-40% of the fuel nitrogen is released in the form of N_2 [32]. However, it is impossible to detect concentration of N_2 from real wildfires due to the abundance of atmospheric N_2. Hydrogen cyanide (HCN) has been proposed as a valuable tracer of biomass burnings since it can be determined by remote sensing from space [33].

3.2 Emissions at Different Stages of Wildfire

Thermal degradation of biomass starts by a drying step in which water and volatiles are released, followed by pyrolysis, during which thermal cracking of the fuel molecules occurs. Char, tar volatile compounds (a flammable white smoke) are released at this stage. When temperatures in the fuel bed exceed 450 K, the process becomes exothermic and glowing combustion starts at ~ 800 K. More tar and volatiles are produced at this stage and form a flammable mixture with air. This mixture easily ignites and flaming combustion takes place. At this stage, oxidation of the relatively complex species produced during pyrolysis occurs and CO_2, H_2O, NO, N_2O, N_2, and SO_2 are produced. Depending on the interaction between chemical kinetics and physical dynamics in the flame, intermediate products of flame radical chemistry, like CO, CH_4, H_2, C_2H_4, C_2H_2 and PAH are also released during this stage. Flaming combustion stops when all volatiles are released from the near-surface of the fuel. At this phase, smoldering begins and the energy is produced via the gas-solid reaction between atmospheric oxygen and char. This mainly produces CO at <850 K in addition to large amounts of incompletely oxidized pyrolysis products. This phase is responsible for most of the fire emissions.[28]

In wildfires, all these combustion stages take place simultaneously and their combined emissions are released into the smoke plume. However, smoldering can take place for days or even weeks. Thus, it is difficult to separate the emissions in each stage in real airborne measurements. However, each vegetation type has a characteristic fuel type which tends to have a specific flaming to smoldering combustion behaviour and dictate the composition of the fire emissions. For example, savanna flaming combustion dominates and the emission factors for reduced species are fairly low [29]. Nevertheless, other factors (moisture content of fuel, terrain slope, and wind direction relative to flame propagation) may interfere and alter the emissions factors of a vegetation.

3.3 Emission Factors

One of the terms frequently used to characterize emissions from fires is the emission factor, which is defined as the amount of a compound released (M_x) per amount of dry fuel consumed ($M_{biomass}$) [29]. This term is calculated using the carbon content of the biomass burned and the combustion efficiency of the fire. Both parameters are well-known in laboratory experiments, however they are difficult to establish in the field [29].

$$EF_i = \frac{M_i}{M_{biomass}} = \frac{M_i}{M_c}[C]_{biomass}$$

where EF_i is the emissions factor of species i. M_i , $M_{biomass}$ and Mc are the mass of species I (g), biomass and carbon emitted; respectively. $[C]_{biomass}$ is the carbon concentration in the biomass burned.

The total carbon emitted is estimated by adding the measured concentrations of CO_2, CO, hydrocarbons and PAH, when this information is available. A fuel carbon content of 45% is usually assumed (the typical carbon content of fuels 37-45 %) when fuel and residue data at the ground are missing [29]. The emission factors of compounds that contain only C, H and O are predominantly a function of the combustion process. Charcoal burning is an exception due to its high carbon content. The emission of substances containing minor elements, such as nitrogen, sulfur, and the halogens, is determined both by the concentrations of those elements in the fuel and by the combustion conditions.

Several studies [34]–[36] measured the EF of several gases and particles from Canadian wildfires. Based on these data and others, Andreae and Merlet [29] compiled the emission factors from 130 publications for 7 types of biomass burning (Savanna and Grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, charcoal burning and agriculture residues). They provided data for over 90 species (CO, CO_2, CH_4, alkanes, alkenes, aromatics, aldehydes, furans, PAH, etc.) When more than 2 values were available for a given species and burning type, the results were given as means and standard deviations (x + s). In the case of two available values, they were provided as a range. For single measurements, they assumed that the uncertainty is not less than a factor of 3. When measured data about species were missing, they used estimates. Their estimates were based on the following extrapolation techniques:

(1) For species not closely tied to the smoldering stage and where information was available for most but not all fire types, a weighted estimate was calculated from the averages given for those fire types where data were available. The weighting was based on the global amount of carbon burned in each fire type.
(2) The emission factors of species that were predominantly emitted in the smoldering phase were estimated using the fact that they tend to be closely correlated to the emission factor for CO. For this purpose a mean ratio of EF_x/EF_{co} was calculated from the available data and multiplied by the EF_{co} of the fire types for which EF_x was not measured.
(3) For the remaining cases, where there was no information to derive an objective estimate, a best guess was provided.

Emission factors for temperate forests and rangelands from literature are reported in Table 1 [28]. Emission factors for boreal forests, which are more relevant to Canadian wildfires are reported in Table 2.

Table 1. Emission Factors for temperate forests and rangelands [28].

Species	Temperate forest	Temperate rangeland
1,3-pentadiene (C5H8)	0.028	0.01
1,3-cyclopentadiene (C5H6)	0.025	0.03
.Hexane (C6H14)	0.005–0.033	0.006

Methylcyclopentane	0.006	
1-hexene (C6H12)	0.102	0.03
trans-2-hexene (C6H12)	0.014	
cis-2-hexene (C6H12)	0.004	
2-methylpentene (C6H12)	0.009	
Heptane (C7H16)	0.004–0.032	0.005
Octane (C8H18)	0.017	0.003
1-octene (C8H16)	0.018	0.003
1-nonene (C9H18)	0.019	0.003
Decane (C10H22)	0.027	0.002
Benzene (C6H6)	0.250–0.440	0.22
Toluene (C7H8)	0.150–0.510	0.13
mþp-xylene (C8H10)	0.171	0.039
o-xylene (C8H10)	0.051	0.009
Xylenes (C8H10)	0.020–0.051	0.02
Methanol (CH4O)	0.31–2.03	0.14
Formic acid (CH2O2)	1.17	
Acetic acid (CH4O2)	3.11	
Formaldehyde (CH2O)	2.25	
Acetaldehyde (C2H4O)	0.24	0.25
Propanal (C3H6O)	0.035	0.01
Propenal (C3H4O)	0.123	0.08
2-methylpropanal	0.206	
2-methylbutanal	0.015	
Acetone	0.347	0.25
2-butanone (C4H8O)	0.4	0.26
2,3-butanedione	1.5	
2-pentanone (C5H10O)	0.079	0.01
Cyclopentanone (C5H8O)	0.014	
Furan (C4H4O)	0.445	0.1
2-methyl-furan (C5H6O)	0.521	
3-methyl-furan (C5H6O)	0.052	
2-ethylfuran (C6H8O)	0.006	
2,5-dimethyl-furan	0.053	
2-vinyl-furan (C6H6O)	0.013	
Benzofuran (C8H6O)	0.038	
Nitrogen oxides (as NO)	1.7	
Nitrous oxide (N2O)	0.16	0.32
Ammonia (NH3)	0.56–1.13	
Carbonyl sulfide (OCS)	0.03	0.01

PM2.5	11.775.0	9.7±4.3

Table 2. Emission Factors for boreal forests.

Species	Emission Factor	References
Methanol (CH4O)	1.23–1.57	[37]–[41]
Formic acid (CH2O2)	0.71–1.57	[38]–[41]
Acetic acid (CH4O2)	1.61–3.38	[38]–[41]
Formaldehyde (CH2O)	1.50–2.38	[38]–[42]
Nitrogen oxides (as NO)	1.1–3.3	[39], [41]–[45]
Nitric oxide (NO)	1.5–2.3	[40], [41], [46]
Nitrous oxide (N2O)	0.14–0.41	[35], [43], [44], [47], [48]
Ammonia (NH3)	0.10–0.49	[38]–[44]
PM2.5	1.5–7.2	[46], [49]

4 Health Effects of Wildfire Smoke

Smoke from wildfires was once considered a fleeting nuisance except for the most vulnerable populations. But it's now seen in some regions as a recurring and increasing public health threat. Most of the health hazard from smoke are caused by the microscopic particles that can trigger heart attacks, breathing problems and other health issues. The particles, about 1/30th of the diameter of a human hair, penetrate deeply into the lungs to cause coughing, chest pain and asthma attacks. Children, the elderly and people with lung diseases or heart trouble are most at risk. Moreover, fine particles can lead to premature deaths.

Reid et al. [50] thoroughly reviewed the literature to investigate the effects of exposure to wildfire smoke on health and identify susceptible populations. They found consistent evidence of associations between wildfire smoke exposure and respiratory morbidity in general. They recommended further research to determine whether wildfire smoke exposure is consistently associated with cardiovascular effects, specific causes of mortality, birth outcomes, and mental health outcomes.

Several studies investigated populations who might be at greater risk from the adverse health effects of wildland fire smoke or $PM_{2.5}$. Susceptible populations include people with pre-existing respiratory disease, middle-aged and older adults [50], [51], children, pregnant women and fetuses [50]. Recent studies [52], [53] showed higher risks for those with indicators of lower socio-economic status.

Moreover, the travel of smoke and wildfire emissions imposes transboundary air pollution on public health. For example, Le et al. [54] investigated the health effect of long-range transported smoke from the Quebec wildfires in 2002. Their results showed significant increase in respiratory and cardiovascular hospital admissions for the elderly across the east coast of the U.S. as far south as Washington D.C., USA.

Tinling et al. [55] studied the relationship between PM from wildfire and respiratory health during the 2012 Pains Bay peat fire in eastern North Carolina. They concluded that there was an increase of respiratory/other chest symptoms and upper respiratory infections in adults and children when exposed to wildfire-$PM_{2.5}$. This was also observed by Vicedo-Cabrera et al. [56] when they surveyed Valencia birth cohort for health effects after the 2012 wildfire in Valencia, Spain. In addition, Tinling et al. showed that as daily $PM_{2.5}$ increased, hypertension and cardiac outcomes increased on the day of exposure and up to two days after exposure.

A study conducted in Taipei, Taiwan, between 2013 and 2014, in which the authors tested the effect of air home air filtration on biomarkers of inflammation, oxidative stress and blood pressure. The crossover intervention study showed that increased exposure to $PM_{2.5}$ and total VOCs increased inflammation, oxidant stress and blood pressure, and that in-home air filtering decreased biomarkers of inflammation, oxidative stress and the acute phase reactant fibrinogen .

Landscape[1] fire emissions are an important contributor to global mortality. Johnston et.al [58], estimated the exposure to landscape fires was attributable to approximately 350,000 deaths (260,000–600,000) annually around the globe. Forest fires are approximately 14% of landscape fires [59]. Ford et al. [60] found that in contiguous United States approximately 138,000 deaths (5.1% of total deaths) are attributable to total $PM_{2.5}$ (Particulate Matter smaller than 2.5 micrometre) in the early 21st century with 17,000 (0.7%) of these deaths attributable to fire-related $PM_{2.5}$.

Table 3 shows a summary of the health hazards associated with PM from wildfires according to recent research [52], [61].

Table 3. Associations between Wildfire-PM or Smoke Exposure and Health Outcomes [52], [61].

Outcome	Direction of association	Strength of evidence
Mortality		
All	Increased	Strong
Respiratory	No assoc.	
Cardiovascular	Increased	Inconclusive
Morbidity		
Respiratory	Increased	Very strong
Asthma	Increased	Very strong
COPD	Increased	Very strong
Infection	Increased	Strong
Cardiovascular	Increased	Inconclusive
Acute MI	Mixed	Inconclusive
Heart failure	Mixed	Inconclusive
Cardiac arrest	Mixed	Inconclusive
Hypertension	Mixed	Inconclusive
Arrhythmia	No assoc.	
IHD	Increased	Inconclusive
Angina	Increased	Inconclusive
Cerebro-vascular	Mixed	Inconclusive

5 Air Pollution Control Technologies

[1] Landscape fires include wildfires, prescribed forest fires, tropical deforestation fires, peat fires, agricultural burning, and grass fires. Fires in grasslands and savannas contributed 44% of total carbon emissions, while tropical deforestation and degradation fires contribution was 20%, woodland fires mostly confined to the tropics, 16%, forest fires mostly in the extratropics, 15%, agricultural waste burning 3%, and tropical peat fires (3%) [57].

In order to protect residents from health hazards of wildfire smoke, it is required to improve the indoor air quality during these events. The main focus of indoor air quality control is the particulate matter. Air filters can help to lower indoor concentrations of pollutants and potentially reduce adverse health effects. Communities subjected to wildfire smoke are encouraged to have either a HCAS which utilizes portable or in-duct filtration in homes, or a CCAS which has well-maintained heating, air conditioning and ventilation (HVAC) system.

5.1 Classification of Air Filters

Filters can be standalone units (portable) or installed as part of HVAC system in buildings (in-duct filtration). In-duct devices are designed to clean air for the entire building, while portable devices are designed to clean air for a single room in a building. Each type of setup is associated with advantages and disadvantages. In-duct devices may be associated with higher operating costs and will only filter air when the HVAC system is turned on. A portable air cleaner, while having lower operating costs, is designed to clean the air in the room in which it is placed, although studies have found that, in some conditions, portable units can reduce the entire house's $PM_{2.5}$ levels [62]. In addition, a portable air cleaner must be sized appropriately for the room in which it is used in order to be effective.

Based on operating technologies, air filters can be classified into: i**) mechanical filter-based**, which incorporate the use of flat, pleated, or HEPA filters. HEPA filters are the most efficient ones that can capture at least 99.97% of 0.3 μm particles; **ii) electrostatic precipitators**, which operate by charging the incoming stream of particles and collecting them on an oppositely charged metal plate within the device; **iii) ion generators**, which also charge particles, but may not collect particles within the cleaner. Instead, charged particles deposit onto room surfaces (e.g. walls, floor, etc.) where they are no longer airborne or inhalable, but can be re-entrained to air if disturbed.; **iv) hybrid devices** using more than one type of technology. Only filters incorporating activated carbon are capable of removing some gases.

However, some air cleaning technologies may have negative health impacts. Particularly, units which produce ozone either intentionally (e.g., ozone generators) or as a by-product (e.g., some electrostatic precipitators). Ozone can cause respiratory irritation, particularly when used in homes with low air exchange rates [63]. Thus, Health Canada [64] advises against the use of ozone generators in residential settings. Moreover, ozone can react with other compounds in indoor air to form new pollutants; for example, ozone can react with terpenes to form submicron particles and with nitric oxide to form nitrogen dioxide.

5.2 Rating of Air Filters

The effectiveness of any air cleaning device depends on two factors: i) the efficiency of the device at removing a specific pollutant, and ii) the volume of air that is cleaned by the device. These factors in turn are influenced by variables such as air exchange within the room or building, the levels of pollutants in the air, the location of the device within the room and the size of the room for portable air cleaners. Two industry rating systems have been developed to provide performance measures of filters: the Minimum Efficiency Reporting Value (MERV) [65] for in-duct HEPA filters and the Clean Air Delivery Rate (CADR) [66] for portable HEPA filter devices. The MERV rating system, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [65], assigns a number between 1 and 16 to a filter based on a performance test comparing concentrations of particles, sized between 0.3 and 10 μm, upstream and downstream of the filter. A rating for each filter corresponds to the particle removal efficiency of the filter, based on the specific size category of particles tested. The CADR ratings are assigned to a device for three pollutants: tobacco smoke, dust, and pollen. The efficiency of the device is based on the difference between pollutant concentrations in a test chamber with and without air cleaner use. These efficiencies are then translated to CADR ratings which describe efficiencies at various room sizes. Filters become saturated with use and must be replaced according to manufacturer instructions. Replacement frequency depends on the frequency and duration of use, as well as pollution concentrations for which they are used.

Another quantity used in investigating the effectiveness of air filter is infiltration efficiency of particles during periods with and without filter use. Infiltration efficiency is a unit-less quantity defined as the fraction of the outdoor concentration of a pollutant that penetrates indoors and remains suspended [67].

5.3 Portable vs In-Duct Air Filters

Few studies have investigated the use of air filters to reduce PM generated from wildfires (e.g., [62], [68]). No studies have investigated the use of in-duct filters to reduce infiltration of wildfire smoke into homes or buildings.

Myatt et al. [69] modeled the effectiveness of high efficiency electrostatic precipitator in-duct filter and portable HEPA filter air cleaners in reducing levels of several asthma triggers, including environmental tobacco smoke (ETS) particles, in one and two story single family homes. Use of in-duct filters was estimated to result in 90–98% reductions in ETS, while use of portable HEPA filter air cleaners were estimated to result in reductions of ETS between 70–80%. Macintosh et al. [70] concluded that high efficiency in-duct filters were more effective than portable filters at removing particles in a home. Generally, in-duct filters are expected to provide higher removal rates of particles since they filter air in the whole building in contrast to portable filters which are designed to clean air in a single room. However, the use of in-duct filters may not be feasible in all settings. For example, most residential HVAC systems are not designed to handle the added energy demands required of HEPA filters, due to increased airflow resistance [11].

6 Existing Guidelines and Regulations

Internationally, the Australian Building Codes Board (ABCB) [71] has a performance standard for private bushfire shelters. They recommend the use of adequate seals around typical openings like doorways, glazed panels and service penetrations to avoid the entry of wildfire smoke. In addition, sealed private bushfire filters must have sufficient air supply to provide a tenable environment for the required period of occupation. The standard provides a table of the theoretical duration (hrs) of occupancy as a function of the volume of the shelter (m^3) and number of occupants. They also advise providing a sealed ventilation system that may be opened after a fire front has passed and when the external air has sufficient quality.

The United States Environmental Protection Agency (EPA) [72] provides a guide for wildfire smoke for public health officials. This Guide provides the information needed by state, tribal and local public health officials to be prepared for smoke events and to communicate health risks and take measures to protect the public during the wildfire smoke events. The document suggests specific strategies to reduce exposure to wildfire smoke as follows:

1- Stay indoor
   It is recommended to stay in tightly-closed, air-conditioned homes in which the air conditioner recirculates the air. Doors and windows should be always closed during the wildfire smoke event; however residents are allowed to air out their homes to reduce air indoor pollution.
2- Reduce physical activity to lower the dose of inhaled air pollutants and reduce health risk.
3- Reduce other sources of indoor air pollution such as smoking, cooking, spraying aerosol, wood-burning stoves
4- Use air conditioners and filters
   Generally, homes with air conditioners have lower concentrations of PM from outdoors relative to homes that use windows and doors for ventilation. Central heating and air conditioning systems (and some

room air conditioners) contain filters that remove some airborne particles. It is recommended to use pleated medium or HEPA filters.

5- Use air cleaners, which should be appropriately chosen for the size of the indoor environment (either a room or whole home). The location and operation of the air cleaner should be optimized to maximize particle removal. It is recommended to place the air cleaner in the most used room and to operate it at highest fan speed and continuously. Air cleaners can be used with central air system filter.
6- Use humidifiers
The benefit of using humidifiers during a smoke event is not studied yet. However, humidifiers decrease PM through condensation and absorption and reduce eyes and airway irritation.
7- Create a clean-air room at home
This is important in case one of the residents is within the at-risk category (e.g., elders, with respiratory issues, pregnant women).
8- Choose between leaner air shelters and cleaner air spaces
The choice between staying at home in a cleaner-air room or going to cleaner air shelter or space depends on the willingness to drive and the stress of evacuating for long stay.
The public health authorities in area that are in risk of wildfire smoke events should a priori identify areas/buildings that can be used as shelters during the event. The guide lists specifications for a cleaner air shelter. It should be air-tight with tightly sealed windows and doors and public access (e.g., libraries, school gymnasiums, civic auditoriums). It should have a central air conditioner with high efficiency filtration (MERV 13 or higher). It could have air cleaners where appropriate. The shelter should handle the increased cooling load due to the high occupancy. The shelter should have carbon monoxide detectors, radio for communicating the updates and suitable services and facilities.

Other suggestions to reduce the risk of wildfire smoke are using respiratory protection equipment (masks), avoiding periods of high smoke levels during the day, cancelling outdoor events and evacuation.

There is no Canadian guide or national code for provisions related to shelter-in-place or wildfire smoke. The Canadian National Building Code (NBC) states that the outdoor air quality conditions of the building site shall conform to appropriate provincial or territorial requirements. In the absence of such requirements, the air pollutants in these areas shall be equal to or less than the maximum acceptable levels stated in the Canada-wide Standards. Only standards for PM and ozone have been developed, which are:

a) a 24 hour average of 30 $\mu g/m^3$ for particulate matter that is 2.5 µm or less in diameter ($PM_{2.5}$), and
b) an 8 hour average of 65 ppb (part per billion) for ground-level ozone.

In case the outdoor air quality conditions don't meet the above mentioned requirements, ventilation shall be provided by a ventilation system designed to include devices that reduce particles and gases to the indicated levels.

Moreover, the NBC states that the outdoor air at the local area of the building site, including its immediate surroundings, should be assessed to identify the levels of contaminants that may be of concern for allowing occupants to enter the building. This includes emission from wildfires (even if this is not explicitly stated in the code). Factors that can influence the infiltration of contaminants, such as the building's geometry and prevailing winds and seasonal activity in the local area, should also be considered. Features can be incorporated in the design of the building to mitigate the effects of the identified contaminants of concern to the building occupants.

On the provincial level, Manitoba, British Columbia and Alberta have their own guidelines to protect the public from wildfire smoke. Manitoba Health published Interim guidelines for Protecting Community Health and Wellbeing from wildfire smoke. The main objectives of the guidelines are to support the health sector, communities and other stakeholders to communicate health risks and recommend actions or precautions to protect people from wildfire smoke exposure. The guidelines set criteria for selecting cleaner air shelters based on accessibility, size, tightness, HVAC system, ventilation, facilities and communications. They recommend the use of air tight buildings to minimize the air exchange between indoors and outdoors. Also, the shelter should be able to isolate quickly from the HVAC system to prevent the entrance of the smoke to the shelter. They classify the shelters into: ventilated and pressurized with filtered air, ventilated with little or non- pressurized filtered air, and non-ventilated (sealed) filters. However, the guidelines don't provide any recommendations for the type of air filters to be used in any of these shelters.

British Columbia (BC) provides guidance for Public Health Decision Makers during wildfire smoke events [73]. The guide provides BC with tools for situational awareness, i.e., smoke and health surveillance. It also summarizes the evidence for effectiveness of intervention measures to protect public health. The interventions proposed by the guide are similar to those of the EPA guide.

Alberta incorporates a Simplified Wildfire Smoke Guide [74] to provide consistent and specific messages, resources and information to help organizations in planning for and responding to wildfire smoke events. The main focus of the guide is communicating and informing the public about the effects of wildfire smoke on health. The guide provides some recommendations to lower the health risk of smoke exposure, which are adopted from the EPA guide.

All the aforementioned guidelines recommend the availability of cleaner air shelters or cleaner air rooms within the house in areas which are prone to wildfire smoke. They suggest the use of air filters or cleaners in order to provide an adequate environment. However, the effectiveness of these filters against wildfire smoke is not well-understood. Moreover, the main concern of these guidelines was the PM. However, recent studies show that PM from wildfire smoke are more hazardous than just the PM from anthropogenic activities [75] , which might be attributed to the adsorption of VOC from wildfire emissions on the surface of the PM.

7 Conclusions and Future Work

Climate change has greatly contributed to the increase of wildfires events in Canada and subsequently the increase of associated smoke emission. Wildfire smoke consists of many emissions including but not limited to volatile organic compounds (VOC) and particulate matter (PM). Many of these emissions are associated with acute and chronic diseases. Smoke can travel long distances and affect communities which are not even subjected to wildfires. Thus, it is crucial to ensure clean air homes or shelters to protect communities from wildfire smoke and its hazards.

The main air treatment technologies currently available are either portable air filters or in-duct air filters. Generally, these filters are not tested against wildfire smoke and designed mainly to filter PM. Moreover, the NBC sets requirements only for ozone and $PM_{2.5}$. Recent studies at the British Columbia Center for Disease Control (BCCDC) show that the hazard from wildfire $PM_{2.5}$ is higher than that from regular $PM_{2.5}$, which might be attributed to the interaction between wildfire VOC and $PM_{2.5}$.

Accordingly, this report suggests the development of a standard test for assessing air filters against wildfires smoke. In addition, concentrations of VOC should also be considered as a potential health hazard that needs to be regulated. Finally, it is highly recommended to develop guidelines for best practice for homes or community shelters to protect residents from wildfire smoke.

An indirect objective of this work was to highlight the issue of indoor air quality during wildfires and the research gaps and needs. That was successfully achieved since the project team was approached by Health Canada for future collaboration and expansion of the work presented in this report and the experimental test report.

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