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Review

Long-term health effects of wildfire exposure: A scoping review

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ABSTRACT

Wildfires pose a number of acute and chronic health threats, including increased morbidity and mortality. While much of the current literature has focused on the short-term health effects of forest fires and wildfire smoke, few reviews have sought to understand their long-term impact on human health. This scoping review aims to map the state of evidence as it pertains to the long-term health effects of wildfires, including physical health, mental health, and healthcare costs. A literature search identified 17 research studies meeting inclusion and review criteria. Descriptive and thematic analyses were conducted and synthesized in a narrative form for the following health topics: premature mortality; increased morbidity including respiratory disease, cardiovascular disease, cancer, mental health, and other health outcomes; and health-related economic outcomes or healthcare costs. The resulting evidence revealed limited papers, many of which were of low or mixed quality, that pointed to increased population-level mortality due to wildfire exposure and increased respiratory morbidity. While the results of lung cancer research were mixed, exposure to $PM_{2.5}$ and chemicals in wildfire smoke were correlated with an increased risk of cancer of all types. Future research should include prospective longitudinal studies and collection of demographic information to assess the impacts of wildfires on the most vulnerable, expand the evidence-base for the mental health consequences of wildfire events, and include more research in low- and middle-income countries.

1. Introduction

Wildfires are increasing in size and frequency worldwide, due in part to the hotter and drier conditions caused by global climate change [1,2]. While heat from fires can cause bodily injury, the smoke is also concerning due to the large amounts of carbon dioxide, carbon monoxide, and fine particulate matter released into the air as vegetation burns [1]. Previous research and literature reviews have focused on acute health effects immediately following a wildfire, such as reduced lung function, and exacerbation of chronic lung disease [3,4]; as well as neurological and cardiovascular effects and increased mortality [4]. In the U.S., the nine most devastating fire seasons have occurred since 2005, when record keeping began [5]. To date, the record-setting 2020 and 2021 fire seasons in the western U.S. have resulted in 7.7 million acres burned and poor air quality across the nation [6–8]. Historically dry conditions brought on by drought and compounded by record-breaking heat wave events, all due to a changing climate, are responsible for fires spreading more quickly and burning more land area [9,10]. However, as the risk and extent of wildfires, particularly in the western U.S., continues to increase, it is imperative that research shift beyond the acute effects of wildfire exposure to the longitudinal health outcomes of populations exposed to wildfires and wildfire smoke.

Wildfire smoke contains a number of components known to be harmful to human health, including fine particulate matter, carbon monoxide, ozone, and many hazardous air pollutants (HAPs) [11]. The known health effects of exposure to wildfire include increased respiratory morbidity, including respiratory infections, asthma, chronic obstructive pulmonary disease, and all-cause mortality [12]. Fine particulate matter, such as $PM_{2.5}$, refers to particles which are 2.5 micrometers in diameter or smaller. The particles can be made up of hundreds of different chemical compounds, and once inhaled can cause cardiovascular disease, lung disease, or premature mortality [13]. $PM_{2.5}$ is the primary air pollutant of concern in wildfire smoke [11]. Within the contiguous U.S., it is expected that $PM_{2.5}$ levels due to wildfires will increase 55–190% by 2100, accounting for over 50% of all ambient $PM_{2.5}$ [14].

CDN, Canadian dollars; COPD, Chronic obstructive pulmonary disease; GAD, Generalized anxiety disorder; GCM, General circulation model; GHG, Greenhouse gas; HAP, Hazardous air pollutants; IFLS, Indonesian Family Life Survey; MDD, Major depressive disorder; PM, Particulate matter; PTSD, Post-traumatic stress disorder; SF-36, Short Form 36 Medical Outcomes Survey; USD, U.S. dollars

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Table 1
Selection of wildfire events included in the scoping review. Selection includes the wildfire event, the location of the event, the acres burned (as an estimation, by the source provided), the number of reported casualties, the cost of the event in local currency, and the studies which focused on the event.

Wildfire Event	Location	Acres Burned	Reported Casualties	Estimated Cost of Wildfire Event*	Studies Which Observed This Wildfire
1997 Indonesian forest fires	Indonesia	20 million [36]	240 [37]	$5 billion USD [36]	Kim et al., 2017; Tan-Soo & Pattanayak, 2019
2009 Black Saturday bushfires	Victoria, Australia	1.1 million [38]	173 [38,39]	$4.4 billion AUD [39]	Wasiak et al., 2013
2014 Northwest Territories fires	Northwest Territories, Canada	8.4 million [40]	0 [40]	$55 million CAD	Dodd et al., 2018
2016 Fort McMurray wildfire	Fort McMurray, Alberta, Canada	1.5 million [41]	2 [41]	$3.6 billion CAD [41]	Agyapong et al., 2020; Brown et al., 2019a; Brown et al., 2019b; Moosavi et al., 2019
2018 Woolsey fire	Woolsey Canyon, California, US	97,000 [42]	3 [42]	$4.2 billion USD [43,44]	None – included as reference

In an effort to understand the future impact of these increasingly frequent natural disasters, several studies have sought to assess current and projected human exposure to wildfire smoke. A recent study predicts that the current rate of population exposure to wildfire smoke (less than 10 per 1,000 persons exposed from 1981 to 2010) will increase to between 12 and 20 per 1,000 persons across Europe in the years 2071–2100 [15]. Mendoza et al. [16] found that at baseline, $PM_{2.5}$ indoors is equal to 25–33% of the $PM_{2.5}$ outdoors; however, indoor $PM_{2.5}$ pollution increases to 77–78% of that found outdoors in the presence of wildfire activity. Another study found that while wildfires burned outdoors, ambient $PM_{2.5}$ levels increased to the 90th percentile and correlated with increased levels of ambient carbon monoxide (CO), ozone (O_3), and nitric oxide (NO) [17].

Previous longitudinal studies have focused on the long-term health effects of occupational exposure to wildfires in firefighters, a vulnerable group characterized by chronic exposure to wildfire smoke. A systematic review found that occupational exposure to smoke may increase the risk of hypertension [18]. The review did not, however, find sufficient evidence to comment on the long-term respiratory impacts and increased cancer risk of firefighters, possibly due to the challenges of following firefighters from one season to the next, leading to poor follow-up.

There are additional challenges to understanding the health effects of wildfires. Firstly, the combination of pollutants in smoke, such as fine particulate matter and HAPs, may be significantly different depending on the type of vegetation burned in a wildfire, and whether houses and other structures are also burned. Additionally, researchers must distinguish between ambient air pollution caused by natural sources such as wildfires and aeolian dust (particulate matter transported by wind through suspension in the air), and anthropogenic emissions, such as those associated with fossil fuel use, in order to avoid confounding [19].

This scoping review assessed the state of the current literature on the long-term health effects of wildfires. Research questions included: What evidence exists on the longitudinal health effects of wildfire exposure for impacted populations, and what are the unmet health needs for populations residing in geographic areas characterized by high risk of exposure to wildfires? Results will map gaps in the science, inform future population health research priorities, and evaluate the needs for a public health response to the increasing threat of wildfires.

2. Methods

2.1. Search strategies

A literature search was performed March – June of 2021 using PubMed and Embase. A search was also performed of the Cochrane Library, but yielded no results for combinations of search terms "wildfires" and "health." A full list of search terms is included in Supplemental Table 1.

Inclusion was limited to human studies which evaluated long-term health effects of wildfire and wildfire smoke exposure (follow-up after 12 months) including morbidity and mortality related to burns or smoke inhalation, mental health effects, healthcare expenses related to wildfires, wildfires from all vegetation types, occupational and non-occupational exposures, exposures to single or multiple wildfire events, and all age groups. Original peer-reviewed research studies (qualitative or quantitative designs) published in the past ten years (2011 to 2021), from any country, in English were included. Ineligible studies were on animals only, did not disaggregate wildfires from other natural disasters, focused on fires other than vegetation fires (i.e. electrical fires, open-fire cooking), and examined only short-term health effects. In the full-article review, one article was removed because it did not distinguish between the measures of wildfires with those of aeolian dust and therefore could not properly address the research question. A list of select wildfires included in this scoping review, as well as a comparison wildfire, with information on the size, cost, and mortality of the wildfires is included in Table 1.

Relevant titles and abstracts were compiled in an Excel spreadsheet, and duplicates were removed. Data were extracted from each article and included the first author listed, the title, location of the study, study methods, health outcomes, financial impacts, public health conclusions (i.e. what lack of resources or gaps in knowledge were addressed by the authors), and limitations.

2.2. Data synthesis

The long-term health effects of wildfires mapped in this review represent those most commonly studied, including premature mortality, respiratory health, cardiovascular health, mental health (symptoms of mental illness and post-traumatic stress disorder [PTSD], suicidal ideations, and alcohol or illicit substance abuse), cancer (lung cancer and cancer from exposure to HAPs) and other health effects (height, self-reported overall health and physical health, and self-reported housing instability and lack of access to medical care). The health effects of occupational exposure were included, but separated from non-occupational exposure. Economic impacts were also included, as these represent increased healthcare utilization and reduced workforce due to wildfire-related morbidity. Data synthesis was presented in narrative form and included in Table 2.

3. Results

A total of 81 articles were identified which discussed the long-term health effects of exposure to wildfires. Of these, 12 outside the date range were excluded, and 44 articles met exclusion criteria. Of the remaining papers (n = 25), 17 peer-reviewed research papers were included in data synthesis (including one paper that was found via sources from other cited research papers) (Fig. 1).

Several studies used a case series study design (n = 5) and only one article used a prospective cohort design. Data for the peer-reviewed articles (n = 17) are synthesized and grouped into categories of the most commonly reported health outcomes – premature mortality, and increased morbidity including respiratory disease,

Table 2
Location, sample characteristics, and wildfire exposure assessment for each study included in the scoping review. Wildfire exposure assessment was categorized into proximity-based (residence in directly impacted or adjacent communities) or model-based (exposure derived from a statistical model).

Study	Health effect	Location	Sample	Wildfire exposure assessment	Results cited in this review
Ayapong et al., 2020	Mental health	Alberta, Canada	1,446 school staff; 725 teachers (teachers and teaching assistants) and 721 support and management staff	*Proximity-based*. Fort McMurray is the urban service area of the Regional Municipality of Wood Buffalo in Northern Alberta. The area has two school districts: the public school district and the Catholic school district. In an effort to achieve the greatest possible total sample, the online survey link was sent to the emails of all staff in the two school districts in November 2018.	Prevalence of likely MDD in school staff was 18.3% versus 9.7% for Alberta, CA and 12.6% for Canada. Prevalence of likely GAD in school staff was 15.7% versus 2.4-3% for Canada. Prevalence was higher among those who had been fearful for their life or the life of a loved one at the time of fire, or who had received limited support from their support network or from the government. Prevalence of likely PTSD in school staff was 10.2% versus 8-9% for Canada. Prevalence of self-reported PTSD diagnosis prior to the fire was 0% for respondents. Prevalence was higher among those who had been fearful for their life or the life of a loved one at the time of fire, who had watched their home burn, or who had received limited support from their support network or from the government. Female staff had almost three times the likelihood as male staff of likely PTSD. Likely MDD, GAD, and PTSD all showed significant correlation with drug abuse, but not with alcohol abuse.
Brown et al., 2019a	Mental health	Alberta, Canada	3,070 students (grades 7-12) in impacted area; 2,796 students (grades 7-12) in control area	*Proximity-based*. Data from students from Fort McMurray, Alberta, Canada (collected in 2017, 18 months after the 2016 wildfire) was compared with data from Red Deer, Alberta, Canada (collected in 2014). The same measurement scales were used for both surveys. Both of these cities have populations of approximately 100,000, and both cities are located in Alberta, Canada. For this reason, Red Deer served as a non-disaster impacted community to compare to the disaster impacted community of Fort McMurray.	Students in Fort McMurray showed a statistically significant increased prevalence of probable depression, suicidal thinking, and tobacco use than the control cohort. They had lower self-esteem and quality of life scores. Probable anxiety and alcohol or illicit substance misuse was not significantly different between the two cohorts.
Brown et al., 2019b	Mental health	Alberta, Canada	3,070 students (grades 7-12)	*Proximity-based*. Eighteen months after the wildfire, Fort McMurray public and Catholic schools surveyed 3,252 of the 4,407 students in Grades 7–12 to determine possible long-term psychological impacts. Data analysis was possible for only 3,070 students, i.e., 70% of the total student population.	Students at Fort McMurray who were not present for the fire had survey results more similar to Fort McMurray students present for the fire than to the control cohort in terms of mental health symptoms, self-esteem, quality of life, and rates of probable diagnoses for mental health conditions. Resilience scores and prevalence of suicidal thinking were higher among students impacted by the fire than those who were not. Those who personally saw the fire scored higher for all mental health components, and lower for quality-of-life scores. Those who had their homes destroyed scored higher for all mental health components, and lower for self-esteem, quality of life, and resilience.
Dodd et al., 2018	Mental health	Northwest Territories, Canada	30 participants in four communities	*Proximity-based*. This study was conducted in four Subarctic communities in the Northwest Territories that were affected by the prolonged smoke event following the 2014 wildfires: Yellowknife and N'Dilo; Detah; and Kikisa. While the communities of Yellowknife, N'Dilo, and Detah were never imminently threatened by fire during the summer, the community of Kakisa underwent a voluntary evacuation.	Common themes of interviews included feelings of fear, stress, uncertainty, and personal and community isolation.
Fann et al., 2018	Economic impacts	United States	All U.S. wildfire events from 2008-2012	*Modeling-based*. Researchers conducted an air pollution risk assessment related to daily exposure to fire-$PM_{2.5}$ during wildfire smoke events for the years 2008 to 2012 in the continental US.	A total dollar value within the U.S. for short-term premature deaths and hospital admissions was estimated to be between $11B and $20B (2010 USD); the present net value of these expenses across the 5-year time period (2008-2012) was estimated to be $63B (2010 USD). Expenses related to long-term $PM_{2.5}$-related premature deaths and hospital admissions fall between $76B and $130B per year, with a present net value of $450B for the time period of 2008-2012 (all in 2010 USD).

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Table 2 (*Continued*)

Study	Health effect	Location	Sample	Wildfire exposure assessment	Results cited in this review
Ford et al., 2018	Premature mortality	United States	All U.S. wildfire events from 2000-2010 (baseline)	*Modeling-based*. Employed global climate models to simulate the impact of changes of fire emissions on air quality ($PM_{2.5}$), population-level exposure, and premature death in the contiguous U.S. for mid-(2040-2050) and late (2090-2099) century.	In the early 21st century, 17,000 (0.7%) of deaths are attributable to fire-related $PM_{2.5}$ in the U.S. Based on model RCP4.5, fire-related deaths from $PM_{2.5}$ will increase to 42,000 (1.4%) in 2050 and decrease to 32,000 (1.1%) in 2100. Based on model RCP8.5, fire-related deaths from PM2.5 will increase to 32,000 (1.0%) in 2050 and 44,000 (1.8%) in 2100. *Additional thresholds are included in the research.*
Kim et al., 2017	Lung disease, general health or "other"	Indonesia	15,000+ respondents to the IFLS in 1997 and 2007	*Modeling-based*. Conducted a natural experiment using ordinary least squares regression with standard errors to examine long-term health consequences of the 1997 Indonesian fires (10 years post) for adults and children. The monthly total ozone for each community (Sept, Oct, and Nov 1997) served as a proxy for fire exposure. The data source was the Indonesian Family Life Survey (IFLS), a longitudinal socio-economic survey that tracks and surveys a sample of households for 83% of the Indonesian Population.	In comparing the 1997 and 2007 results of the IFLS, authors found a mean decrease in lung capacity of 20.44 liters per minute across all groups. The effect was greater for men, who experienced a mean decrease in lung capacity of 38.23 liters per minute, while women experienced a decrease of 6.10 liters per minute. The effect was null for those aged 9-21. The authors also found that exposure to each extra unit of pollution lead to an approximately 4.6% increase in the probability of being unhealthy (self-reported) 10 years post-exposure. Older cohorts were found to be more affected. No significant difference in the results between men and women was found.
Matz et al., 2020	Premature mortality, lung disease, cardiac disease, general health or "other", economic impacts	Canada	All wildfires during the May to September wildfire seasons in 2013-2015 and 2017-2018	*Modeling-based*. Conducted retrospective assessment of wildfire-$PM_{2.5}$ exposure and estimated annual premature mortality attributable to short- and long-term exposure in Canada. The model included wildfire emissions from across North America.	Chronic mortality cases associated with wildfire-related $PM_{2.5}$ were, in order from the years 2013-2018: 570, 1,000, 2,500, and 1,400. Chronic mortality valuation (CDN), in order from the years 2013-2018: $4.3B, $5.5B, $7.6B, $19B, $10B. Adult chronic bronchitis cases associated with wildfire-related $PM_{2.5}$ were, in order from the years 2013-2018: 530, 710, 960, 2,300, and 1,300. Chronic morbidity valuation (CDN), in order from the years 2013-2018: $230M, $310M, $420M, $1.0B, $560M.
Moosavi et al., 2019	Mental health	Alberta, Canada	290 residents attending a primary care clinic	*Proximity-based*. Adult residents of Fort McMurray who attended a local clinic during the month of November 2017, 18 months after the May 2016 Fort McMurray wildfires. Data on wildfire exposure and impact was collected by survey.	Primary care patients in Fort McMurray self-reported the following incidence of mental health diagnoses before and after the 2016 wildfire: • PTSD: 0% before, 13.6% after • MDD: 15.2% before, 24.8% after • GAD: 14.5% before, 18.0% after Prevalence of self-reported PTSD was significantly associated with a history of anxiety, having received counseling after the fire, and low levels of social support or support from the government.Prevalence of self-reported MDD had significant associations with patients over the age of 41, those who had witnessed the burning of their homes, a history of depressive disorder, and low levels of social support or support from the government.Prevalence of self-reported GAD was significantly associated with having been fearful for one's life or the life of a loved one, and a history of depression or anxiety.
Neumann et al., 2021	Premature mortality, lung disease, cardiac disease, economic impacts	United States	All U.S. wildfires events from 1996-2005	*Modeling-based*. A simulation approach was used to estimate: 1) spatial location of wildfire emissions and amount of area burned using five Global Climate Models (GCM) under two scenarios (RCP4.5, PCP8.5) in Western U.S.; 2) wildfire and non-wildfire associated $PM_{2.5}$ separately using given GCMs paired with meteorological data; 3) wildfire $PM_{2.5}$-linked health impacts were estimated relying on concentration-response functions and projected mortality/morbidity to 2060s (2000 baseline); 4) wildfire PM2.5 health impacts were linked with economic data.	A baseline average mortality burden of 720 cases per year was measured for the reference period of 1996-2005 in the U.S. An excess burden related to long-term all-cause mortality was estimated to be 1,300-1,600 average excess yearly mortalities in 2050, and 1,900-2,300 in 2090. Acute bronchitis cases attributed to wildfire exposure were estimated to be 1,300 in references years 1996-2005 and projected to increase to 770-1,000 in 2050 and 1,300-1,600 in 2090. Acute myocardial infarction cases attributed to wildfire exposure were estimated to be 500 in references years 1996-2005 and projected to increase to 1,000-1,200 in 2050 and 1,500-1,800 in 2090. Wildfire-attributable $PM_{2.5}$-related mortality was estimated to translate to $29B-$36B in annual total excess economic damages by 2090 (2015 USD).

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Table 2 (*Continued*)

Study	Health effect	Location	Sample	Wildfire exposure assessment	Results cited in this review
Navarro et al., 2019	Premature mortality, lung disease, cardiac disease, cancer	United States	80 wildland firefighters in two cohorts, short season and long season	*Modeling-based*. A previously derived wildfire smoke exposure-response function was used to calculate lung cancer and cardiovascular disease mortality for firefighters. The estimated daily dose of wildfire smoke for each firefight was determined based on breathing rates, length of work shift, and frequency of exposure. A trained field research team measured wildland firefighter exposure to PM_4 across 80 wildland firefighters on different fire crew types performing various suppression tasks on wildfires (2010-2011).	The risk ratio of long-term cardiovascular disease ranged from 1.16-1.24 for short-season firefighters (approximately 49 days spent on fire assignments) and 1.19-1.30 for long-season firefighters (approximately 98 days spent on fire assignments). The risk ratio of lung cancer ranged from 1.08-1.26 for short-season firefighters and 1.13-1.43 for long-seasons firefighters.
O'Dell et al., 2020	Premature mortality, cancer, general health or "other"	United States (Western U.S.)	All Western U.S. wildfire events from 2006-2018	*Modeling-based*. Aircraft-based sampling of wildfire smoke was conducted in Washington, Oregon, California, Idaho, Montana, Wyoming, Nevada, Utah, Colorado that collected data on HAPs (32 used) and PM_1. Exposure was based on age of smoke plume with measurements taken downwind from fire. The following age categories were assigned: if 2-methylfuran > 0.7 ppt (95th percentile of non-smoke background observations), smoke was designated as "young" (< 1 day); if 2-methylfuran was not elevated but acrolein was >7.4 ppt, smoke-impacted data was designated as "medium" (1-3 days); if neither 2-methylfuran nor acrolein was elevated, but acrylonitrile was >2.9 ppt, smoke-impacted data was designated as "old" (>3 days); additionally, 15 data points with no elevated age tracers, but with elevated smoke tracers were combined with the "old" category and labeled as such.	Cancer risk due to gas phase hazardous air pollutants (HAPs) in smoke in the Western U.S. exceeds 10 cases per million persons, compared to a national average of 0.71 cases per million persons. This accounts for nearly 1/3 of the national average total cancer risk from ambient air toxics of 31 cases per million persons.
Orr et al., 2020	Lung disease	Montana, U.S.	Test cohort of 95 adults; comparison cohort of 24 adults	*Proximity-based*. Conducted longitudinal health assessments in Seeley Lake and Thompson Falls, MT, U.S. following July 31 to Sept 18, 2017 wildfires. Full spirometry testing was conducted to examine changes in FEV1 and FEV1/FVC ratio up to two years post-wildfire.	Average lung function, measured in forced expiratory volume in the first second / forced vital capacity (FEV1/FVC), was 77.5% compared to a predicted average of 77.05% immediately following the fires, but decreased to 71.6% one year after the event and 73.4% after two years for the test cohort; however, the comparison cohort also experience a statistically significant decrease, indicating possible confounding.
Rosenthal et al., 2021	Mental health, general health or "other"	California, U.S.	21 health and social service workers	*Proximity-based*. Using a purposive sampling methodology, 21 health and social service personnel who assisted in wildfire recovery efforts in California in 2017 and 2018 were interviewed.	Common themes of interviews included re-traumatization during wildfire season and concerns about increased interpersonal violence. Additional themes included concerns regarding housing instability and unemployment exacerbating physical health issues, as well as an inability to access medical care.
Tan-Soo & Pattanayak, 2019	General health or "other"	Indonesia	560 children included in panel survey from 1997, 2000, 2007, and 2014	*Modeling-based*. Estimated early-life air pollution exposure for each child after the 2017 Indonesian forest fires using satellite-derived data on ozone defined as aerosol index [AI] and controlled for climate factors (temperature, rainfall). The impact of prenatal haze exposure (AI) on adult height (primary outcome) was then assessed using a series of complex spatio-temporal regression models that adjusted for parental and household factors.	In-utero exposure to an aerosol index of 0.1 due to the 1997 Indonesia forest fires resulted in a 3.4 cm decrease in mean level height 17 years later, compared to children who were not exposed to the fire.

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Table 2 (*Continued*)

Study	Health effect	Location	Sample	Wildfire exposure assessment	Results cited in this review
Uda et al., 2019	Premature mortality, lung disease, cardiac disease, cancer	Central Kalimantan, Indonesia	All peatland fires in Central Kalimantan during the period of 2011–2015	*Modeling-based.* Assessed long-term health effects of peat smoke by first determining the increase in yearly $PM_{2.5}$ from peat fires in Central Kalimantan, Indonesia, an area characterized by high volume of peatland, using satellite-based data from 2011–2015. The risk of premature deaths (total and individual disease) was calculated for each study area.	• Peatland fires during the study period resulted in an estimated 648 premature mortality cases per year (26 deaths per 100,000 persons). These were further broken down: Chronic respiratory disease: 55 deaths (2 deaths per 100,000 persons) • Cardiovascular disease: 266 deaths (11 deaths per 100,000 persons) • Lung cancer: 95 deaths (4 deaths per 100,000 persons) Peatland fires were also responsible for a rate of 2 mortality cases per 100,000 children in children under the age of 5 during the same study period.
Wasiak et al., 2013	Mental health, general health or "other"	Australia	Longitudinal follow-up on 15 patients admitted to an adult burn care unit after receiving burn injuries	*Proximity-based.* Characterized health status for 19 patients with burn injuries as a result of the 2009 Black Saturday Wildfires in Victoria, Australia. Follow-up data was available for only 15 patients.	Patients reported a mean 16.4-point (16.4%) reduction in physical health and a mean 5.3-point (5.3%) reduction in mental health scores compared to their pre-injury scores. Scores were based on the Short Form 36 Medical Outcomes Survey (SF-36).

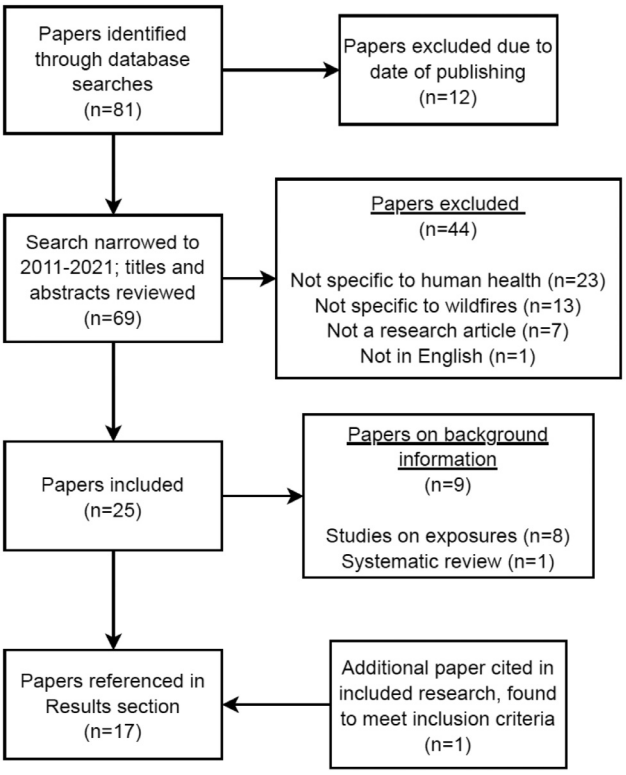

Fig. 1. Flow diagram of studies included in the final scoping review.

cardiovascular disease, cancer, mental health, and other health outcomes – as well as an additional category for health-related economic outcomes (Table 2).

3.1. Premature mortality

A total of four articles assessed premature mortality. Results for present mortality rates included a study in Indonesia, which estimated the long-term exposure of $PM_{2.5}$ due to peat smoke, as measured from 2011 to 2015, caused 648 premature deaths per year (a rate of 26 deaths per 100,000 people per year) [20]. Mortality statistics included chronic respiratory disease, cardiovascular disease, and lung cancer; a mortality rate of 2 deaths per 100,000 per year in children under the age of five was also included. Matz et al. [21] estimated all-cause mortality due to wildfire $PM_{2.5}$ over a five-year period in Canada and found a range of 570 deaths in 2013 to 2,500 deaths in 2017, increasing each year except for 2018 (1,400 deaths).

Two articles measured excess all-cause deaths due to wildfire $PM_{2.5}$ in present day, as well as projections for 2050 and 2100. The first study aggregated age groups from 30 to 99 years and all demographic groups within the contiguous U.S. and found a baseline of 720 excess deaths (reference period 1996–2005), with an excess burden of 1,300 yearly deaths in 2050 and 1,900 in 2090 [22]. The second study aggregated all demographic groups in the U.S. and relied on a 2000–2010 baseline reference period, and observed fire-related $PM_{2.5}$ all-cause mortality attributable mortalities of 17,000 (0.7% of all deaths) in the early 21st century with a projected increase to 32,000–42,000 (1.0–1.4%) in 2050 and 32,000–44,000 (1.1–1.8%) in 2100 [14]. Mortality projections presented by Ford et al. [14] used five different climate models (General Circulation Models [GCMs]) and two different greenhouse gas (GHG) emissions scenarios. The two studies differed in reference period and modeling methods, making them challenging to compare. While Neuman et al. used only wildfire activity from the western U.S. to model mortality projections across the contiguous U.S., Ford et al. used multiple robust climate

models to account for fire activity throughout the U.S., as well as population projections for the modeled time periods.

3.2. Increased morbidities

3.2.1. Respiratory symptoms and illness

Five articles discussed long-term respiratory complications as a health effect of wildfires. Results of the Indonesian Family Life Survey (IFLS) from 1997 to 2007 revealed an average population decrease in mean lung capacity of 20.4 liters per minute, following a large wildfire in Indonesia in 1997 [23]. Mean decrease in lung capacity was more pronounced in men than in women (38.2 liters and 6.1 liters per minute, respectively). Orr et al. [24] also considered lung function for a cohort following the 1997 Indonesian fire, but found that while average lung function, measured in forced expiratory volume in the first second/forced vital capacity (FEV1/FVC), was no different immediately following the fires (77.5% compared to a predicted average of 77.1%), lung function decreased to 71.6% and 73.4% one and two years after the event, respectively. Although the one- and two-year FEV1/FVC measures were statistically significant, a comparison cohort also experienced a statistically significant decrease in lung function, indicating possible confounding.

Two studies compared bronchitis cases. Matz et al. [21] found adult chronic bronchitis cases due to wildfire $PM_{2.5}$ ranging from 530 in 2013 to 2,300 in 2017 in Canada (cases were lower in 2018 at 1,300 cases). Neuman et al. [22] projected the long-term consequences of wildfires on acute bronchitis cases of children aged 8−12 years, establishing a baseline of 1,300 in the reference years 1996−2005, projected to increase to 770−1,000 cases per year in 2050, and 1,300−1,600 cases per year in 2090.

3.2.2. Cardiovascular disease

Two studies looked at cardiovascular disease resulting from wildfires. Neumann et al. [22] projected an increased burden of acute myocardial infarction, among U.S. adults aged 18−99, from a baseline of 500 per year (averaged from 1995 to 2005) to 1,000−1,200 in 2050 and 1,500−1,800 in 2090.

Health effects resulting from occupational exposure of short- and long-season firefighters (approximately 49 days per year and 98 days per year, respectively) in the U.S. were compared in another study that revealed an increased risk ratio for cardiovascular disease of 1.16−1.25 for short-season firefighters and 1.19−1.30 for long-season firefighters [25].

3.2.3. Cancer

Two studies evaluated the risk of cancer from increased exposure to compounds released during wildfires. A U.S. study found that the cancer risk due to gas-phase hazardous air pollutants (HAPs) exceeded a rate of 10 cases per million persons in parts of the western United States commonly experiencing wildfires, compared to a national average of 0.71 per million [26]. This excess cancer risk due to wildfire smoke accounted for nearly one-third of the national average total cancer risk from HAPs.

Lung cancer risks in U.S. firefighters ranged from a risk ratio of 1.08 to 1.26 for short-season firefighters and 1.13 to 1.43 for long-season firefighters [25].

3.2.4. Mental health

A total of seven studies looked at the mental health effects of wildfires. However, four of these studies use data from the Fort McMurray wildfire in Alberta, Canada in 2016 [27−30].

All Fort McMurray wildfire studies were performed 18 months after the wildfire event, among different subgroups of impacted residents in the community, using survey assessments and self-reported mental health symptoms. The first study on school staff found that 15.7% of participants exhibited generalized anxiety disorder (GAD) symptoms (compared to a prevalence of GAD diagnosis of 2.4−3.0% in the general population of Canada) and exhibited a 10.2% prevalence of post-traumatic stress disorder (PTSD) symptoms (compared to a prevalence of PTSD diagnosis of 8−9% for all Canadians), which correlated with self-reports of watching their houses burn, being fearful, and lack of support [27].

Another Fort McMurray study examined self-reported symptoms of depression, suicidal thinking, and tobacco use, as well as self-esteem and quality of life scores for students in the 7th-12th grade in or near the impacted wildfire area and compared responses to a group of students who had not experienced the Fort McMurray wildfire event [28]. GAD symptoms and alcohol or substance abuse scores among students impacted by the wildfire were not significantly different than the control cohort [28]. In a separate study, students living in Fort McMurray who were not directly impacted by the fire had more similar results to their fellow students than to a control group of students for mental health symptoms, self-esteem scores, and quality of life scores [29]. The study also found that rates of resilience (measured as an individual's ability to overcome adversity and continue his or her normal development), but also suicidal thinking were higher for students living in the Fort McMurray area during the fire, and those who personally witnessed the fire or who had homes destroyed by the fire scored higher for all mental health symptoms and lower in quality of life scores [29].

Among a sample of primary care patients in Fort McMurray, self-reported PTSD, MDD, and GAD of 0%, 15.2%, and 14.5%, respectively, prior to the 2016 wildfire increased to 13.6%, 24.8%, and 18.0%, respectively, after the wildfire [30]. Self-reported PTSD diagnoses were positively correlated with a history of anxiety, the receipt of counseling following the wildfires, and a low level of social support or economic recovery support from the Canadian government. A higher prevalence of self-reported GAD diagnosis was associated with patients who felt fearful for their lives or the life of a loved one during the fire, and who had a history of anxiety or depression [30].

Three studies outside of the Fort McMurray wildfire studies focused on mental health. A qualitative study in the Northwest Territories of Canada reported common themes of feelings of fear, stress, uncertainty, and personal and community isolation following the 2014 wildfire season [31]. Another qualitative study in the state of California observed themes of re-traumatization during subsequent wildfire seasons, following the 2017 and 2018 wildfire seasons. Participants also reported an increase in interpersonal violence during community recovery from the wildfires [32].

One study used a questionnaire to assess the health of wildfire burn victims of the 2009 Black Saturday wildfires in Australia, 12 months post-injury, and found a mean 5.3-point reduction in mental health scores (scoring used the Short Form 36 Medical Outcomes Survey [SF-36]) [33].

3.2.5. Other health outcomes

Four studies examined other health outcomes, including height, self-reported overall health and physical health, and self-reported housing instability and lack of access to medical care.

Two studies compared Indonesian Family Life Survey (IFLS) results following the 1997 wildfires in Indonesia. Kim et al. [23] found that exposure to each extra unit of pollution from the 1997 wildfires lead to an approximate 4.6% increase in the probability of being unhealthy (self-reported) 10 years post-exposure. The second study found that in-utero exposure to an aerosol index of 0.1 due to the 1997 Indonesia forest fires resulted in a 3.4 cm decrease in mean level height 17 years later, compared to children who were not exposed to the fire [34].

The other two studies were performed in the U.S. A qualitative study of residents affected by wildfires found common themes of housing instability, unemployment, exacerbated physical health issues, and challenges accessing medical care [32]. And a study

performed on burn victims, using the SF-36 questionnaire, revealed a mean 16.4-point (16.4%) reduction in self-reported general physical health [33].

3.3. Economic impact

There were three studies that considered the economic impact of the long-term health effects of wildfires. In Canada, for the study period of 2013–2015 and 2017–2018, the yearly cost of chronic health impacts was estimated to be $4.3B-$19B (CDN) [21]. Two studies considered the economic impact in the U.S. The estimated costs of long-term $PM_{2.5}$-related premature deaths and hospital admissions were between $76B-$130B (2010 USD), with an estimated total net cost of $450B during the study period of 2008–2012 [35]. Neumann et al. [22] estimated that the wildfire-attributable $PM_{2.5}$-related mortality would translate to $29B-$36B (2015 USD) in annual total excess economic costs by the year 2090.

4. Discussion

This scoping review identified 17 research articles examining the long-term health effects of wildfires globally, published between 2011 and 2021. Results were constrained to a limited evidence-base and suggest that the latent health effects of wildfire exposure may include increased risk of premature deaths, respiratory complications, and population-based increases in cancer risk. Persons occupationally exposed to wildfire smoke may shoulder a higher burden of respiratory complications, including a higher incidence of lung cancer, but longitudinal research that better characterizes individual worker exposure and health effects over time is needed. Findings also showed self-reported mental health sequelae and interpersonal violence were more prevalent among individuals directly exposed to a wildfire, and in some cases adverse mental health effects persisted for at least a year after the event. Yet studies examining the mental health consequences were limited to one large fire event and were not generalizable to other fire events. While limited studies have projected the burden of wildfire exposure and increased risk of mortality in the U.S., future estimates vary widely, ranging from 1,300 to 32,000 deaths per year in 2050 based on the underlying differences in model assumptions. Our review highlights that there are too few studies examining the long-term health effects of wildfires, many of which rely on cross-sectional study designs and self-report of health outcomes.

4.1. Gaps in the literature

We identified several gaps in the literature concerning the demographic profile of the most vulnerable populations affected by wildfires, the need for a wider range of health consequences considered following devastating wildfire events, as well as more prospective or quasi-experimental study designs employed to examine the causal linkage between wildfire exposure and long-term health consequences.

Few studies examined wildfire exposure and health impacts among vulnerable subgroups. For example, only one study discussed the demographic composition of impacted communities that included factors other than age, gender, or in the case of firefighters, occupation [32]. Other underlying health conditions, for example preexisting conditions like asthma or anxiety, and social determinants, like insurance status, housing stock, primary language and literacy, may affect the long-term health outcomes of those exposed to wildfire smoke; geographic location, socioeconomic status, culture, profession, and community-level factors (e.g., structural racism, discrimination, political will) may also affect a person's exposure to wildfires and wildfire smoke, and the type and amount of care they receive after exposure. Agricultural workers are another subgroup which warrant further study, particularly as it pertains to chronic occupational exposure or high levels of exposure during episodic wildfire events. Housing vulnerability, including the loss of housing and the inability to rebuild, and the resultant housing instability or homelessness is another important gap not addressed in the current evidence base [32]. Survivors from socially marginalized groups are typically the most at risk of experiencing long-term housing instability issues. Members of these groups are also more vulnerable to wildfire contamination of indoor air quality due to poor housing quality [16]. Access to medical care and other social services following wildfires is another gap, including access to cancer care, dialysis procedures, and prescription medications. During the response and recovery, public health officials need to address loss of or discontinuity of access to these services; this is another example of why greater understanding on the differential impact for some vulnerable residents based on age, socioeconomic status, and geographic location (urban versus rural) is needed to fully characterize the longitudinal health effects of wildfires.

One additional research priority involves the need for more research and funding for high-quality prospective studies examining the long-term health effects following devastating wildfire events. Only one prospective cohort study was identified for inclusion in this review, and was limited by poor follow-up and a small sample size. More interdisciplinary research is warranted to understand the latent and long-term health effects of wildfire exposure on vulnerable populations (children, elderly, pregnant people, chronically ill), particularly for geographic areas enduring repeated and cyclical exposure to these wildfire events. Research focused on examining which individual and community-level factors contribute to increased risk of adverse health effects is needed, including age, life stage, lifestyle/behavioral factors, and neighborhood disadvantage. Use of advanced analytic approaches and statistical methods that better characterize exposure estimates for impacted populations, particularly the most vulnerable subgroups, is a critical next step.

4.2. Limitations

This scoping review has several limitations. Although no formal critical appraisal was done, most of the research included was found to be of low or moderately-low quality, due to variability in study design (e.g., case-only or cross-sectional), the typically shorter temporal period of study, small sample sizes from disparate geographic areas, and inadequate data on important demographic differences for exposed populations. As a result, the existing studies are not comparable. A protocol for reporting biases inherent in characterizing air pollution from multiple sources (i.e. wildfires versus anthropogenic air pollution sources) is needed to assess exposure misclassification bias and ultimately determine the added impact of wildfire pollutants on communities directly impacted by wildfires, as well as neighboring communities.

Studies included were from high-income countries in North America, Europe, and Australia, and one middle-income country (Indonesia), with wildfire events occurring between the years 1984 and 2013, and were focused on extreme wildfire events. These regions did account for the largest number of retrospective wildfire events; however, both the largest number of total people affected by wildfires and the largest number of deaths from wildfires occurred in Asia [36]. Expanding research to additional countries in Asia, especially low-income countries, will enhance the generalizability of results, as well as including research on the health impacts of chronic exposure to wildfire smoke - such as that of seasonal wildfires - in addition to these large wildfire events. Future studies should focus on increasing the quality of the growing body of evidence about the longitudinal health effects of wildfire exposure by using a prospective study design, incorporating a protocol for reporting biases, and

including low- and middle-income countries as target study populations.

5. Conclusions

Wildfires are increasing in both frequency and severity globally, giving rise to an increased need to understand the longitudinal health effects of wildfire exposure, especially for communities who are facing repeated exposure to high concentrations of wildfire-related $PM_{2.5}$ particles. Articles included in this scoping review show some correlations between wildfire exposure and multiple health effects, including increased mortality, respiratory illnesses, and cancer, but more high-quality and prospective studies are needed to advance understanding on the latent cardiovascular, and mental health effects following wildfire exposure. Public health professionals will benefit from additional information, which can guide messaging and care for impacted populations suffering from the health consequences of wildfires and future preparedness and response efforts in geographic areas most impacted by wildfire events. Future research on the sociodemographic characteristics of vulnerable subgroups who are disproportionately affected by long-term health effects of wildfire exposure is a leading research priority.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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