Burning Questions: Geospatial Insights into Canada's Wildfires, Ontario Air Quality, and Health Risks

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Introduction

Over the past century, climate change has intensified significantly, driven largely by increased greenhouse gas emissions and human activities. One notable consequence of this shift is the global rise in the frequency and severity of wildfires. Globally, the risk of fire has increased due to more frequent and severe weather, acting as a catalyst for wildfires especially in North America, Southern Europe, Scandinavia and Australia (Jones et al. (2020)). 2023 was a particularly intense year in the history of Canadian wildland fires. The government of Canada estimates that wildland fires, (totalling 6, 623 for the year) accounted for over 230,000 evacuations and burned down more than 15 million hectares of land; a figure significantly above average in Canada's history (Natural Resources Canada (2025)). Thus, the 2023 wildfire season in Canada was unprecedented, setting new records in both the number and severity of fires across multiple provinces (Jones et al. (2024)).

Air pollution is a major environmental and public health concern, particularly when driven by natural disasters like wildfires. In recent years, the Canadian wildfire seasons have increased in severity, leading to deteriorating air quality and heightened risks for vulnerable populations (Wang et al. (2024)). This has facilitated a peak in the emission of Fine particulate matter (PM2.5), a key pollutant emitted during wildfires. Increased PM2.5 levels poses significant health risks, including respiratory and cardiovascular diseases, and is an immediate threat to vulnerable populations. In a comprehensive study on wildfire smoke in Canada, Matz et al. (2020) quantified the health impacts of PM2.5 exposure between 2013 and 2018, highlighting thousands of premature deaths and hospital visits attributable to wildfire-related air pollution. While there are certainly other pollutants that are caused by fires and pose health risks worth mentioning, including Carbon Dioxide and methane ,this analysis will focus on PM2.5 emissions as is commonplace in much of the literature (Chowdhury et al (2024)). Understanding the spatial and temporal link between wildfire activity and air pollution is critical for informing public health responses and policy interventions.

This project aims to analyze the relationship between wildfire activity and air quality across Ontario, focusing on the exposure of populations to PM2.5 levels exceeding World Health Organization (WHO) recommendations. According to the World Health Organization (WHO, 2021), the recommended PM2.5 levels should not exceed 5 $\mu g/m^3$ as an annual mean, and 15 $\mu g/m^3$ for short-term (24-hour) exposure, which will be our benchmark values. Using satellite-based air quality datasets, fire data, and demographic statistics at the census division level, we will quantify the extent to which wildfires contribute to poor air quality and estimate the number of people affected. In this regard we will propose a risk-weighted air quality index, which accounts for sensitive sub-portions of the population as well as measuring when air quality exceeded WHO standards.

Exposure to wildfire smoke poses significant health risks, particularly for vulnerable populations (EPA (2025)). Individuals with pre-existing conditions such as asthma and cardiovascular diseases, pregnant women, the elderly, and children are especially susceptible to experiencing negative health effects of poor air quality resulting from wildfires. For instance, studies have shown that exposure to fine particulate matter (PM2.5) from wildfire smoke can exacerbate respiratory conditions like asthma and chronic obstructive pulmonary disease (COPD), leading to increased hospital admissions and emergency room visits.

Previous research has demonstrated that wildfire emissions in Canada can significantly affect air quality well beyond the immediate fire zones. For example, Wotawa and Trainer (2000) found that smoke plumes from Canadian wildfires contributed to elevated pollutant concentrations across the United States, indicating the potential for long-range atmospheric transport of wildfire smoke. Similarly, Sapkota et al. (2005) documented increased PM2.5 levels in Baltimore, Maryland, during the 2002 Canadian wildfire season, linking distant fires to measurable health-related air quality impacts in urban centers.

Building on these findings, this study focuses on Ontario as a downwind region that, while not always the origin of wildfire events, often experiences degraded air quality due to fire activity in neighboring provinces. Ontario is the most populated province in Canada and home to major urban centers like Toronto, making it particularly important to assess the risk exposure to wildfire-driven air pollution in this province.

To assess risk exposure and population sensitivity to deteriorating air quality caused by wildfire activity, we classify individuals under the age of 14 and over the age of 65 as vulnerable groups, using age as a proxy for sensitivity. This classification is based on both established public health guidelines and data availability. While age alone doesn't capture all health risk factors, it correlates strongly with other risk indicators. For example, older adults are more likely to suffer from chronic conditions such as cardiovascular disease or diabetes. In Canada, between 2020 and 2021, 27% of individuals aged 65 and older had been diagnosed with diabetes (Public Health Agency of Canada, 2023), highlighting the increased susceptibility of this age group to air pollution.

Children, on the other hand, are particularly vulnerable due to their developing lungs and higher respiratory rates. Their airways are still maturing, and they inhale more air per kilogram of body weight than adults, which increases the dose of inhaled pollutants. Exposure to fine particulate matter (PM2.5) during early stages of life has been linked to long-term respiratory issues, increased asthma incidence, and impaired lung function development. As such, children are a key group to consider when evaluating health risks related to wildfire smoke and declining air quality.

Data Selection and Description

In all the datasets we consistently make use of the WGS 1984 Coordinate reference System. We make use of 6 datasets, which include:

Canadian Wildland Fire Information System from Natural Resources Canada, 2023-4 Available: https://cwfis.cfs.nrcan.gc.ca/downloads/hotspots/archive/. This dataset contains non-geospatially encoded data pertaining to area burnt on account of wildfires in Canada for 2023-4.

Fire Perimeter Data from Canadian Wildland Fire Information System from Natural Resources Canada. Available: https://cwfis.cfs.nrcan.gc.ca/datamart/download/nfdbpoly. This data contains polygon and multi-polygon vector data which maps the perimeters associated with wildfires in Canada for 2023-4.

Canadian Provinces from RNatural Earth. Available: https://www.naturalearthdata.com/downloads/50m-cultural-vectors/50m-admin-1-states-provinces/. This is a publicly available domain. The Canadian data is sourced largely from Statistics Canada. It is useful for a broader and less detailed geospatial setting, rather than focusing on smaller, more granular spatial denominations (e.g., census divisions). Notably, the scope of this analysis is limited to Ontario due to data restrictions in retrieving up-to-date air quality data for all of Canada. Since Ontario is the most populated province by a significant margin, this analysis is still valuable in exploring the general effect of wildfires on Canadian health outcomes.

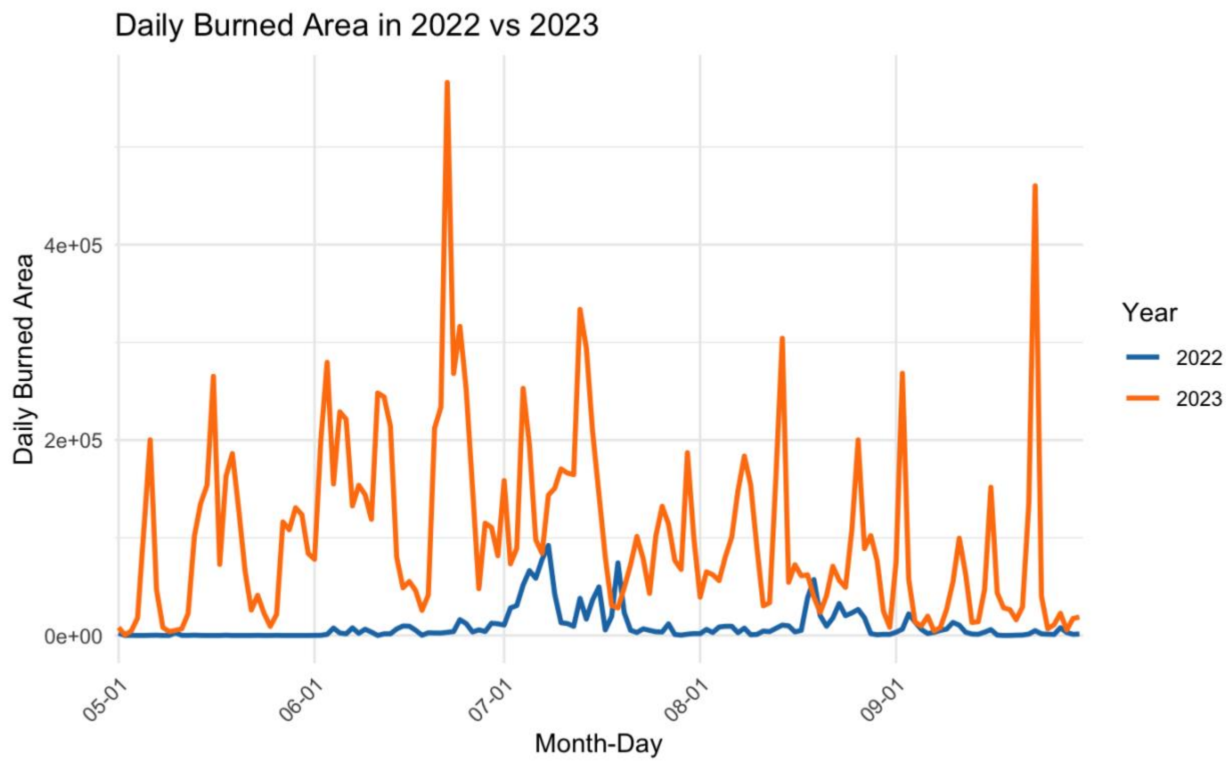
Census Division Data from Statistics Canada, 2021. Available: https://www12.statcan.gc.ca/census-recensement/2021/geo/sip-pis/boundary-limites/index2021-eng.cfm?year=21. This contains polygon data for Canada's census divisions.

Air Quality Ontario, 2023 and 2024. Available: https://www.airqualityontario.com/science/data_disclaimer.php. This data contains hourly readings for Ontario's PM2.5 (Particulate matter 2.5 micrograms) for June, July, and August 2022, which includes air quality historical data for Ontario by air quality monitoring stations. The monitoring stations provide data on air quality levels as well as the geographical points at which the readings were taken. Notably, we use data for June, July, and August 2022 (and 2023) since the largest effects of wildfires are felt in the summer months. Furthermore, we restrict the analysis to a panel of 2022 and 2023 to limit the influence of other latent factors affecting air quality (such as industry development), which would require greater control over a longer panel.

Marital status, age group and gender from Statistics Canada, 2024. Available: https://doi.org/10.25318/9810012701-eng. This data contains demographic information for different provinces, territories, census metropolitan areas, census agglomerations and census subdivisions. It is used in our analysis to incorporate population demographic data into the analysis, particularly when calculating our risk index later in the analysis. This data is not geospatially coded explicitly but contains region and subdivision identifiers.

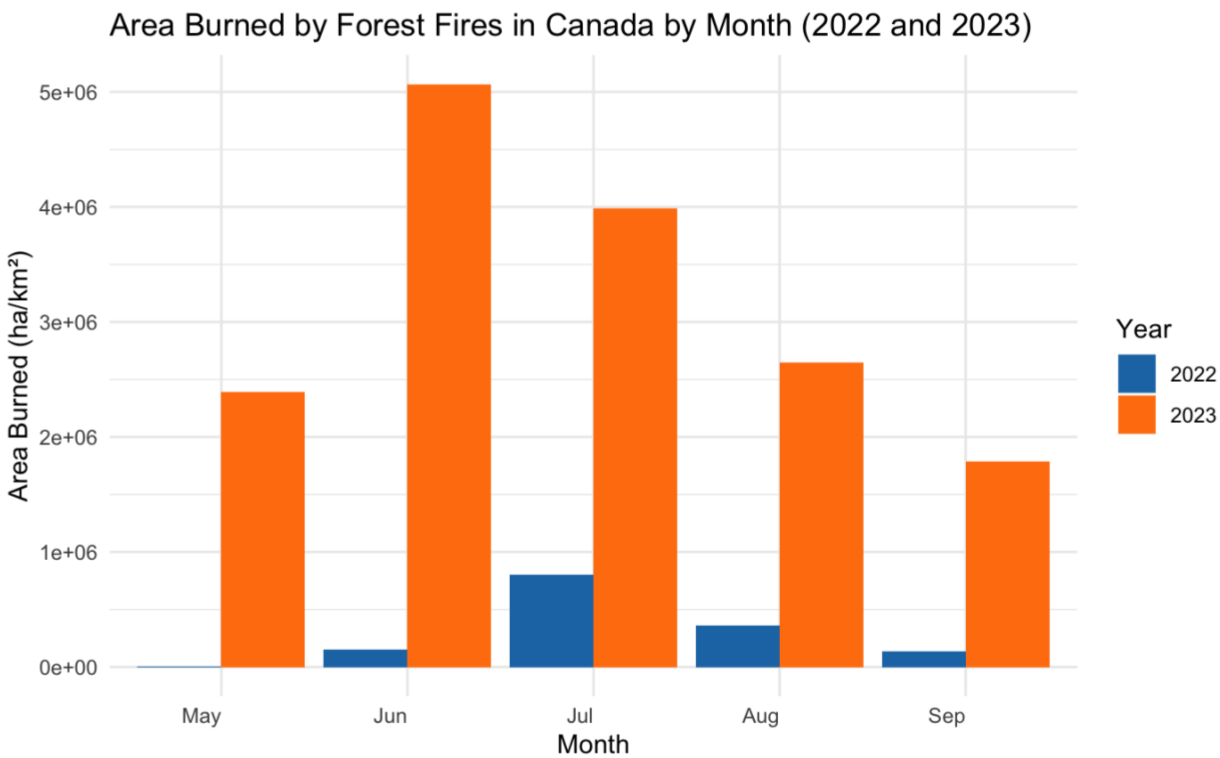
Visualizing the Fire Data

Graphing Daily Area Burned



This plot shows us a time series of daily burned area over the period from May to September in 2022 and 2023. We narrow the scope of area burnt to the May-September period as this coincides with the peak in wildfire activity, with June-August coinciding with Canada's summer months. We can see clear differences between the years in terms of fluctuations and magnitude. The time series for 2022 is relatively flat until the month of July, then at the beginning of the month there is a temporary peak in the burned area, followed by a smaller peak at the end of August. On the contrary, 2023 exhibits much higher daily fluctuations of burned area, starting in May. The most significant peak happens at the end of June, so a little bit earlier than 2022. The following graph will give us more insights in the magnitude differences per month. However, this graph already indicates that in 2023 the daily area burned is significantly higher over all the summer months with some exceptional peaks. This underlines statements of other sources about the severity of the fires of 2023 relative to 2022.

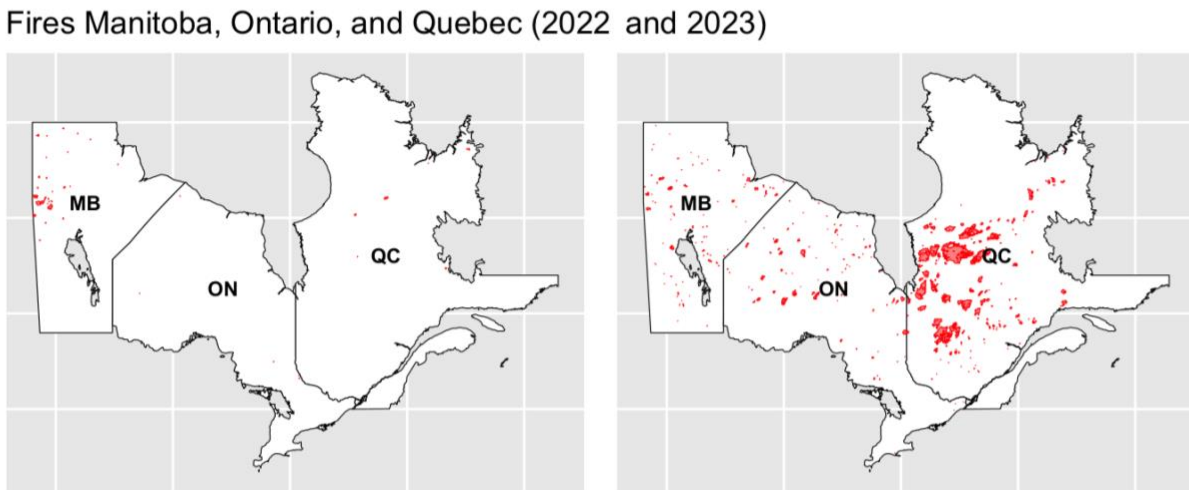
Graphing Monthly Area Burned



The above graph gives us more information about the actual magnitudes of the area burned due to wildfires, but this time aggregated on a monthly basis. We see that the month of May is already an indicator that the fires of 2023 will be extraordinarily severe as in 2022 almost no area was burned but in May 2023 already more than in any other month of 2022. Furthermore, we can see that the month of June had the most devastating effect in 2023, coinciding with the significant wildfires evidenced in Quebec in the same period. Henceforth, we will narrow the focus of our analysis on the months of June to August (summer) as we saw that during this time the most fires must have taken place in both years, and so will be the most suitable candidate to assess the impact of wildfires on air pollution outcomes.

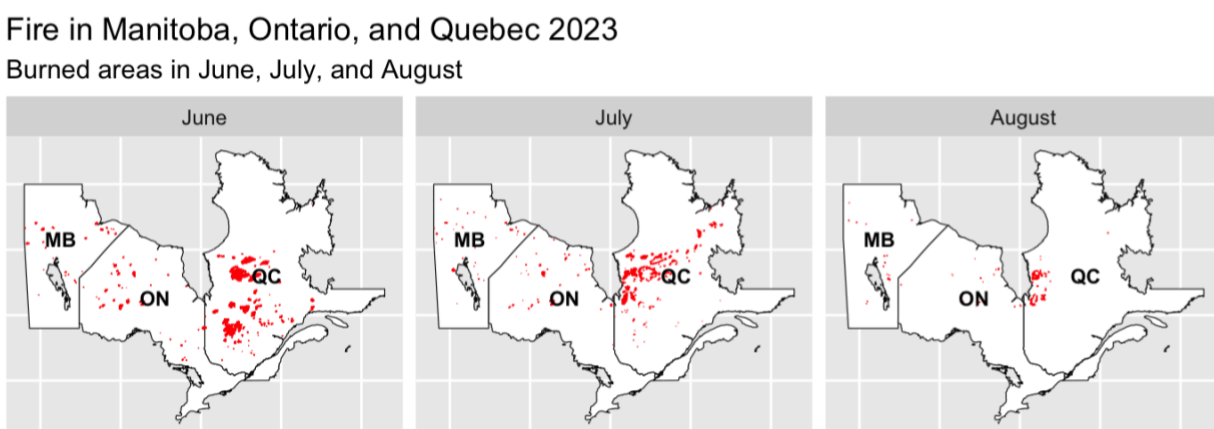
We have already observed the stark difference in the extent of wildfires between 2022 and 2023. In the following, we aim to visualize the fires to better understand their spatial distribution and scale. Our unit of analysis will focus specifically on Ontario, as motivated in the introduction. It is worth noting that we expect spillover effects on the air quality in Ontario especially from the neighboring provinces, Manitoba and Quebec. Therefore, we look at these three provinces specifically. This allows us to keep the analysis within a manageable scope. The first thing we observe is that the fire clusters in 2023 are significantly more in quantity, larger in size, and more widely distributed compared to those in 2022. In particular, there is a significant amount of fires in Quebec close to the eastern border of Ontario in 2023. We hypothesize that the spillover effects from Quebec wildfires will likely impact air pollution in Ontario, especially on its Eastern border.

Mapping Yearly Burnt Area



Mapping Monthly Burnt Area

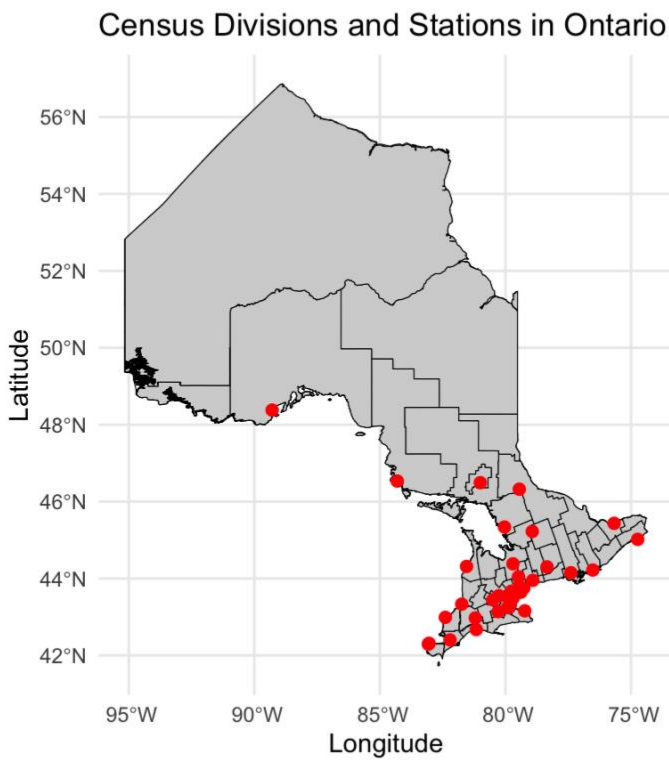
To map the monthly area burned data we use the daily progression polygon data. We use this since the perimeter data is divided by individual fires, some of which lasted over multiple months. Whereas the progression data has the daily geographic progression of every active fire.



Now, we zoom in on the summer months of June to August, the period during which we previously observed the highest wildfire activity. The maps clearly show that fires in June and July were particularly widespread and intense, especially in Quebec, including several large fires occurring near the Ontario border and in Ontario itself, while activity in August appears to have decreased considerably in both scale and distribution. This temporal breakdown highlights the peak of the 2023 fire season and provides context for assessing its impact on air quality and population exposure.

Visualizing the Air Quality Data

Plot of Ontario and its Air Quality Stations



The map displays the spatial distribution of air quality monitoring stations (red points) across Ontario’s census divisions. It is immediately clear that the majority of stations are clustered in southern Ontario, particularly around densely populated urban centers. This reflects a population-focused monitoring strategy, which ensures coverage in areas where the health burden of air pollution may be highest due to both population density and vulnerability. However, northern Ontario, where wildfire activity tends to be more intense and widespread, as we saw in the figure before, is significantly under-monitored. Several large census divisions in the north have no direct station coverage, which may limit our ability to fully assess air quality impacts in those regions. Additionally, stations located in eastern Ontario, near the Quebec border, are positioned to capture transboundary effects. This is particularly relevant given the intense wildfire activity in Quebec during the summer of 2023. We will have to take this into account in our further analysis, especially when assessing risk exposure based on air quality data.

Data Preparation for Change in Air Quality Map

To estimate the effect of wildfires on air quality in Ontario, we will perform a difference calculation. That is, we will compute the difference in average monthly air quality for each census division in Ontario. However, to ensure that we account for seasonal fixed effects, we will do this on an annual basis. That is, We will compute the average change in monthly air quality from June 2022 to June 2023, and do the same calculation for July 2022 - 2023, and August 2022-2023 respectively. This will all be collected onto one map (with a slider) to show the evolution in air quality in the summer months in Ontario from 2022-2023. To enhance the analysis, we will overlay the fires (area burnt) 2023 data collected previously in the project. This, we hypothesize, will correlate with higher PM2.5 levels in the region. Notably, this will include the area burnt/fire data for neighbouring provinces (such as Quebec) to illustrate the spillover effects of neighbouring provinces who also experiences significant forest fires in the summer of 2023.

Aggregating Air Quality Data by Census Division

Since we are performing this analysis at a Census Division level, it will be necessary to aggregate the various readings of different air quality stations by census division. As seen in the above map, the air quality stations miss some of the census divisions and some census divisions contain more than one air quality station. The former is a problem which requires imputation, while the latter will be resolved by taking the mean over the various air quality stations.

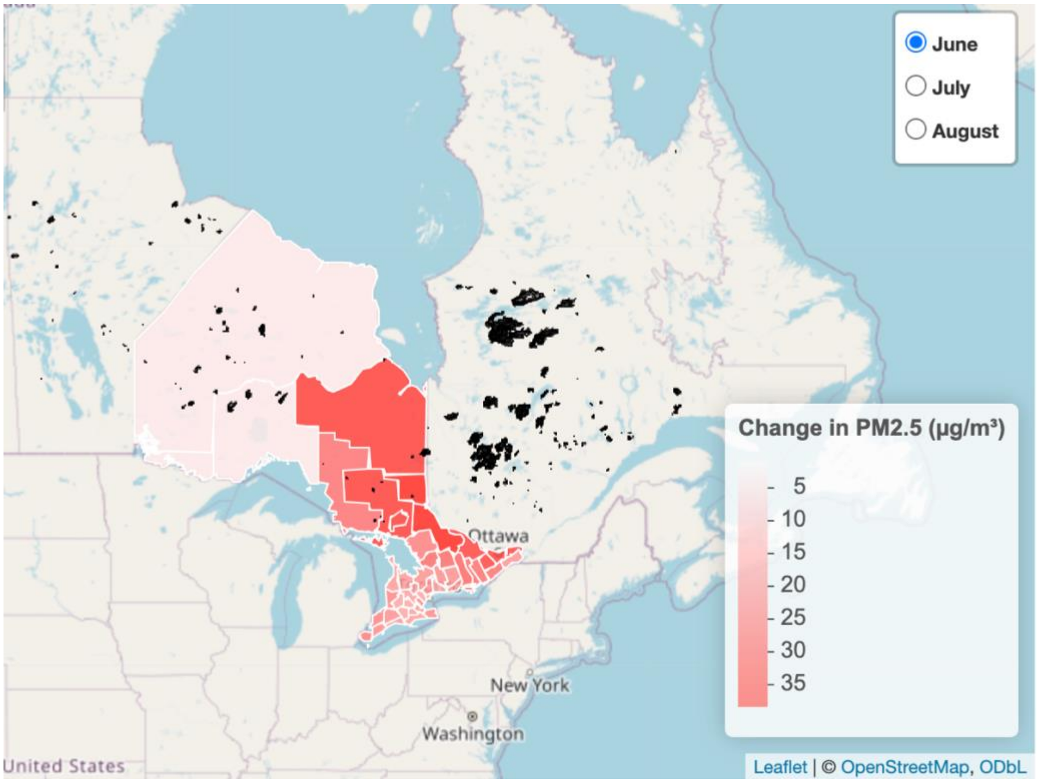
Accordingly we follow the following aggregation strategy: -If a census divison has one air quality station, this station's readings form the average reading for the division. -If the census division has more than one air quality station, we average out all the air quality stations in that census division and this becomes the division's air quality index. For divisions with no air quality stations we perform an imputation outlined below.

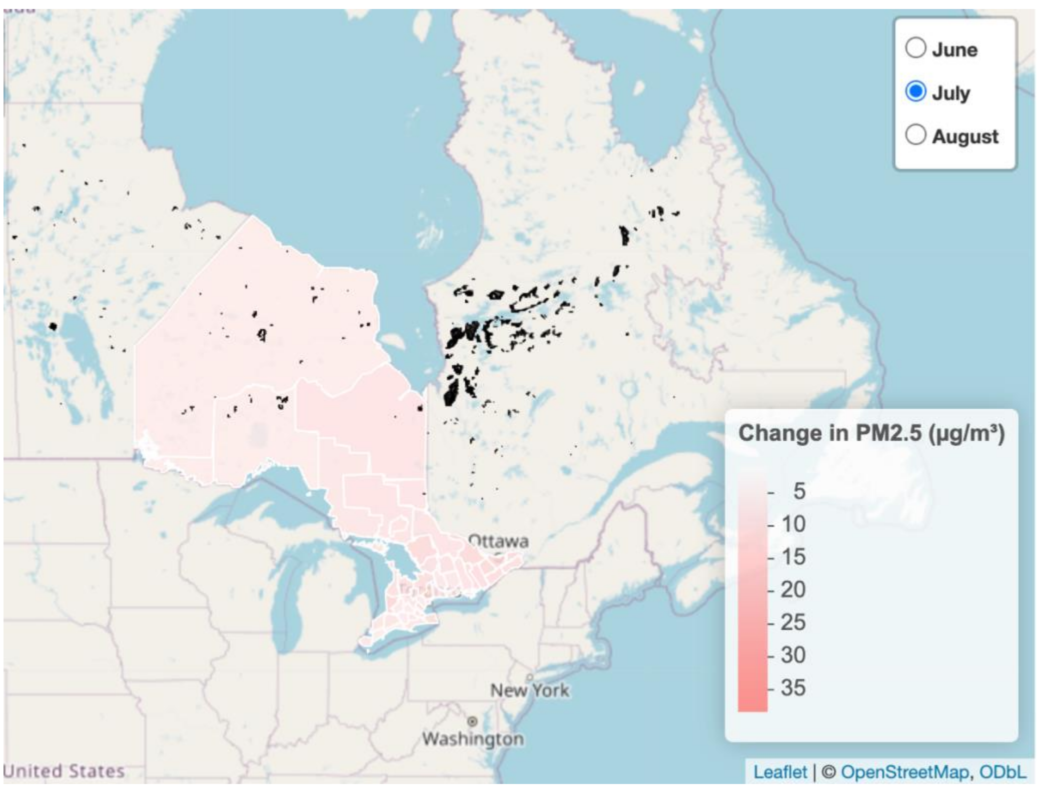
Census Divisions with Missing Stations Imputation

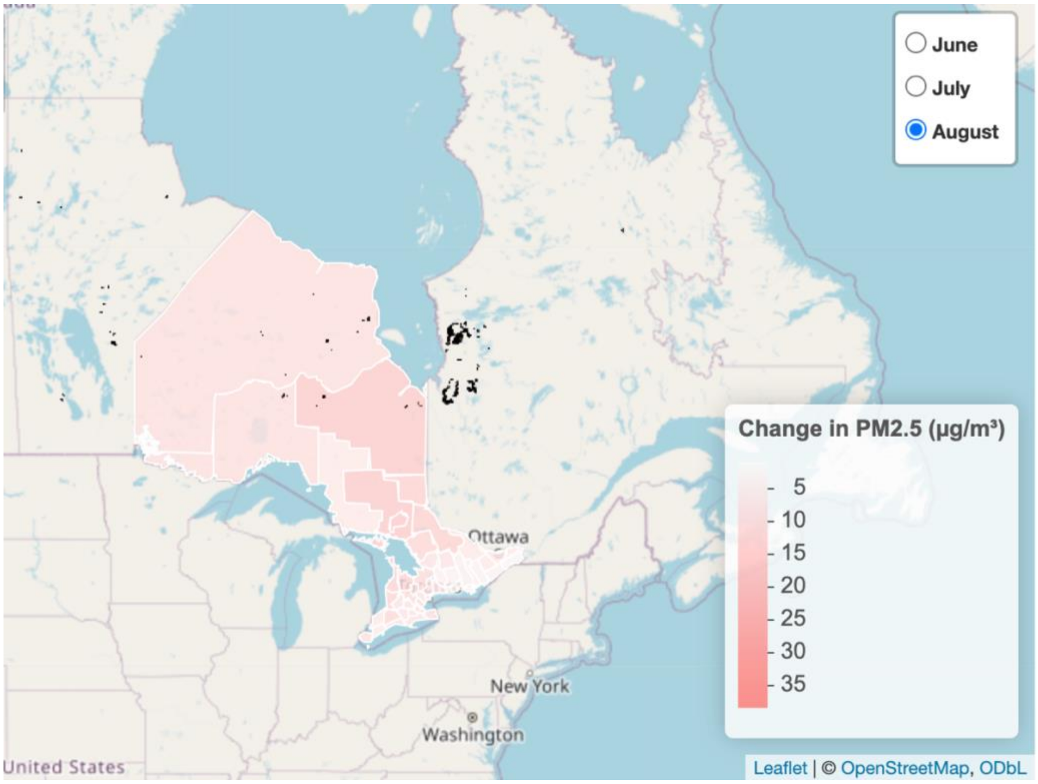
If a census division has no station present, we perform a distance calculation. However, to maintain the integrity of the data, it makes sense to collect the distance from the centroid of the census division and compute the distance to the closest air quality station. We use the centroid as it is the most representative location of a particular census division. The air quality station's readings will be the estimated air quality for that census division. This approach is preferable to using neighboring divisions' readings since these readings are themselves calculated and not given, adding more uncertainty to the integrity of the results.

Notably, since air quality does not travel via roads, but rather by air, it is appropriate to collect the Euclidean distance between the centroids of the appropriate census division and the nearest air quality station.

Change in Air Quality and Fires Map: June, July, and August 2023





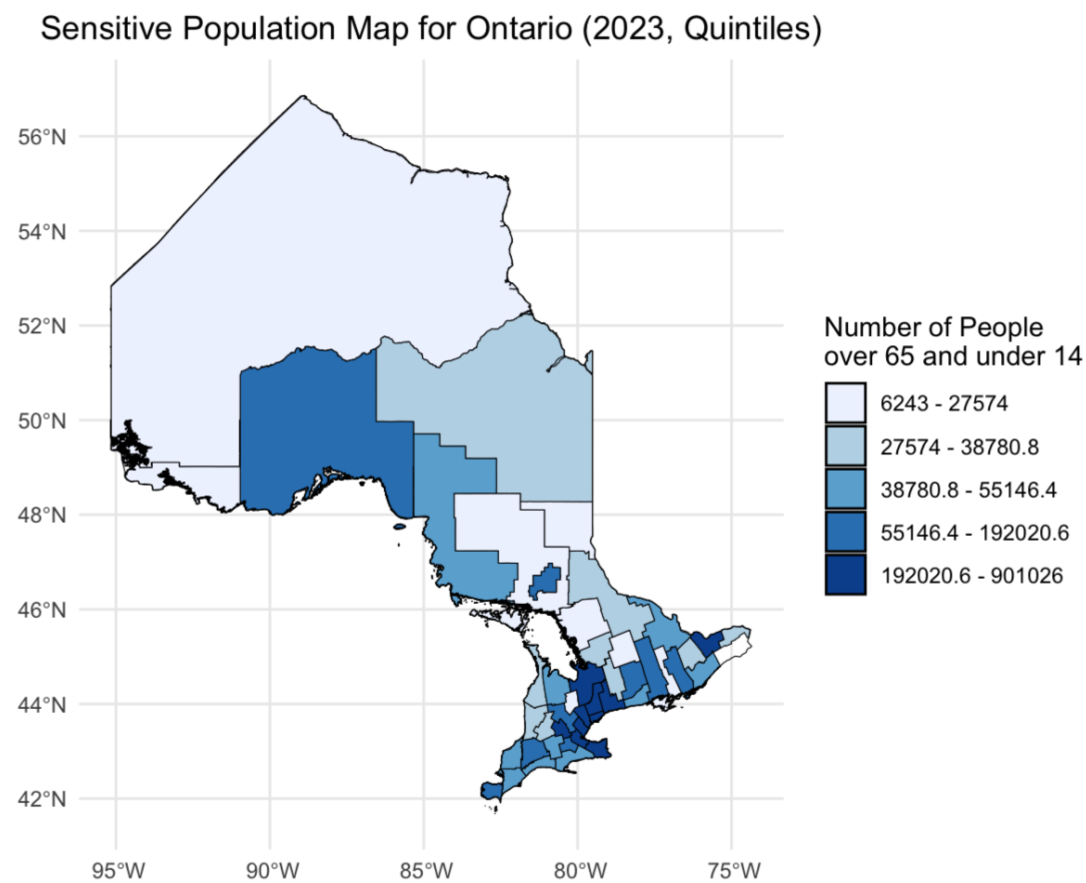


This leaflet map visualizes the monthly change in PM2.5 concentrations (µg/m³) across Ontario's census divisions by comparing 2023 values to those of the same months in 2022. It allows us to switch between June, July, and August to explore how air quality changes across time and space. One notable observation is that in northeastern Ontario, along the Quebec border, we see the largest increases in PM2.5, particularly in June, which aligns with the most intense wildfire activity of 2023, located in Quebec. Several areas experienced increases of over 30 µg/m³, clearly reflecting the timing and location of nearby fire outbreaks. In contrast, southern Ontario shows more moderate changes. This lends credence to the hypothesis that Wildfires have a significant (and detrimental) effect on air quality outcomes due to the significant presence of wildfires along the North-Eastern Ontario-Quebec border, while less fires occurred further south. These patterns reveal not only the temporal concentration of wildfire-driven pollution—peaking in June—but also geographic disparities in exposure, with more remote regions facing the greatest deterioration. The months of July and August exhibit significantly less change in air quality relative to 2022, which aligns with the fact that fewer (and less intense fires) occurred in these months relative to June.

Creating a Sensitive Population Index

The next step in our analysis seeks to link the effect of these wildfires (in terms) of air quality, with portions of the population who are particularly susceptible to worsened air quality conditions. From our review of literature, persons aged below 14 and above 65 were noted to be particularly susceptible and at risk to worsened air quality conditions.

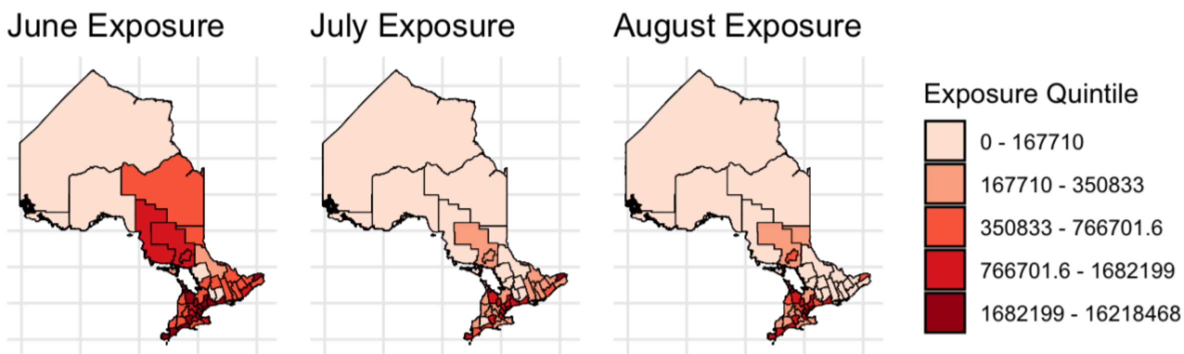
Sensitive Population Mapped Over Ontario



This map highlights the distribution of Ontario's sensitive population, defined here as individuals under 14 and over 65 years of age, by census division in 2023, grouped into quintiles. The highest concentrations of sensitive populations are found in southern Ontario, particularly in and around the Greater Toronto Area and other urbanized regions. While northern Ontario shows lower absolute numbers, some large census divisions still rank in mid to higher quintiles, suggesting meaningful levels of at-risk populations despite lower density. This spatial breakdown helps identify regions where air quality shifts due to wildfire smoke could pose increased public health risks.

Index for Air Pollution Exposure and Sensitive Populations

Next, we calculate an exposure index and visualize its distribution across census divisions in Canada for the summer months of 2023. The exposure index is defined as the product of the number of days with high $PM_{2.5}$ levels (above 15 µg/m³) and the number of sensitive individuals in the area. This approach accounts for both the intensity and population vulnerability to wildfire smoke, where higher values indicate greater potential health risks. To analyze spatial patterns, we classify the index into quintiles and create geographic visualizations for June, July, and August. These maps highlight areas with the highest exposure, providing insights into regional disparities and identifying locations that may require targeted interventions, such as air quality alerts or public health measures.



As expected, the exposure rate in June is significantly higher as evidenced in the East and South East portions of Ontario exhibiting much higher values.

While the exposure rate drops in July relative to the other months, there is a consistently high exposure rate in southern Ontario census divisions, getting closer to Toronto. The likelihood here is that the worsened air quality due to city industry and activity are the predominant cause of this high exposure. August's exposure further suggests that once again census divisions in the East of Ontario were exposed, albeit not as significant as in June.

Interestingly, in these eastern portions of Ontario, the relatively low sensitivity of the population is completely outweighed by the high air pollution rates.

Conclusion

This analysis highlights several key findings about the relationship between wildfire activity and air quality in Ontario. First, wildfires in Quebec exhibited significant spillover effects, with smoke and pollutants crossing into Ontario and contributing to notable air quality degradation. Second, the intensity, frequency, and total area burned were all substantially higher during the summer months, particularly in June, when wildfire activity was at its peak.These wildfire spillover effects extended to the risk-weighted exposure index which exhibited high values inJune near the Quebec border.

We find that the increase in wildfires is significantly associated with worsened air pollution, with the most severe PM2.5 spikes observed in June. Interestingly, the "most vulnerable" members of the population—defined here as individuals under 14 and over 65—do not primarily reside in the regions with the greatest air quality deterioration. However, with climate change continuing to intensify, this disconnect may not persist, and it remains a critical area for future monitoring and mitigation.

Our risk-weighted air quality pollution index appears to be significantly higher in regions in Southern Ontario, coinciding with higher population density. Nevertheless,the index was sensitive and indeed reflected the worsened air quality. on the Eastern Ontario border. These findings suggest that further research should extend this analysis to all of Canada, incorporating additional risk factors such as lung disease prevalence, asthma rates, and other respiratory-related health indicators. Finally, employing a difference-in-differences model using adjacency to the Quebec border as a potential treatment may provide stronger causal evidence of the detrimental impact of wildfire activity on air quality—particularly given the clear spatial and temporal alignment observed in this study.

In this project, we demonstrated the relationship between wildfire activity, changes in air quality, and potential population exposure in Ontario—largely confirming our expectations. We observed clear spatial and temporal patterns in PM2.5 concentrations that aligned with wildfire outbreaks, particularly during the peak fire months of June and July 2023. By combining air quality data with demographic information, we highlighted regions with both high pollution levels and large vulnerable populations.

If we had access to more time and data, it would be valuable to extend this analysis to all of Canada to better understand interprovincial patterns and broader national impacts. Additionally, incorporating health outcome data—such as emergency department visits, respiratory-related hospital admissions, or chronic disease prevalence—would enable a more direct assessment of the health impacts of wildfire smoke exposure. This would also improve our ability to identify and prioritize at-risk groups, especially beyond basic age-based categories. Together, these additions would allow for more targeted public health interventions and stronger evidence to guide climate and health policy.

References

Chowdhury, S., Hänninen, R., Sofiev, M., & Aunan, K. (2024). Fires as a source of annual ambient $PM_{2.5}$ exposure and chronic health impacts in Europe. *Science of the Total Environment, 922*, 171314. https://doi.org/10.1016/j.scitotenv.2024.171314

Jones, M. W., et al. (2020). *Climate change increases the risk of wildfires* (No. 20203193113). https://www.preventionweb.net/files/73797_wildfiresbriefingnote.pdf

Jones, M. W., et al. (2024). State of wildfires 2023–2024. *Earth System Science Data, 16*(8), 3601–3685. https://essd.copernicus.org/articles/16/3601/2024/essd-16-3601-2024.html

Matz, C. J., Egyed, M., Xi, G., Racine, J., Pavlovic, R., Rittmaster, R., ... & Stieb, D. M. (2020). Health impact analysis of $PM_{2.5}$ from wildfire smoke in Canada (2013–2015, 2017–2018). *Science of the Total Environment, 725*, 138506. https://www.sciencedirect.com/science/article/pii/S0048969720320192

Natural Resources Canada. (2025). *Forest fires: What you need to know*. Government of Canada. https://natural-resources.canada.ca/forest-forestry/wildland-fires/forest-fires# (Accessed March 23, 2025)

Public Health Agency of Canada. (2023). *Snapshot of diabetes in Canada, 2023* (Cat. No. HP35-180/2023E-PDF; ISBN 978-0-660-68701-8; Pub. No. 230557). https://www.canada.ca/en/public-health/services/publications/diseases-conditions/snapshot-diabetes-canada-2023.html

Sapkota, A., Symons, J. M., Kleissl, J., Wang, L., Parlange, M. B., Ondov, J., ... & Buckley, T. J. (2005). Impact of the 2002 Canadian forest fires on particulate matter air quality in Baltimore City. *Environmental Science & Technology, 39*(1), 24–32. https://pubs.acs.org/doi/full/10.1021/es035311z

U.S. Environmental Protection Agency. (2025). *Patient exposure and the Air Quality Index*. https://www.epa.gov/pmcourse/patient-exposure-and-air-quality-index

Wang, Z., et al. (2024). Severe global environmental issues caused by Canada's record-breaking wildfires in 2023. *Advances in Atmospheric Sciences, 41*, 565–571. https://link.springer.com/article/10.1007/s00376-023-3241-0

World Health Organization. (2021). *WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. https://iris.who.int/handle/10665/345329

Wotawa, G., & Trainer, M. (2000). The influence of Canadian forest fires on pollutant concentrations in the United States. *Science, 288*(5464), 324–328. https://www.science.org/doi/full/10.1126/science.288.5464.324