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Key Points:

- Wildfire smoke is a large source of $PM_{2.5}$ exposure across Canada
- Hundreds to thousands of premature deaths per year are attributable to wildfire-$PM_{2.5}$
- The annual health burden of wildfire-$PM_{2.5}$ is millions to billions of dollars (CDN$)

Supporting Information:

Supporting Information may be found in the online version of this article.

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Health Impact Analysis of Wildfire Smoke-$PM_{2.5}$ in Canada (2019–2023)

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Abstract Wildfires are a source of air pollution, including $PM_{2.5}$. Exposure to $PM_{2.5}$ from wildfire smoke is associated with adverse health effects including premature death and respiratory morbidity. Air quality modeling was performed to quantify seasonal wildfire-$PM_{2.5}$ exposure across Canada for 2019–2023, and the annual acute and chronic health impacts and economic valuation due to wildfire-$PM_{2.5}$ exposure were estimated. Exposure to wildfire-$PM_{2.5}$ varied geospatially and temporally. For 2019–2023, the annual premature deaths attributable to wildfire-$PM_{2.5}$ ranged from 49 (95% CI: 0–73) to 400 (95% CI: 0–590) due to acute exposure and 660 (95% CI: 340–980) to 5,400 (95% CI: 2,800–7,900) due to chronic exposure, along with numerous non-fatal cardiorespiratory health outcomes. Per year, the economic valuation of the health burden ranged from $550M (95% CI: $19M–$1.2B) to $4.4B (95% CI: $150M–$9.9B) for acute impacts and $6.4B (95% CI: $2.2B–$12.9B) to $52B (95% CI: $18B–$100B) for chronic impacts. Additionally, a long-term average annual exposure for 2013–2023 was estimated using air quality modeling. From this, more than 80% of the population had an average seasonal wildfire-$PM_{2.5}$ exposure of at least 1.0 $\mu g/m^3$ and there were 1,900 (95% CI: 980–2,800) attributable premature deaths and a total economic valuation of $18B (95% CI: $6.1B–$36B), per year. Evaluating and understanding the health impacts of wildfire-$PM_{2.5}$ is important given the sizable contribution of wildfire smoke to air pollution in Canada, as well as the anticipated increases in wildfire activity due to climate change.

Plain Language Summary Wildfires are a source of air pollution that can cause adverse effects on human health. For this study, air quality modeling was used to quantify the exposure levels of particulate matter (PM) from wildfires in Canada. From the exposure levels, the health burden attributable to PM in wildfire smoke was estimated. Hundreds to thousands of premature deaths per year are attributable to wildfire smoke exposure along with many non-fatal cardiorespiratory health impacts, such as emergency room visits for respiratory issues. The economic burden of the health impacts from wildfire smoke is estimated in the millions to billions of dollars per year. Having an understanding of the health burden of wildfire smoke is important—it is a large source of air pollution that is expected to increase as climate change will increase the frequency and severity of wildfires.

1. Introduction

Wildfires are both a natural hazard and an important part of terrestrial ecosystems. Wildfire smoke is a complex mixture of water vapor, gases, and particles. It is comprised of primary emissions of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), methane, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons, and secondary pollutants that form in the smoke plume including ozone (O_3) and secondary organic aerosols (Urbanski et al., 2008). Additionally, wildfire smoke can travel great distances, leading to increased exposures and adverse health impacts both in populations in proximity to wildfires as well as those at a distance (Johnston et al., 2024; Matz et al., 2020). Globally, there is interest in understanding the adverse effects of wildfire smoke on human health. Research in this field is expanding as climate change is anticipated to increase wildfire activity due to hotter and drier conditions and increased lightning (Curasi et al., 2024; Pechony & Shindell, 2010).

Epidemiological studies have identified that wildfire smoke exposure, including wildfire-$PM_{2.5}$ specifically, is strongly associated with increased risks of all-cause mortality and respiratory morbidity (e.g., exacerbation of

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asthma and chronic obstructive pulmonary disease) (Gould et al., 2024; Karanasiou et al., 2021). There is some evidence of an association with cardiovascular morbidity, especially in older populations (Barros et al., 2023; Karanasiou et al., 2021), and reproductive/developmental outcomes (e.g., low birth weight) (Foo et al., 2024; Y. Zhang et al., 2024). Also, there is emerging evidence of associations with other health outcomes including impaired cognitive function (Cleland et al., 2022) and cancer (Gao et al., 2024).

In Canada, wildfire activity is highly variable both spatially and temporally. Over the past decade, there have been on average about 6,000 wildfires burning about 2.8M ha per year (CIFFC, 2023). Most frequently, wildfires occur in the forested areas of British Columbia (BC), the Prairie provinces, Ontario (ON), Quebec (QC), Northwest Territories, and Yukon. Although most wildfire activity occurs in remote, sparsely populated areas, long-range transport of the smoke can impact air quality in population centers at distances from the fires in both Canada and the United States (K. Chen et al., 2023; Schneider et al., 2021). The 2023 wildfire season was unprecedented in Canada, with approximately 15M ha burned (∼4% of the forested area in Canada) which was more than seven times the historical average, and resulted in smoke impacting major population centers in Canada and US (Jain et al., 2024). On a national level, wildfire smoke is a leading contributor to population-weighted $PM_{2.5}$ exposure, accounting for 17.1% of the total exposure in Canada (Meng et al., 2019). Furthermore, understanding the health impacts of wildfire smoke is important as wildfire activity in Canada is anticipated to increase with greater frequency and intensity (Coogan et al., 2019).

A previous health impact assessment of wildfire smoke in Canada, considering 2013 to 2018, estimated that wildfire-$PM_{2.5}$ exposure was associated with up to 240 and 2,500 premature deaths per year due to short-term and long-term exposure, respectively and had an annual economic valuation of up to $1.8B for acute health impacts and $19B for chronic health impacts (Matz et al., 2020). The present study, representing a continuation and update of the previous analysis, evaluates the annual health impacts and associated economic valuation due to wildfire-$PM_{2.5}$ in Canada for 2019–2023, providing analysis of the unprecedented 2023 Canadian wildfire season. Additionally, the long-term wildfire-$PM_{2.5}$ exposure, considering 2013–2023, and attributable chronic health impacts, including decreases in life expectancy, were evaluated.

2. Methods

For this study, a multi-step was employed. First, air quality modeling was used to estimate wildfire-specific $PM_{2.5}$ concentrations across Canada. Next, the geolocated exposure data and Census data were used to calculated population-weighted average wildfire-$PM_{2.5}$ exposures. Annual exposures were calculated for each of 2019–2023, and a long-term 10-year annual average was calculated for 2013–2023. Lastly, a health impacts assessment was conducted to estimate the health burden and associated economic valuation of wildfire-$PM_{2.5}$ exposure in Canada, considering both annual impacts for 2019–2023 and the impacts of the long-term (2013–2023) exposures.

2.1. Air Quality Modeling

Estimates of daily air quality across Canada for the study period were generated using two models: (a) Global Environmental Multi-scale—Modeling Air Quality and Chemistry (GEM-MACH), and (b) FireWork. These models are used by the Meteorological Service of Canada (MSC) to forecast atmospheric air pollutant concentrations. The models are routinely validated against surface and satellite observational data; technical details of the models and performance evaluations are available (Munoz-Alpizar et al., 2017; see also Ainslie et al., 2022; J. Chen et al., 2019; ECCC, 2019; Pavlovic et al., 2016). Daily performance statistics for $PM_{2.5}$ across the modeling domain have been reported: for GEM-MACH, R ranged from 0.15 to 0.24 and RMSE (root mean square error) ranged 14 to 29 μg/m^3; and for FireWork, R ranged from 0.24 to 0.64 and RMSE ranged from 14 to 64 μg/m^3 (J. Chen et al., 2019). GEM-MACH is an atmospheric chemistry prediction numerical model that is embedded within the Global Environmental Multi-scale (GEM) model used by MSC for weather forecasting (Côté, Desmarais, et al., 1998; Côté, Gravel, et al., 1998). GEM-MACH includes air quality processes for gas-phase, aqueous-phase and heterogeneous chemistry, a number of PM processes as well as wet and dry deposition. FireWork is an augmented version of GEM-MACH, using the same air quality forecasting system as GEM-MACH and incorporating Canadian and American near-real time hourly emissions from biomass burning. Both GEM-MACH and FireWork generate at least a 48-hr forecast twice daily at 00 and 12 UTC. For this study, the first 24-hr forecasts generated at 00 UTC daily were used. The wildfire season was considered to extend from

May 1 to September 30 of each year. The modeling domain is a 10 km × 10 km grid and covers most of Canada, the United States, and northern Mexico. Fire activity across the domain is incorporated, as such transboundary smoke is be included in the analysis. As FireWork does not distinguish between wildland, prescribed and agricultural fires, the biomass emissions considered in this analysis, referred to as wildfire emissions, included wildland, prescribed, and agriculture fire emissions. Notably, prescribed fires are relatively uncommon in Canada, though the modeling domain includes other jurisdictions in which prescribed and agricultural fires are more common (Ryan et al., 2013).

2.2. Wildfire-$PM_{2.5}$ Population Exposure Estimation

Wildfire-$PM_{2.5}$ concentrations (i.e., the $PM_{2.5}$ concentration attributable to wildfire activity) were quantified as the difference between FireWork and GEM-MACH estimates, as the models are only different based on inclusion or exclusion of emissions from biomass burning. This approach removes the anthropogenic and non-wildfire natural sources of $PM_{2.5}$ that are included in both models. To determine the landmass area with exposures at or above wildfire-$PM_{2.5}$ threshold concentrations (0.2, 1.0, 5,0, and 10 μg/m^3), each 10 km × 10 km grid cell of the air quality modeling domain was associated to a province or territory using the "FAST" interpolation method and the 2016 Canadian Census shapefile polygons to support the health impact analysis. Fast interpolation is a rapid remapping method using a line rasterization algorithm in which a grid cell will only be selected if the center of the grid cell is within the polygon. The grid cells covering only water or another country were excluded. The landmass area assigned to the grid cells with a corresponding exposure concentration were summed to determine the aggregate area at or above the threshold. These threshold concentrations are consistent with previous analyses (Matz et al., 2020; Munoz-Alpizar et al., 2017). The lower threshold of 0.2 μg/m^3 represents the lowest value not susceptible to numerical noise from the models (Munoz-Alpizar et al., 2017). The upper threshold represents the Canadian Ambient Air Quality Standard for annual $PM_{2.5}$ levels in Canada (CCME, 2015). The intermediate thresholds (1.0 and 5.0 μg/m^3) were chosen to transition between the upper and lower values.

To determine population exposures, Dissemination Areas (DAs) were used as the smallest standard geographic area of Canadian Census data (Statistics Canada, 2016a). Each DA polygon has an average of 400–700 people and covers all of Canada (Statistics Canada, 2016b). To calculate the population exposure, the population of each DA polygon was interpolated to the 10 km × 10 km grid of the air quality modeling domain using the "normalized conservative" method. This remapping method distributes the grid cell concentrations on to the DA polygons using the proportion of each grid cell surface covering the polygon to estimate the average concentration in a given polygon. The population of each DA was assigned to the modeling grid cells either wholly or partially based on the fractional area of the polygon on the grid cell and assuming uniform population density. In order to estimate population exposures at or above wildfire-$PM_{2.5}$ threshold concentrations (0.2, 1.0, 5.0, and 10 μg/m^3), the population counts assigned to the grid cells with a corresponding exposure concentration were summed to determine the aggregate population exposure at or above the threshold.

For the health impact assessment, wildfire-$PM_{2.5}$ concentrations were treated a continuous variable for the health impact analyses. The population-weighted exposure at the DA level was then used to calculate the exposure at the Census Division (CD)-level, as CDs are composed of DAs. CDs are intermediate geographic areas between the provincial or territorial level and the municipality, and are often used in longitudinal analyses as they are considered stable geographic areas (Statistics Canada, 2022).

2.3. Health Impacts Assessment

The health impacts, including premature death and non-fatal health outcomes, attributable to wildfire-$PM_{2.5}$ were estimated using Health Canada's Air Quality Benefits Assessment Tool (AQBAT) (https://health-infobase.canada.ca/aqbat/). AQBAT estimates the number of excess health outcomes attributable to a change in ambient air quality based on baseline incidence rates of the health outcomes, population counts, concentration response functions (CRFs), and a quantified change in air pollution concentration. For the present study, the change in air pollution concentration was the estimate of the seasonal (May to September) average wildfire-$PM_{2.5}$ concentration (i.e., the difference between FireWork and GEM-MACH results). The baseline incidence rates of health outcomes were derived from 2023 data. The CRFs are statistically-derived estimates of the percentage of excess risk for a given health outcome (e.g., premature death) associated with a specified increment in the short-term or long-term pollutant concentration (e.g., per 10 μg/m^3 $PM_{2.5}$). The CRFs are derived from primary studies, as well as from reviews or meta-analyses, with a preference for Canadian studies. Health Canada endorsed CRFs are based on exposure response relationships considered causal or likely causal in Health Canada science assessments. CRFs are specified as distribution functions in the calculations, accounting for the empirical uncertainty in the CRF estimates. The health impacts estimates are based on a log linear calculation. Details of the CRFs are provided in Appendix: Table S1 in Supporting Information S1. AQBAT also calculates the economic value of the health impacts based on valuation estimates developed from surveys and economic studies. Similar to the CRFs, the economic valuation estimates are specified as distribution functions in the calculations, accounting for the empirical uncertainty in these estimates. The economic valuation estimates are provided in Table S2 in Supporting Information S1. All valuations are presented in 2023 Canadian dollars (CAD), the most current value in AQBAT at the time of analysis. The 293 CDs included in AQBAT are based on the 2016 Canadian Census. For the AQBAT analysis, Monte Carlo simulations of 10,000 iterations were used to propagate uncertainty by iteratively sampling from the specified distributions of CRFs and valuation estimates.

For the health impact assessments for 2019–2023, the seasonal exposure to wildfire-$PM_{2.5}$ was assumed to be equal to the average of the daily exposures to wildfire-$PM_{2.5}$ from May 1 to September 30. To estimate the impacts of sustained or chronic exposure to wildfire-$PM_{2.5}$, the seasonal concentration of wildfire-$PM_{2.5}$ was averaged over the entire year, imputing all days outside the wildfire season as 0 $\mu g/m^3$. For this part of the study, the annual acute and chronic health impacts were estimated based on the wildfire-$PM_{2.5}$ exposure associated with a given year from 2019 to 2023. The CRFs for both acute and chronic premature death are derived from Canadian studies of ambient air pollution (Crouse et al., 2012; Huang et al., 2023), and are comparable in magnitude to the CRFs used in other health impact analyses of wildfire-$PM_{2.5}$ (Connolly et al., 2024; Fann et al., 2018; Johnston et al., 2012; Matz et al., 2020).

Additionally, to assess the annual chronic health impacts and estimated decreases in life expectancy due to long-term exposure to wildfire smoke, the long-term average wildfire-$PM_{2.5}$ exposure for 2013–2023 (excluding 2016) was determined, by determining the average of the individual annual exposures (i.e., a 10-year annual average). This long-term annual average addresses a limitation in assessment of chronic health impacts based on a single year's exposure, and as it represents a multi-year exposure, estimating the acute health impacts was considered inappropriate. As substantial changes to the air quality modeling grids of GEM-MACH and FireWork were made in 2016, analyses combining the model grid outputs cannot be computed. This precluded the ability to compute the wildfire-$PM_{2.5}$ concentrations for 2016 (Matz et al., 2020); thus, the results for this year were excluded from the long-term average analysis. Only the health outcomes due to chronic $PM_{2.5}$ exposure that are included in AQBAT were considered in this long-term (multi-year) analysis. For decreases in life expectancy, standard Canada life table (2017–2019) methods were used to estimate changes in life expectancy in relation to wildfire-$PM_{2.5}$. At each age group, all-cause and age-specific mortality rates were modified by the proportional change in mortality associated with a specified change in wildfire-$PM_{2.5}$. These changes in the probability of surviving to the next age group were then propagated through the life table to estimate the change in life expectancy.

3. Results

3.1. Air Quality Modeling (2019–2023)

The seasonal wildfire-$PM_{2.5}$ concentrations for 2019–2023 demonstrate considerable spatial and temporal variability (Figure 1). The greatest concentrations were estimated in areas in close proximity to the fires and long-range transport spread wildfire-$PM_{2.5}$ across Canada and the US. The interannual variability in wildfire activity is most evident comparing the relatively minor wildfire activity in Canada of 2020 to the unprecedented fire season of 2023. As Canada comprises a large landmass with a sparse and unevenly distributed population, the wildfire-$PM_{2.5}$ concentrations were evaluated, at multiple threshold levels (Figure 2). For each year of the 2019–2023 period, over 80% of the population had wildfire seasonal average exposure concentrations at or above 0.2 $\mu g/m^3$ wildfire-$PM_{2.5}$, indicative of long-range transport of the smoke pollutants to populations at distances from wildfire activity. Over 20% of the population was exposed to average wildfire-$PM_{2.5}$ concentrations above 1 $\mu g/m^3$ across the wildfire season in four of the years. The interannual variability in wildfire activity is also evident in both panels A and B, especially at the higher threshold levels.

Although wildfire activity was most common in the western provinces (BC, Alberta, and Saskatchewan) and the Northwest Territories over the study period, nearly all regions were impacted by wildfire smoke (Figure 1). The provincial and territorial analyses of the percentage of the landmass and population impacted by wildfire smoke at

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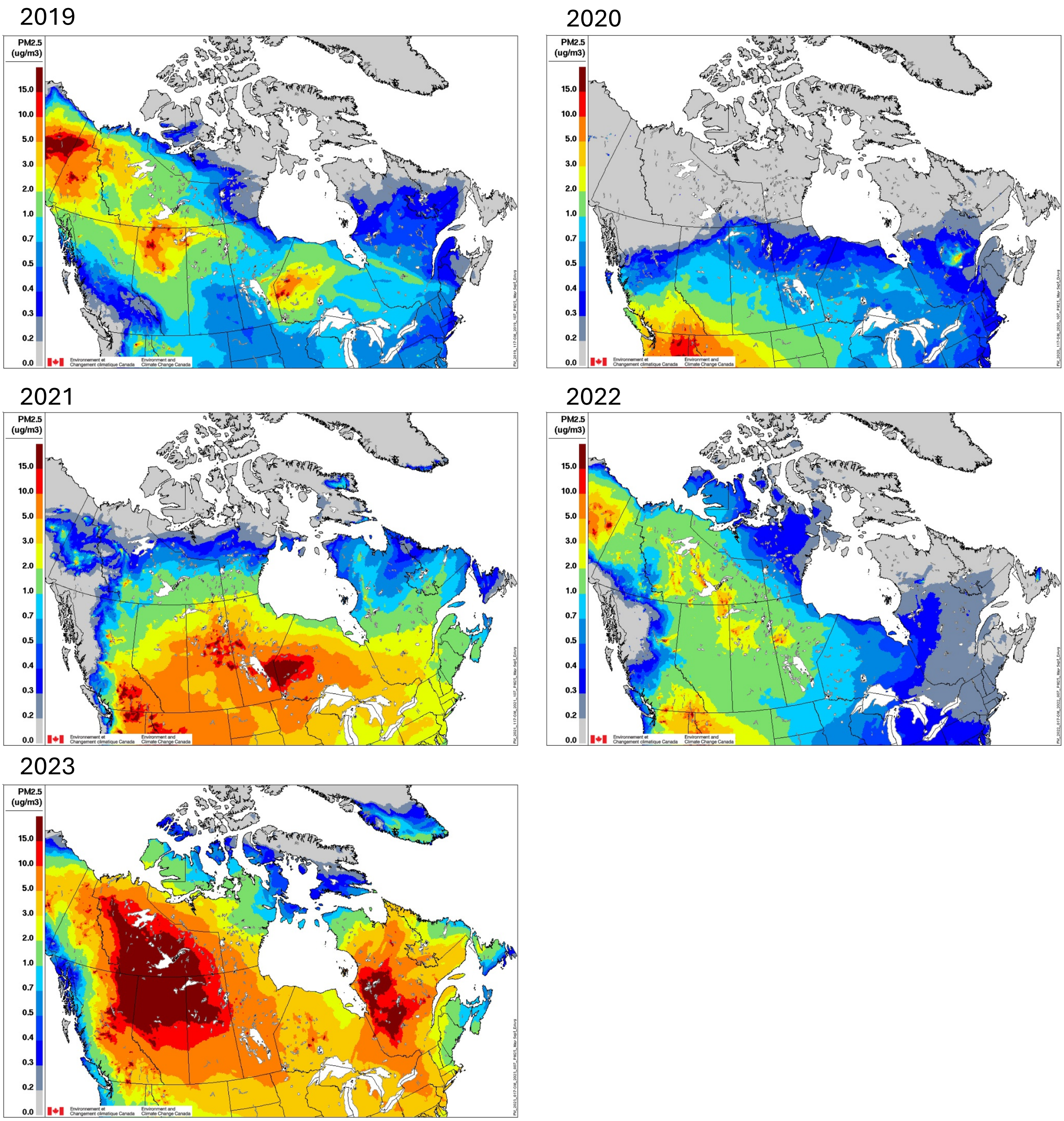

Figure 1. $PM_{2.5}$ concentrations (May–September) for 2019–2023 attributable to wildfire sources based on FireWork and GEM-MACH model results.

the thresholds are provided in Appendix A: Tables S3 and S4 in Supporting Information S1. The CDs most impacted by smoke were located in the Northwest Territories, BC, and Alberta (Table S5 in Supporting Information S1). Notably, for these jurisdictions, wildfire smoke accounted for approximately 33%–90% of the total annual $PM_{2.5}$ exposure. Considering only 2023 due to the extreme wildfire activity of that year, the most wildfire smoke impacted CDs were also in the Northwest Territories, BC, and Alberta, with the wildfire-$PM_{2.5}$ contribution ranging from approximately 70% to 97% of the total annual $PM_{2.5}$ exposure (Table S6 in Supporting Information S1).

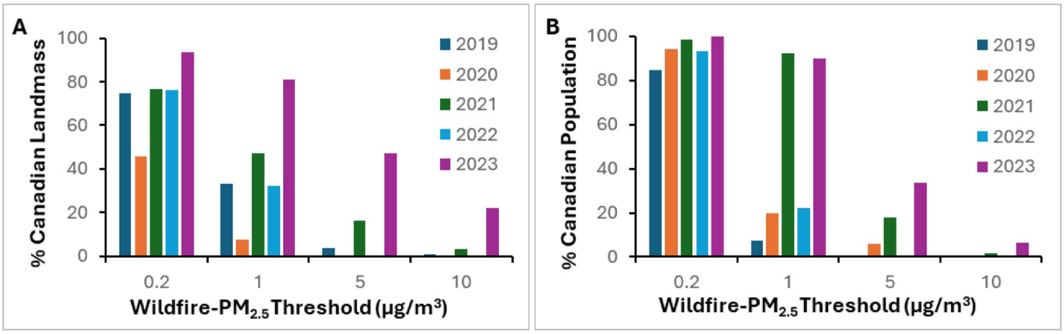

Figure 2. Percent of the Canadian landmass (a) and population (b) with average wildfire-$PM_{2.5}$ (May–September) concentrations at and above the indicated thresholds.

3.2. Health Impact Analysis of Annual Wildfire-$PM_{2.5}$ (2019–2023)

Short-term exposure to wildfire-$PM_{2.5}$ was associated with a range of 49 (95% CI: 0–73) to 400 (95% CI: 0–590) premature deaths per year for 2019–2023 (Table 1). There were also numerous non-fatal cardio-respiratory health impacts, such as millions of acute respiratory symptom days and hundreds of emergency room visits for respiratory conditions. The annual economic valuation for acute health impacts ranged from $550M (95% CI: $19M–$1.2B) to $4.4B (95% CI: $150M–$9.9B), with premature deaths accounting for approximately 81% of the total valuation. The greatest health impacts and associated economic valuation were observed for 2023 and 2021, due to the widespread wildfire smoke for those years (Figure 1). Over the study period, the attributable acute premature deaths and non-fatal health outcomes had a combined economic valuation of $9.6B (95% CI: $330M–$21B).

For chronic health impacts, wildfire-$PM_{2.5}$ was associated with ranges of 660 (95% CI: 340–980) to 5,400 (95% CI: 2,800–7,900) premature deaths per year and 610 (95% CI: 5–1,200) to 4,700 (95% CI: 41–9,300) adult chronic bronchitis cases per year (Table 2). The range of annual economic valuation for chronic health impacts was $6.4B

Table 1
Acute Health Impacts and Economic Valuation[a] From Wildfire-$PM_{2.5}$, for 2019–2023 [95% Confidence Intervals]

	2019	2020	2021	2022	2023
Acute premature deaths[b]	49 [0–73]	85 [0–130]	280 [0–410]	50 [0–73]	400 [0–590]
Acute premature death valuation (2023 CAD)	$450M [$0–$980M]	$780M [$0–$1.7B]	$2.5B [$0–$5.5B]	$450M [$0–$980M]	$3.6B [$0–$7.9B]
Acute respiratory symptom days	1,600,000 [0–3,200,000]	2,700, 000 [0–5,500,000]	8,700,000 [0–18,000,000]	1,600,000 [0–3,200,000]	12,000,000 [0–25,000,000]
Asthma symptom days[c]	140,000 [30,000–260,000]	230,000 [49,000–420,000]	780,000 [160,000–1,400,000]	140,000 [30,000–260,000]	1,100,000 [240,000–2,000,000]
Child acute bronchitis episodes	2,800 [0–6,400]	4,600 [0–10,000]	15,000 [0–34,000]	2,800 [0–6,400]	22,000 [0–50,000]
Respiratory emergency room visits	220 [140–290]	330 [220–440]	1,200 [770–1,600]	210 [140–290]	1,700 [1,200–2,300]
Respiratory hospital admissions	43 [28–57]	66 [43–88]	230 [150–310]	42 [28–57]	350 [230–460]
Cardiac emergency room visits	74 [40–110]	120 [65–180]	420 [220–610]	74 [39–110]	610 [320–890]
Cardiac hospital admissions	56 [30–83]	93 [50–140]	320 [170–470]	56 [30–82]	460 [250–680]
Restricted activity days	870,000 [530,000–1,200,000]	1,500,000 [910,000–2,100,000]	4,700,000 [2,900,000–6,500,000]	850,000 [520,000–1,200,000]	6,800,000 [4,100,000–9,400,000]
Acute morbidity valuation (2023 CAD)	$100M [$19M–$260M]	$180M [$33M–$440M]	$570M [$110M–$1.4B]	$100M [$19M–$260M]	$820M [$150M–$2.0B]

[a]The dollar values are socio-economic values associated with small changes in the risk of various health outcomes. AQBAT provides economic valuation estimates of those health impacts, considering the potential social welfare consequences, including medical costs, reduced productivity, pain and suffering, and the impacts of increased mortality risk. [b]Values represent mean valuation of multiple iterations; [2.5th–97.5th percentiles]. [c]Asthma symptom days are only estimated for children (5–19 years of age).

Table 2
Chronic Health Impacts and Economic Valuation[a] From Wildfire-$PM_{2.5}$, for 2019–2023 [95% Confidence Intervals]

	2019	2020	2021	2022	2023
Chronic premature deaths[b]	660 [340–980]	1,100 [590–1,700]	3,800 [1,900–5,500]	670 [350–990]	5,400 [2,800–7,900]
Chronic premature death valuation (2023 CAD)	$6.1B [$2.2B–$12B]	$11B [$3.9B–$20B]	$34B [$13B–$66B]	$6.1B [$2.2B–$12B]	$49B [$18B–$94B]
Adult chronic bronchitis cases	610 [5–1,200]	1,100 [9–2,100]	3,300 [28–6,500]	610 [5–1,200]	4,700 [41–9,300]
Chronic morbidity valuation (2023 CAD)	$330M [$1.4M–$860M]	$560M [$2.4M–$1.5B]	$1.8B [$7.7M–$4.6B]	$320M [$1.4M–$850M]	$2.5B [$11M–$6.6B]

[a]The dollar values are socio-economic values associated with small changes in the risk of various health outcomes. AQBAT provides economic valuation estimates of those health impacts, considering the potential social welfare consequences, including medical costs, reduced productivity, pain and suffering, and the impacts of increased mortality risk. [b]Values represent mean valuation of multiple iterations; [2.5th–97.5th percentiles].

(95% CI: $2.2B–$12.9B) to $52B (95% CI: $18B–$100B), with premature deaths accounting for 95% of the total. Similar to acute health impacts, the greatest chronic health impacts were estimated for 2023 and 2021. Of note, this analysis represents the estimated chronic health impacts that would be anticipated if a similar wildfire season for a given year was a recurring event over a multi-year period.

The greatest health impacts were identified for the provinces of Ontario, Quebec, BC, and Alberta, due to their large populations and relative proximity to the wildfire activity from 2019 to 2023. Although wildfire activity is generally greater in the Western provinces than in Central Canada, substantial wildfire activity occurred in Central Canada in both 2021 and 2023 (Figure 1). Health impacts were also noted for Saskatchewan and Manitoba; these provinces typically experience wildfire activity and smoke, but the smaller population sizes resulted in relatively smaller counts of the health impacts. A breakdown of the attributable acute and chronic exposure premature deaths by provinces and territories is provided in Table S7 in Supporting Information S1.

To further evaluate the regional variability in wildfire activity and wildfire smoke exposure, the CDs with the greatest health impacts based on acute premature death attributable to wildfire-$PM_{2.5}$, for 2019–2023, were identified (Table 3). The top 10 CDs are evenly split between the western provinces (BC, Alberta, and Manitoba) and central Canada (Ontario and Quebec). Four of the top 10 CDs are located in Ontario (Toronto, Ottawa, Peel, and York), and two in each of BC (Greater Vancouver and Central Okanagan) and Alberta (Edmonton and Calgary). Although the average wildfire-$PM_{2.5}$ exposure over the analysis period for Toronto (0.8 $\mu g/m^3$) was about half the exposure for Edmonton (1.7 $\mu g/m^3$), a similar number of acute premature deaths was estimated mainly due to the much larger population size of Toronto. Additionally, the acute premature deaths attributable to wildfire-$PM_{2.5}$ represented a greater proportion of the health baseline and attributable mortality for Central Okanagan, reflective of the relatively smaller population size and greater wildfire-$PM_{2.5}$ exposure compared to the other CDs in the top 10.

Given that 2023 was an unprecedented wildfire season in Canada, the top 10 CDs based on acute premature death attributable to wildfire-$PM_{2.5}$ were also identified for this year only (Table 4). Seven of the top 10 CDs are located in central Canada, and the remaining three are the most populous cities in the Prairie provinces. Edmonton was the most impacted CD in terms of number of premature deaths (29), proportion of health baseline (0.31%), attributable mortality (1.8 per 100k), and wildfire-$PM_{2.5}$ exposure (4.5 $\mu g/m^3$).

3.3. Health Impact Analysis of Long-Term Exposure to Wildfire-$PM_{2.5}$ (2013–2023)

As noted above (Section 3.2), the chronic health impacts based on an annual wildfire-$PM_{2.5}$ exposure concentration represent the health impacts that would be anticipated if a similar wildfire season and wildfire smoke exposure were experienced on a consistent and recurring basis, year over year. As air quality modeling to estimate wildfire-$PM_{2.5}$ exposure was available for 2013–2023 (excluding 2016), the 10-year average annual exposure concentration was estimated (Figure 3a) to more accurately evaluate the chronic health impacts of long-term exposure. Substantial portions of the Canadian landmass and population had an average seasonal wildfire-$PM_{2.5}$ exposure of at least 1.0 $\mu g/m^3$ (Figure 3b), and approximately 99% of the population has exposure concentrations of at least 0.2 $\mu g/m^3$ over the 10-year analysis period. The regional differences in long-term wildfire-$PM_{2.5}$ exposure were evident as nearly the entire populations of BC, Alberta, Saskatchewan, Manitoba, Ontario,

Table 3
Health Impacts of Wildfire-$PM_{2.5}$: Top 10 CDs Based on Total Acute Premature Death and Associated Valuation for 2019–2023 [95% Confidence Intervals]

CD (province)	Average wildfire-$PM_{2.5}$ exposure (μg/m^3)	Acute exposure premature deaths[a]	Valuation[a,b] (2023 CAD)	Proportion of health baseline (%)[a]	Attributable mortality (per 100k)
Toronto (ON)	0.8	53 [0–78]	$480M [$0–$1.0B]	0.29 [0–0.43]	1.7
Division No. 11 Edmonton (AB)	1.7	52 [0–78]	$480M [$0–$1.0B]	0.58 [0–0.86]	3.2
Montréal (QC)	0.7	41 [0–60]	$370M [$0–$800M]	0.26 [0–0.39]	1.9
Division No. 6 Calgary (AB)	1.4	40 [0–60]	$370M [$0–$800M]	0.49 [0–0.73]	2.3
Greater Vancouver (BC)	0.7	38 [0–56]	$350M [$0–$750M]	0.25 [0–0.37]	1.5
Division No. 11 Winnipeg (MB)	1.5	30 [0–44]	$270M [$0–$600M]	0.51 [0–0.75]	3.9
Ottawa (ON)	0.9	21 [0–31]	$190M [$0–$410M]	0.32 [0–0.48]	2.0
Peel (ON)	0.8	19 [0–27]	$170M [$0–$370M]	0.28 [0–0.42]	1.2
York (ON)	0.8	17 [0–25]	$150M [$0–$330M]	0.28 [0–0.42]	1.4
Central Okanagan (BC)	2.5	16 [0–24]	$150M [$0–$320M]	0.88 [0–1.30]	7.9

[a]Values represent mean valuation of multiple iterations; [2.5th–97.5th percentiles]. [b]The dollar values are socio-economic values associated with small changes in the risk of various health outcomes. AQBAT provides economic valuation estimates of those health impacts, considering the potential social welfare consequences, including medical costs, reduced productivity, pain and suffering, and the impacts of increased mortality risk.

and the Northwest Territories had average seasonal exposures of at least 1.0 μg/m^3, and sizable portions of the population of BC and the Northwest Territories had exposure levels at or above 5.0 μg/m^3. The provincial and territorial analysis of the percentage of the landmass and population impacted by wildfire smoke at the thresholds are provided in Appendix A: Tables S8 and S9 in Supporting Information S1.

When considering chronic health impacts, 1,900 (95% CI: 980–2,800) premature deaths and 1,700 (95% CI: 14–3,300) adult chronic bronchitis cases per year were attributable to the 10-year average wildfire-$PM_{2.5}$ exposure. The estimated annual economic value was $18B (95% CI: $6.1B–$36B), with the premature deaths accounting for

Table 4
Health Impacts of Wildfire-$PM_{2.5}$: Top 10 CDs Based on Total Acute Exposure Premature Death and Associated Valuation for 2023 [95% Confidence Intervals]

CD (province)	Average wildfire-$PM_{2.5}$ exposure (μg/m^3)	Acute exposure premature deaths[a]	Valuation[a,b] (2023 CAD)	Proportion of health baseline (%)[a]	Attributable mortality (per 100k)
Division No. 11 Edmonton (AB)	4.5	29 [0–43]	$260M [$0–$570M]	0.31 [0–0.46]	1.8
Toronto (ON)	2.0	26 [0–39]	$240M [$0–$530M]	0.14 [0–0.21]	0.9
Montréal (QC)	1.8	20 [0–30]	$190M [$0–$410M]	0.13 [0–0.19]	1.0
Division No. 6 Calgary (AB)	2.7	16 [0–24]	$150M [$0–$320M]	0.19 [0–0.28]	0.9
Ottawa (ON)	2.8	13 [0–19]	$120M [$0–$260M]	0.20 [0–0.29]	1.2
Division No. 11 Winnipeg (MB)	2.7	11 [0–17]	$100M [$0–$220M]	0.18 [0–0.27]	1.4
Peel (ON)	1.9	9 [0–13]	$82M [$0–$180M]	0.13 [0–0.20]	0.6
York (ON)	2.0	8 [0–12]	$74M [$0–$160M]	0.14 [0–0.20]	0.7
Niagara (ON)	2.1	7 [0–11]	$65M [$0–$140M]	0.15 [0–0.22]	1.4
Hamilton (ON)	2.0	7 [0–10]	$64M [$0–$140M]	0.14 [0–0.20]	1.2

[a]Values represent mean valuation of multiple iterations; [2.5th–97.5th percentiles]. [b]The dollar values are socio-economic values associated with small changes in the risk of various health outcomes. AQBAT provides economic valuation estimates of those health impacts, considering the potential social welfare consequences, including medical costs, reduced productivity, pain and suffering, and the impacts of increased mortality risk.

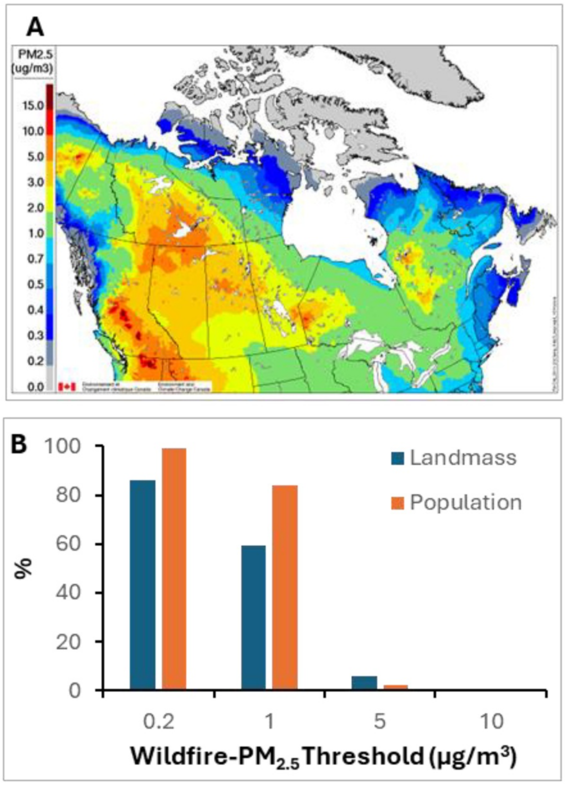

Figure 3. Average $PM_{2.5}$ concentrations (May–September) for 2013–2023 (excluding 2016) attributable to wildfire emissions based on FireWork and GEM-MACH model results (panel (a)). Percent of Canadian landmass and population with average wildfire-$PM_{2.5}$ concentrations for 2013–2023 (excluding 2016) at and above the indicated thresholds (panel (b)).

96% of the total. Additionally, this long-term exposure was estimated to result in a national population-weighted average decrease in life expectancy of 0.06 years (95% CI: 0.03–0.09) due to wildfire smoke. Although the national impact on individual life expectancy was modest, the greatest decreases were noted for the Northwest Territories (0.17 years), Alberta (0.12 years), and BC (0.11 years) indicative of the recurrent and significant wildfire smoke exposures in these jurisdictions. A breakdown of the chronic health impacts and decrease in life expectancy by province and territory is provided in Table S10 in Supporting Information S1.

4. Discussion

Although wildfires represent an important naturally occurring process in the forest ecosystem, wildfire smoke contains many pollutants and presents a health risk to populations both in proximity to wildfire activity and those at distance due to long-range transport of the smoke plume. For both 2021 and 2023, sizable portions of the Canadian landmass and population were exposed at levels of 5 $\mu g/m^3$ and above of wildfire-$PM_{2.5}$. For population exposures, the most impacted provinces were BC, Alberta, Saskatchewan, Manitoba, Ontario and Quebec, reflecting both the proximity of wildfires to and the long-range transport of smoke into population centers. A study of wildfire-$PM_{2.5}$ exposure in the continental US from 2007 to 2018 also reported substantial spatial and temporal variability in exposure over the study period, with some regions persistently impacted by smoke and having annual exposure levels often exceeding 8 $\mu g/m^3$ (D. Zhang et al., 2023).

The present study, an evaluation of the health impacts of wildfire-$PM_{2.5}$ in Canada for 2019–2023, builds on a previous analysis of wildfire-$PM_{2.5}$ in Canada for 2013–2018 (Matz et al., 2020). In the previous analysis, the annual premature deaths were estimated at 54 to 240 attributable to acute exposure and 570 to 2,500 attributable to chronic exposure. The annual economic valuation of this health burden ranged $410M to $1.8B for acute impacts and $4.3B to $19B for chronic impacts. In the present study, the health burden of wildfire-$PM_{2.5}$ for 2019–2022 was similar to the preceding years, while the unprecedented and record-setting wildfire season of 2023 was associated with a substantially greater number of health impacts and correspondingly increased economic valuation. Overall for 2019–2023, the annual premature deaths attributable to wildfire-$PM_{2.5}$ ranged from 49 (95% CI: 0–73) to 400 (95% CI: 0–590) due to acute exposure and 660 (95% CI: 340–980) to 5,400 (95% CI: 2,800–7,900) for chronic exposure. The associated economic valuation ranged from $550M (95% CI: $19M–$1.2B) to $4.4B (95% CI: $150M–$9.9B) for acute impacts and $6.4B (95% CI: $2.2B–$12.9B) to $52B (95% CI: $18B–$100B) for chronic impacts, per year. For comparison, the annual health burden of wildfire-$PM_{2.5}$ is similar in magnitude to that of traffic-related air pollution in Canada ($9.5B) (Health Canada, 2022). Wildfires and transportation are the leading sources of population-weighted $PM_{2.5}$ exposure in Canada (Meng et al., 2019).

A recent analysis of the national annual health impacts attributable to wildfire-$PM_{2.5}$ for the continental US estimated 4,080 premature deaths and numerous non-fatal cardio-respiratory outcomes due to short-term exposure and 28,000 to 39,700 premature deaths due to long-term exposure based on the 2020 wildfire season (Cromar et al., 2024), similar to previous health impact analysis for wildfire-$PM_{2.5}$ for the continental US for 2008–2012 (Fann et al., 2018). Both Cromar et al. (2024) and Fann et al. (2018) identified considerable regional differences in health impacts, with the greatest impacts in the regions with more wildfire activity and with wildfires contributing to a sizable portion of the total $PM_{2.5}$ exposure. Globally, emissions from landscape fires are an important contributor to adverse health outcomes, as an estimated 339,000 to 677,745 premature deaths per year are attributable to $PM_{2.5}$ from landscape fire smoke, with the greatest impacts in sub-Saharan Africa and Southeast Asia (Johnston et al., 2012; Roberts & Wooster, 2021).

Although most wildfires occurred in remote, less densely populated areas, the 10 most impacted CDs were split between population centers in Western and Central Canada. The wildfire-$PM_{2.5}$ exposure levels were typically greater in the western population centers, associated with the more frequent wildfire activity in this region. While the wildfire-$PM_{2.5}$ exposure levels were lower in the central region of Canada, a large health burden was noted as these include the major population centers of Toronto and Montreal and the region had significant wildfire activity in both 2021 and 2023. A health impact analysis of wildfire-$PM_{2.5}$ in California, for 2008–2018, also identified that although the wildfire activity was mainly located in rural, forested regions, the mortality impacts were greatest in the population centers (Connolly et al., 2024). The authors noted that while other sources of $PM_{2.5}$ are dominant in urban areas, wildfires accounted for 19%–42% of the $PM_{2.5}$-attributable deaths per year. Thus, the long-range transport of wildfire smoke, including across borders, results in public health impacts that can extend geographically beyond the wildfire zones (Sacks et al., 2023; Wen et al., 2023).

The inherent assumption in using a single year's exposure to estimate the chronic health impacts attributable to wildfire-$PM_{2.5}$ exposure is that the given wildfire season is representative of the recurring situation year after year. However, substantial variability is noted between wildfire seasons. To address this limitation, the long-term average wildfire-$PM_{2.5}$ exposure was determined for 2013–2023, and the associated chronic health impacts were estimated. Based on this long-term average exposure, 1,900 premature deaths per year were attributable to wildfire-$PM_{2.5}$. By comparison, over the 10-year period, the range of chronic premature deaths varied by almost an order of magnitude—from 570 in 2013 (Matz et al., 2020) to 5,400 in 2023, with an average of about 1,800 premature deaths annually. This illustrates the potential over- or under-estimation of health impacts from a variable exposure source, when relying on an annual average exposure based on a single year.

There are some limitations and uncertainties in the air quality modeling data and health impact analysis used in this study. For the air quality modeling, GEM-MACH and FireWork are forecasting models which presents some inherent limitations for the current analysis. FireWork is based on a 10 km × 10 km grid and assumes uniform emissions within a grid cell, which likely underestimates the $PM_{2.5}$ concentrations near sources. Predictions of $PM_{2.5}$ are also influenced by emission factors and plume injection heights, which are areas of refinement and improvement in the model (J. Chen et al., 2019; Munoz-Alpizar et al., 2017; Pavlovic et al., 2016). The key strength of the current approach is the ability to separate wildfire-specific $PM_{2.5}$ from other sources, as FireWork incorporates the emissions from biomass burning in addition to those from other natural and anthropogenic sources already contained in GEM-MACH.

For the estimation of the health impacts, a key assumption is that the concentration-response relationships, derived from the epidemiological literature for ambient $PM_{2.5}$, are applicable for the analysis of wildfire-$PM_{2.5}$. The use of CRFs derived from ambient $PM_{2.5}$ studies is consistent with the approaches taken by other authors (Cromar et al., 2024; Fann et al., 2018; Johnston et al., 2012; Matz et al., 2020). Some analyses have developed wildfire-specific CRFs (Connolly et al., 2024; Cromar et al., 2024; Wen et al., 2023). Typically these are derived from studies of a single wildfire event or a single wildfire season in a limited geographical area, which have limitations in terms of generalizability to other populations and regions. In the present study, the acute and chronic mortality CRFs were derived from large Canada-wide studies (Huang et al., 2023; Crouse et al., 2012; Table S1 in Supporting Information S1) and were considered the most appropriate for a national analysis. These CRFs have been used in other Health Canada health impact assessments of ambient air pollution (Health Canada, 2024; Pappin et al., 2024). Although this may under- or over-estimate the health impacts, it is a reasonable assumption as wildfire smoke is a contributor to total ambient $PM_{2.5}$, and is one of the main contributors in Canada (Meng et al., 2019). Further research is necessary to support development of wildfire-specific CRFs for both acute and chronic exposure, as well as to understand the potential shapes of the functions as wildfire episodes can lead to periods of intense smoke exposure. Wildfire smoke episodes can cause behavior change in the exposed population (e.g., reduced mobility, less time outdoors), which may be greater during periods of intense smoke exposure (Burke et al., 2022; H. Chen et al., 2025; Heft-Neal et al., 2023). These differential behavior changes would be anticipated to impact the shape of the functions. Although most studies have focused on wildfire-$PM_{2.5}$, wildfire smoke contains many chemicals that are known to have adverse health effects; thus, the development of CRFs for the other components could help to fully characterize the health impacts. Cromar et al. (2024) also identified a pressing need for wildfire-specific values for use in health impact analyses.

To address a known limitation in the analysis of chronic wildfire-$PM_{2.5}$ exposure, a 10-year average exposure was derived for this study. This approach assumes that the contribution to the long-term average from short-term periods of intense or elevated exposure to $PM_{2.5}$ during the wildfire season are equivalent to the same annual averages in exposure from consistent or steady sources of $PM_{2.5}$ throughout the time period. It is possible that other metrics of wildfire smoke exposure (e.g., peak exposure, days above exposure threshold, etc.) may also be relevant in terms of the health risks; however, investigations into the associations between long-term exposure to wildfire-$PM_{2.5}$ and health effects are limited. In a study of the continental US, a non-linear association between wildfire-$PM_{2.5}$ and non-accidental mortality, with an increase of 0.16–2.11 deaths per 100,000 when the 12-month moving average of wildfire-$PM_{2.5}$ was 0.1 to ≥5 μg/m^3 was observed (Ma et al., 2024). The authors also identified that although wildfires contributed to 5% of all-source $PM_{2.5}$, an estimated 11,415 deaths per year were due to wildfire-$PM_{2.5}$ or 16.8% of all $PM_{2.5}$-attributable deaths. In the present study, an estimated 1,900 premature deaths per year were attributable to long-term exposure to wildfire-$PM_{2.5}$ which is about 15% of the total $PM_{2.5}$-attributable premature deaths for Canada (estimated at 12,500 per year [Health Canada, 2024]) corresponding to the estimated population-weighted exposure to wildfire-$PM_{2.5}$ (17.1% of total $PM_{2.5}$ exposure [Meng et al., 2019]). Together, these studies underscore the relative importance of wildfire smoke for public health and the need for continued research into the health risk associated with long-term exposure.

5. Conclusions

This study is a Canada-wide analysis of the health impacts of wildfire-$PM_{2.5}$ for 2019–2023 and the health impacts of long-term exposure to wildfire-$PM_{2.5}$ for 2013–2023. Wildfire smoke is a major source of air pollution in Canada, and for 2019–2023, the annual premature deaths attributable to wildfire-$PM_{2.5}$ were 49–400 due to acute exposure and 660 to 5,400 due to chronic exposure, along with numerous non-fatal cardiorespiratory health outcomes. The economic valuation of the health burden was $450M to $3.6B for acute impacts and $6.1B to $49B for chronic impacts, per year. Considering the long-term average exposure to wildfire-$PM_{2.5}$ from 2013–2023, there were 1,900 attributable premature deaths and a total economic valuation of $18B, per year. Further research to refine the air quality modeling and to support development of wildfire-specific CRFs would improve the health impact analysis. Continued evaluation of the health impacts of wildfire smoke is important given the sizable contribution of wildfire smoke to air pollution in Canada, as well as the anticipated increases in wildfire activity.

List of Abbreviations

AB	Alberta
AQBAT	Air Quality Benefits Assessment Tool
BC	British Columbia
CAD	Canadian dollars
CCME	Canadian Council of Ministers of the Environment
CD	Census Division
CI	confidence interval
CIFFC	Canadian Interagency Forest Fire Center
CO	carbon monoxide
CRF	concentration response function
DA	Dissemination Area
ECCC	Environment and Climate Change Canada
GEM-MACH	Global Environmental Multi-scale—Modeling Air Quality and Chemistry
MB	Manitoba
MSC	Meteorological Service of Canada
NO_x	nitrogen oxides
NT	Northwest Territories
ON	Ontario

PM	particulate matter
$PM_{2.5}$	fine particulate matter with diameter ≤2.5 μm
QC	Quebec
VOCs	volatile organic compounds
YT	Yukon

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The air quality modeling data for this project were developed under an agreement between Health Canada and Environment and Climate Change Canada. The are available at: https://hpfx.collab.science.gc.ca/~smco810/Deliveries/GeoHealth/ForestFiresHC_2026/ (ECCC, 2026). Health Canada's Air Quality Benefits Assessment Tool (AQBAT), a computer application designed to estimate the human health impacts of changes in Canada's ambient air quality, is available at https://health-infobase.canada.ca/aqbat/.

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