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Original Article

Spatiotemporal trends of wildfire distribution and smoke exposure metrics across selected provinces in Canada.

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Abstract

Background: Wildfire activity in Canada has intensified remarkably in recent years, leading to a record-breaking 2023 season during which transboundary smoke dispersed and affected populations across North America and Europe. Beyond immediate fire-related hazards, wildfire smoke represents a severe environmental and public health threat. Increasing fire frequency, duration, and severity have been linked to climate change, land-use transformation, and prolonged drought.

Methodology: An ecological time-series analysis at the provincial level was used to examine spatiotemporal trends in wildfire distribution and $PM_{2.5}$ metrics. Two primary data sources were integrated: wildfire activity indicators (area burned and number of fires) and air quality measurements ($PM_{2.5}$ concentrations and high-risk air quality days). Data were aggregated at the provincial level for each calendar year, enabling temporal trend analysis and ecological correlation assessment. $PM_{2.5}$ concentrations were used as a proxy for wildfire smoke exposure. R statistical software (version 4.4.1) was used for visualization and regression analysis.

Results: Temporal trend analysis revealed consistent increases in burned area across the provinces. Ontario demonstrated the largest proportional growth despite non-significant interannual differences. Heat-map visualization demonstrated significant spatial and temporal variability in wildfire burned areas. Quebec recorded the highest wildfire extent in 2023 (>4 million hectares), while British Columbia and Alberta each exceeded 1 million hectares. Ontario consistently exhibited lower burned areas compared to the other provinces.

Conclusion: The results from the study revealed that fire intensity, scale, and persistence play a more critical role in determining pollution exposure than the number of fire events alone. These findings highlight the complex interplay between climatic, environmental, and human influences in shaping wildfire dynamics and their public health implications across Canada.

Keywords: Spatiotemporal, Wildfire, $PM_{2.5}$, Provinces, Canada.

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Introduction

Wildfire smoke, a major source of fine particulate matter ($PM_{2.5}$), has been recognized as an increasing environmental and public health concern globally.[1] In recent years, Canada has experienced significant rises in wildfire frequency, duration, and intensity. The 2023 wildfire season represented the largest recorded fire event in the country's history, with smoke dispersing across North America and reaching parts of Europe [2]. Canada's vast forest ecosystems, covering nearly 40% of the national landmass, place several provinces, including British Columbia, Alberta, Saskatchewan, and Ontario, at heightened wildfire risk due to dense vegetation combined with progressively drier summer climates [3]. In 2023 alone, more than 17 million hectares were burned, far exceeding historical averages and previous national records [4]. These escalating trends are largely linked to climate change, land-use modifications, and prolonged drought conditions[1].

Wildfire occurrence is influenced by complex interactions among climatic factors, landscape characteristics, and human activities. Although regions with higher population density often benefit from improved fire suppression capacity, they simultaneously experience increased ignition rates, particularly during spring, underscoring the dual influence of human presence on wildfire initiation and spread [5]. Future climate projections indicate continued growth in wildfire risk, emphasizing the importance of national-scale assessments of wildfire susceptibility, ecosystem recovery, and spatiotemporal fire–environment interactions to support long-term monitoring and climate adaptation planning [6]. Consequently, analyzing spatial and temporal patterns of wildfire occurrence and burned area is essential due to the significant ecological, socio-economic, and environmental impacts associated with wildfire activity [5]. Smoke exposure also varies across provinces, with British Columbia and Alberta experiencing recurrent and severe impacts driven by geographic and climatic conditions [7].

Despite advancements in atmospheric monitoring through satellite systems and sensor technologies, important knowledge gaps remain regarding population-level exposure patterns and broader environmental health consequences. Immediate wildfire impacts include injuries, displacement, and infrastructure damage, while the long-term effects of sustained smoke exposure and increasing wildfire intensity remain insufficiently understood, particularly across Canadian provinces [7]. Beyond direct destruction, wildfire smoke produces widespread indirect effects, exposing populations far beyond fire boundaries [8]. Provinces already burdened by elevated background air pollution may face heightened health risks during wildfire events [9]. Exposure patterns further reveal socio-demographic disparities, as urban populations often experience prolonged elevations in $PM_{2.5}$ concentrations compared with rural communities, potentially influenced by monitoring and reporting differences [9]. During peak wildfire periods, elevated $PM_{2.5}$ levels pose substantial health threats; however, limitations in ground-based monitoring networks restrict epidemiological analysis and emergency response effectiveness [10].

This study, therefore, seeks to examine spatiotemporal trends in wildfire distribution and associated $PM_{2.5}$ exposure across selected Canadian provinces, to assess regional variability and evaluate the relationship between wildfire activity and population-level air quality outcomes. The findings are expected to support climate-resilient public health planning, strengthen emergency preparedness strategies, and reforms to provincial health guidelines, air quality regulations, and disaster response frameworks while enabling evidence-based identification of vulnerable populations.

Beyond its national relevance, this research contributes to the broader global discourse on climate change, environmental health, and wildfire management. As wildfire frequency and severity continue to increase globally, improving understanding of wildfire dynamics and smoke exposure is essential for advancing international strategies addressing climate-related health risks and long-term disease burdens.

Methodology

Study Area

This study was carried out in selected provinces in Canada, namely Alberta, British Columbia, Ontario, Quebec, and Saskatchewan. These provinces are of particular interest because they are provinces with high and frequent wildfire activities, they possess an established and comprehensive air quality monitoring system, which will enhance the reliability of the retrospective exposure assessment, and demographically diverse populations [3].

Research Design

This research adopted an ecological time-series analysis at the provincial level, relying on data from 2010-2023 to assess spatiotemporal trends in wildfire distribution and associated $PM_{2.5}$ exposure across selected Canadian provinces to evaluate regional variability and the relationship between wildfire activity and population-level air quality impacts. The study integrated two primary data sources: wildfire activity indicators (area burned, number of fires) and air quality measurements ($PM_{2.5}$ concentrations, high-risk air quality days). Data were aggregated at the provincial level for each calendar year, enabling temporal trend analysis and ecological correlation assessment. $PM_{2.5}$ concentrations were used as a measure of exposure to wildfire smoke, since these particles serve as a widely recognized proxy for smoke intensity [11].

Study Population

This study is an ecological time-series analysis at the provincial level. Secondary data were used for this study, which involved all air quality records from the five selected provinces and the wildfire activities within the five selected provinces. The inclusion criteria are: All records of $PM_{2.5}$ concentration within the selected province, and all records within the selected years for the study, only those of naturally occurring wildfires. Excluded from the study were wildfire incidents that occurred outside the 2010–2023 timeframe, and prescribed fires were excluded.

Sample and Sampling Techniques

For the secondary data, a non-probability selection approach was used to aggregate and select 5 provinces in Canada.

Data Sources and Collection

Wildfire Activity Data were obtained from the Canadian Wildland Fire Information System (CWFIS),[12][13], providing detailed information on wildfire perimeters and causes. Only natural-origin, non-prescribed fires were included. Data were aggregated to estimate total area burned (hectares) and the number of wildfire events per province per year.

Air Quality Data were retrieved from the National Air Pollution Surveillance (NAPS) Program [14] using $PM_{2.5}$ concentrations as a proxy for air pollution exposure. Hourly $PM_{2.5}$ measurements were averaged to produce daily and annual provincial means. Days with $PM_{2.5}$ concentrations exceeding 25 $\mu g/m^3$ were classified as high-risk days, consistent with Air Quality Health Index values ≥ 7 under Canadian health guidelines.

Data was provided by fiscal year, and harmonized to match calendar years used in environmental datasets.

Data Analysis Methods

Data were systematically coded, cleaned, and analyzed using Statistical Package for the Social Sciences (SPSS version 25) and R statistical software (version 4.4.1) for advanced visualization and regression modeling. Multiple analytical approaches were employed: Descriptive Statistics summarized wildfire activity, air quality indicators, and health outcomes through frequencies, percentages, means, standard deviations, medians, and interquartile ranges, while Temporal Trend Analysis employed time-series methods to assess changes in wildfire activity and air pollution from 2010 to 2023. Line graphs illustrated yearly variations, and percentage changes between baseline (2010) and endpoint (2023) quantified directional trends. Inferential Statistics included Analysis of Variance (ANOVA) to compare mean values across provinces, with Kruskal-Wallis tests employed where data violated normality assumptions. Statistical significance was determined at $p \leq 0.05$. Furthermore, correlation analysis utilized Pearson's correlation coefficient to examine linear relationships between wildfire activity indicators and air quality measures. Correlation strength was interpreted using conventional thresholds (weak: $r < 0.3$, moderate: 0.3-0.6, strong: >0.6). Graphical visualization included scatter plots with regression lines, heat maps illustrating spatiotemporal variations, and trend line graphs highlighting longitudinal shifts in air quality metrics.

Ethical Considerations

This study did not require research ethics board (REB) approval for the data collection because it used only publicly available and fully de-identified data, in accordance with the Canadian Tri-Council Policy Statement (TCPS 2) guidelines on research exempt from REB review.

Results

Table 1 presents inter-provincial variation in wildfire area burned across five Canadian provinces between 2010 and 2023. Quebec recorded the highest average burned area, followed by Saskatchewan and British Columbia, while Alberta and Ontario showed comparatively lower averages. The data revealed strong skewness and substantial year-to-year variability across provinces. Temporal analysis indicated increasing burned areas in most provinces, particularly in Quebec and British Columbia, with Ontario showing notable proportional growth despite statistically non-significant annual differences, suggesting episodic wildfire activity. Saskatchewan was the only province to exhibit a slight decline over time. Overall, the results demonstrate heterogeneous wildfire patterns and a general upward trend in wildfire activity across most provinces.

Table 1: Provincial Comparison of Wildfire Area Burned (2010–2023)

Provinces	Mean Area Burned (± SD)	**ANOVA (p-value)**	Median Area Burned **(IQR)**	**Kruskal-Wallis (p-value)**	**Area Burned in 2010**	**Area Burned in 2023**	**% Change (2010–2023)**	**Trend Direction**
Alberta	266,846 ± 372,469		91,926 (53,934–316,682)		67105.80	998637.22	13.88	↑ Increasing
British Columbia	529,541 ± 817,228		174,117 (79,064–599,070)		252837.42	2140916.33	7.47	↑ Increasing
Ontario	256,360 ± 277,857	0.37 (0.828)	198,721 (8,241–449,329)	3.88 (0.423)	8240.68	326992.93	38.68	↑ Increasing
Quebec	765,496 ± 1,699,444		31,855 (11,884–279,398)		279398.09	4227951.38	14.13	↑ Increasing

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Saskatchewan	611,380 ± 465,071		543,576 (213,994 – 883,227)		1291321.82	883227.24	-0.32	↓ Decreasing

*Statistically Significant (p<0.05); **SD**=Standard Deviations; **IQR**=Inter-quartile Range

Table 2 presents the provincial distribution and temporal changes of wildfire occurrences across five Canadian provinces from 2010 to 2023, revealing notable inter-provincial variability in central tendency, dispersion, and longitudinal trends.
Substantial inter-provincial variability in wildfire frequency and trends was observed between 2010–2023.
British Columbia recorded the highest fire frequency and a strong upward trend.
Ontario and Quebec showed marked increases; Ontario's rise was statistically significant.
Alberta experienced a slight decline in fire events.
Saskatchewan exhibited relatively stable wildfire occurrence over time.

Table 2: Provincial Comparison of Number of Fires (2010–2023)

Provinces	Mean Number of Fires (+SD)	**ANOVA (p-value)**	Median Number of Fires **(IQR)**	**Kruskal-Wallis (p-value)**	**Number of Fires in 2010**	**Number of Fires in 2023**	**% Change (2010–2023)**	**Trend Direction**
Alberta	92.3 ± 33.3		94 (80–119)		131	91	-0.31	↓ Decreasing
British Columbia	230.7 ± 148.1		220.5 (152–287)		193	473	1.45	↑ Increasing
Ontario	54.2 ± 35.3	4.66 **(0.006)***	69 (18–82)	10.17 **(0.038)***	18	72	3.0	↑ Increasing
Quebec	63.7 ± 69.9		34 (24–67)		43	202	3.69	↑ Increasing
Saskatchewan	86.7 ± 62.9		87 (41–88)		88	87	-0.01	↓ Decreasing

*Statistically Significant (p<0.05); **SD**=Standard Deviations; **IQR**=Inter-quartile Range

Figure 1 illustrates the longitudinal trends in total wildfire area burned across Canada from 2010 to 2023, highlighting substantial temporal variability characterized by alternating phases of decline, stabilization, and rapid escalation.

The wildfire burned area exhibited high interannual variability between 2010 and 2023.

A substantial decline occurred between 2010–2012. Gradual and sustained growth was observed from 2013–2021. 2022 recorded the lowest burned area in the study period. 2023 showed an exceptional surge, exceeding 1.6 million hectares—the highest level recorded.

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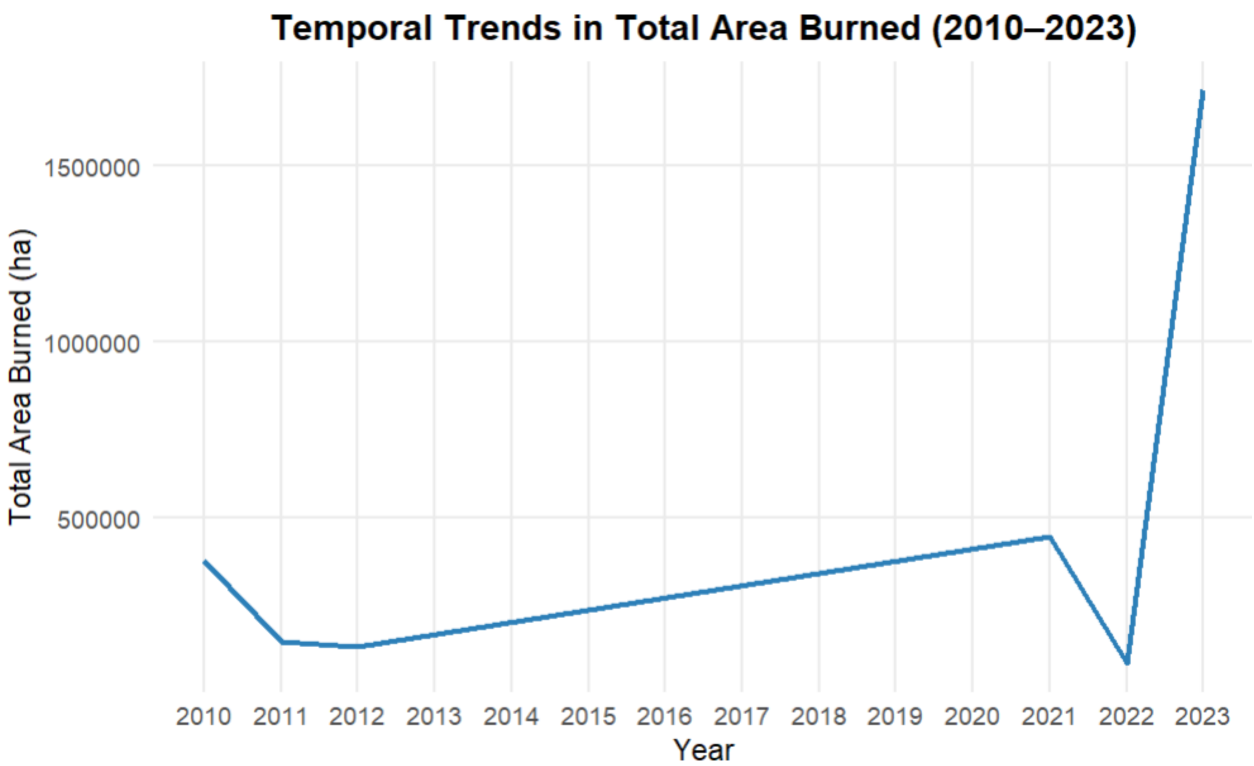

Figure 1: Temporal Trends in the Total Area Burned (2010-2023)

Figure 2 illustrates the provincial distribution of total wildfire area burned across Canada from 2010 to 2023. Across all provinces, the data reveal substantial fluctuations, with sharp peaks and troughs occurring in different years. While Alberta, British Columbia, Ontario, Quebec, and Saskatchewan all demonstrated varying magnitudes of burned area, a common pattern emerged in 2023, when all provinces recorded dramatic increases compared to previous years.

Provincial wildfire burned areas showed substantial variability from 2010–2023. A synchronized and dramatic surge occurred across all provinces in 2023. Quebec experienced the largest spike, followed by British Columbia. Alberta and Saskatchewan each exceeded 1 million hectares in 2023, while Ontario showed a smaller but significant increase. Earlier trends (2012–2021) reflected gradual growth but remained far below the exceptional 2023 levels.

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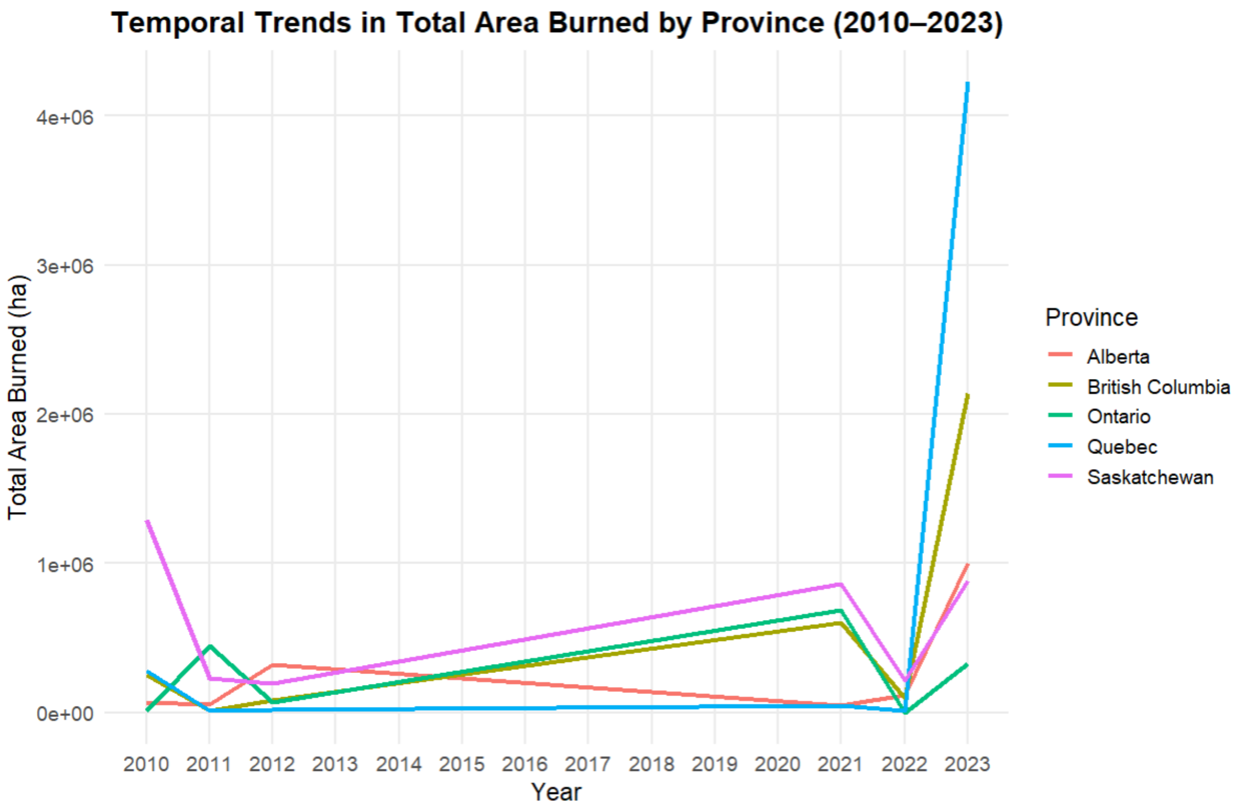

Figure 2: Temporal Trends in the Total Area Burned by Provinces (2010-2023)

Figure 3 presents a heat map visualization of the total area burned across provinces between 2010 and 2023. The colour intensity reflects the scale of burned area, ranging from lighter shades (smaller areas burned) to darker shades (larger areas burned).

Heat map visualization demonstrates significant spatial and temporal variability in wildfire burned areas.
Quebec recorded the highest wildfire extent in 2023 (>4 million hectares).
British Columbia and Alberta also experienced extensive wildfire activity in 2023 (>1 million hectares each).
Saskatchewan showed relatively high wildfire activity in 2010–2011.
Ontario consistently exhibited lower burned areas compared to western provinces.

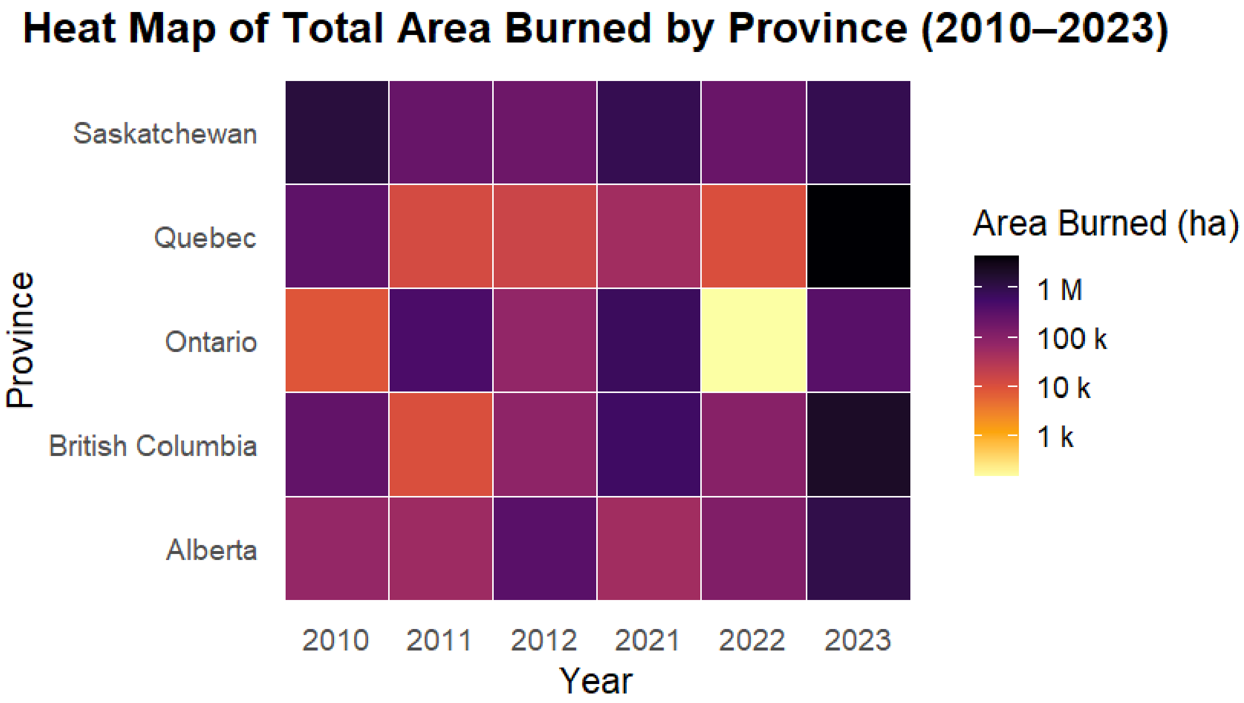

Figure 3: Heat maps showing the Total Area Burned by Provinces (2010-2023)

Figure 4 presents the temporal evolution of wildfire frequency across five Canadian provinces between 2010 and 2023.

The results reveal marked inter-provincial variation in fire activity. British Columbia consistently recorded the highest number of fires across the study period, with an especially sharp increase in 2023 when the number exceeded 450, the peak for any province. From 2010 onwards, British Columbia showed a steady upward trajectory, with only a modest decline in 2022 before the dramatic rebound.

Saskatchewan showed rising but volatile fire activity, with peaks in 2021 and partial recovery in 2023. Ontario's fires increased gradually until 2021, followed by a sharp decline and partial rebound in 2023. Quebec displayed a steady upward trend in fire frequency, though overall counts remained lower. Alberta maintained relatively stable fire numbers, fluctuating between 90–130 annually.

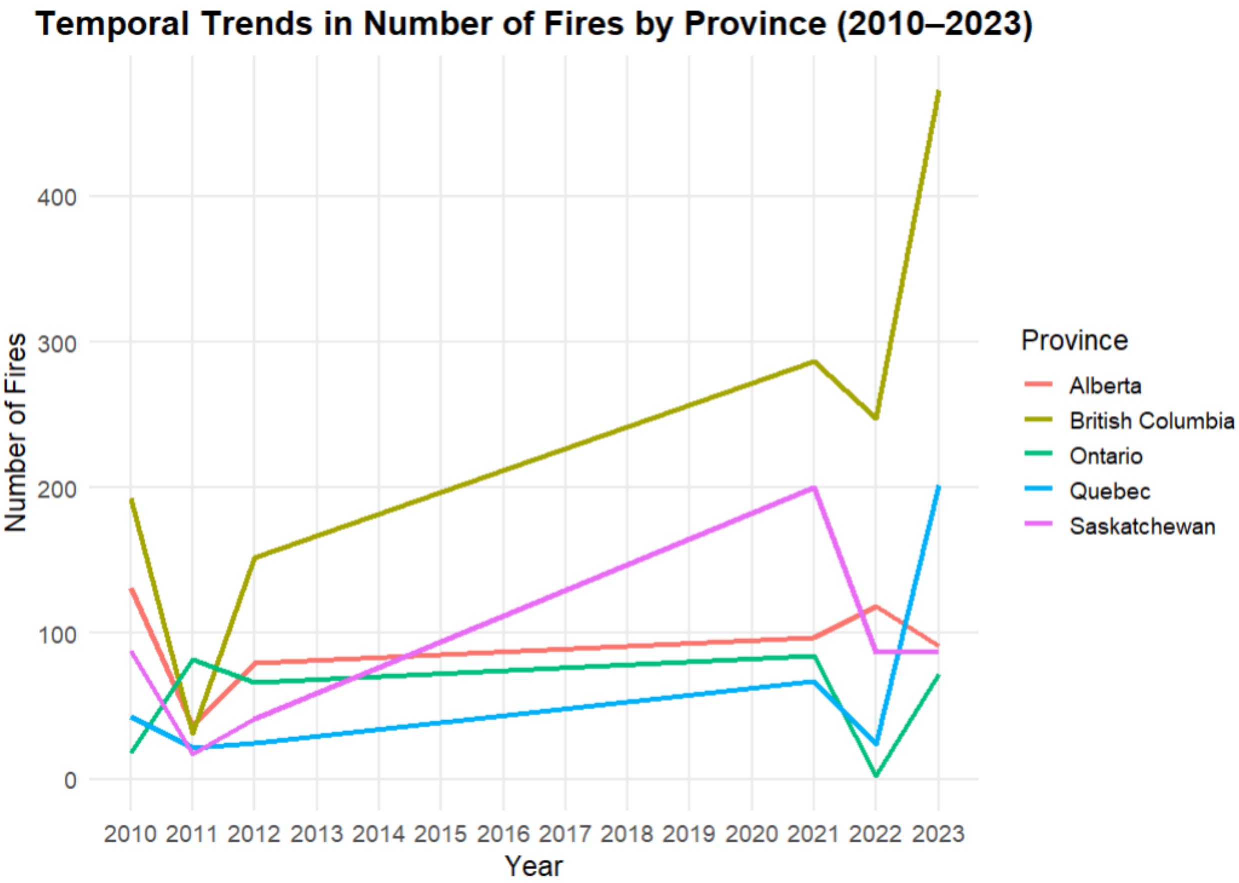

Figure 4: Temporal Trends in the Number of Fires by Provinces (2010-2023)

Table 3 summarizes the provincial trends in mean fine particulate matter ($PM_{2.5}$) concentrations across Canada from 2010 to 2023, highlighting both inter-provincial differences and temporal dynamics. $PM_{2.5}$ levels increased across all provinces between 2010–2023, reflecting deteriorating air quality.

Saskatchewan (+147%) and Alberta (+90%) experienced the largest relative increases.

Ontario and British Columbia showed moderate rises (+54% and +26%, respectively).

Quebec maintained the highest baseline $PM_{2.5}$, with a smaller increase (+8.5%). Trends generally align with provincial wildfire frequency and magnitude, indicating a likely link between fire activity and particulate matter concentrations.

Table 3: Provincial Comparison of Average PM25 (2010–2023)

Provinces	**Mean $PM_{2.5}$ (µg/m³ ± SD)**	**ANOVA (p-value)**	**Median $PM_{2.5}$ (IQR)**	**Kruskal-Wallis (p-value)**	**$PM_{2.5}$ in 2010 (µg/m³)**	**$PM_{2.5}$ in 2023 (µg/m³)**	**% Change (2010–2023)**	**Trend Direction**
Alberta	8.64 ± 3.64		7.18 (6.88–8.37)		8.37	15.93	0.90	↑ Increasing

British Columbia	6.11 ± 0.90		6.19 (5.20–6.69)		5.81	7.32	0.26	↑ Increasing
Ontario	6.69 ± 1.19	1.06 (0.395)	6.25 (5.89–7.01)	7.02 (0.135)	5.79	8.93	0.54	↑ Increasing
Quebec	7.68 ± 0.73		7.90 (7.00–8.16)		7.83	8.50	0.085	↑ Increasing
Saskatchewan	8.14 ± 3.82		6.66 (5.59–9.47)		6.19	15.28	1.47	↑ Increasing

*Statistically Significant ($p<0.05$); **SD**=Standard Deviations; **IQR**=Inter-quartile Range

Figure 5 shows temporal variations in average $PM_{2.5}$ concentrations across Canadian provinces from 2010 to 2023, revealing clear regional differences and notable increases in recent years associated with major wildfire events. Alberta and Saskatchewan experienced the most pronounced rises, with $PM_{2.5}$ levels sharply increasing by 2023, indicating significant wildfire smoke impacts. British Columbia and Quebec maintained relatively stable concentrations with modest upward trends, while Ontario showed a gradual increase despite statistically non-significant annual differences.

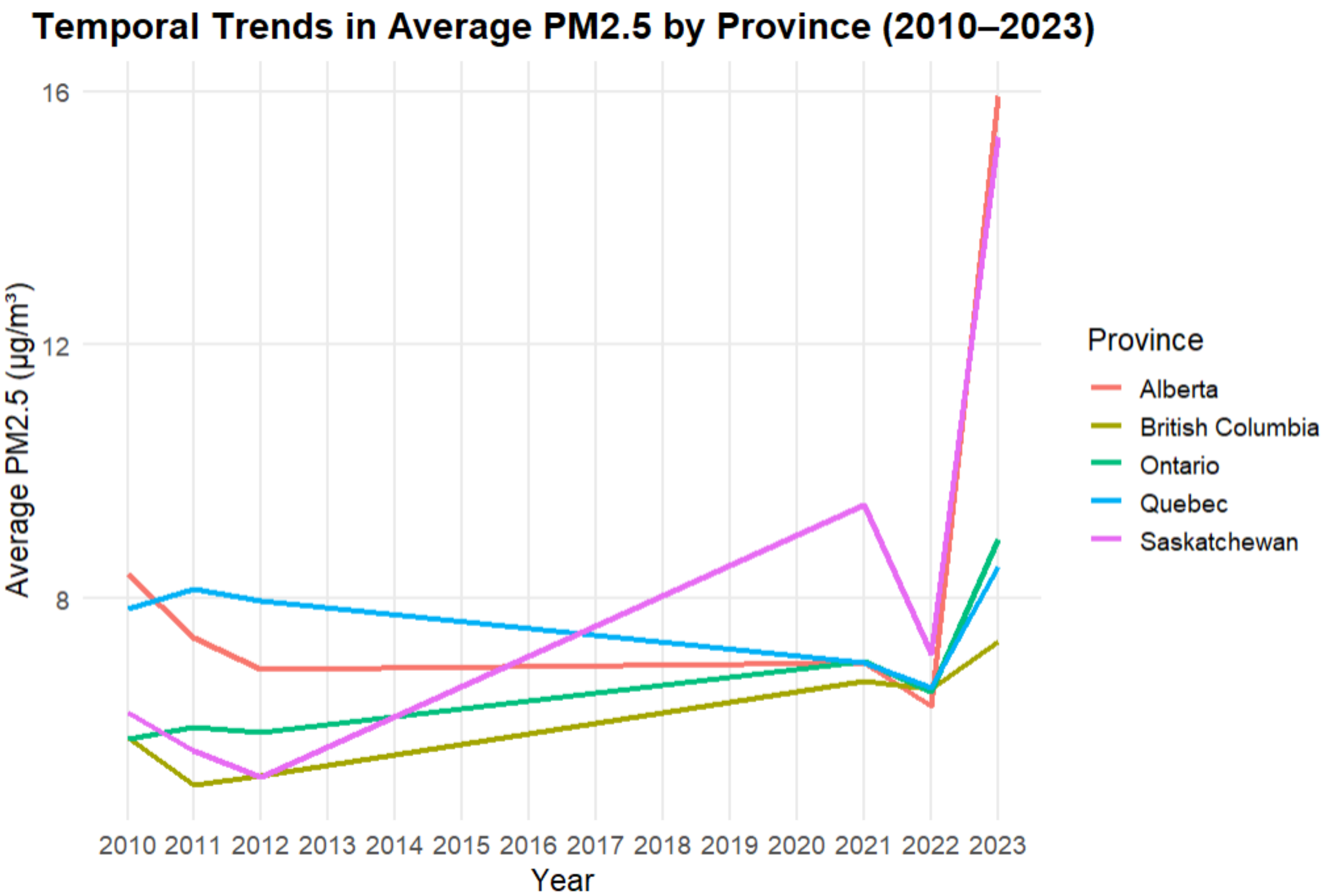

Figure 6: Temporal Trends in the Average $PM_{2.5}$ by Provinces (2010-2023)

Table 4 presents the results of correlation analyses assessing the association between wildfire activity (measured as total area burned and number of fires) and smoke exposure (measured by average $PM_{2.5}$ concentrations) across Canadian provinces from 2010 to 2023.

The correlation between the number of fires and $PM_{2.5}$ was even weaker ($r = 0.038$), with a negligible positive relationship and a wide confidence interval (−0.009 to 0.011).

Table 4. Correlation Between Wildfire Activity and Smoke Exposure (2010–2023)

Scope	Pearson's Correlation Coefficient (r)	p-value	Interpretation
Area burned vs $PM_{2.5}$	0.273	0.144	Weak, non-significant positive correlation
Number of fires vs $PM_{2.5}$	0.038	0.841	Negligible, non-significant correlation

Figure 7 illustrates the relationship between total area burned and average $PM_{2.5}$ concentrations across provinces between 2010 and 2023. Most observations clustered at lower burned areas with moderate $PM_{2.5}$ levels, while larger burned areas were associated with higher $PM_{2.5}$ concentrations and several extreme values. The regression analysis shows no statistically relationship between burned area and $PM_{2.5}$ exposure ($r = 0.273$, $p = 0.144$).

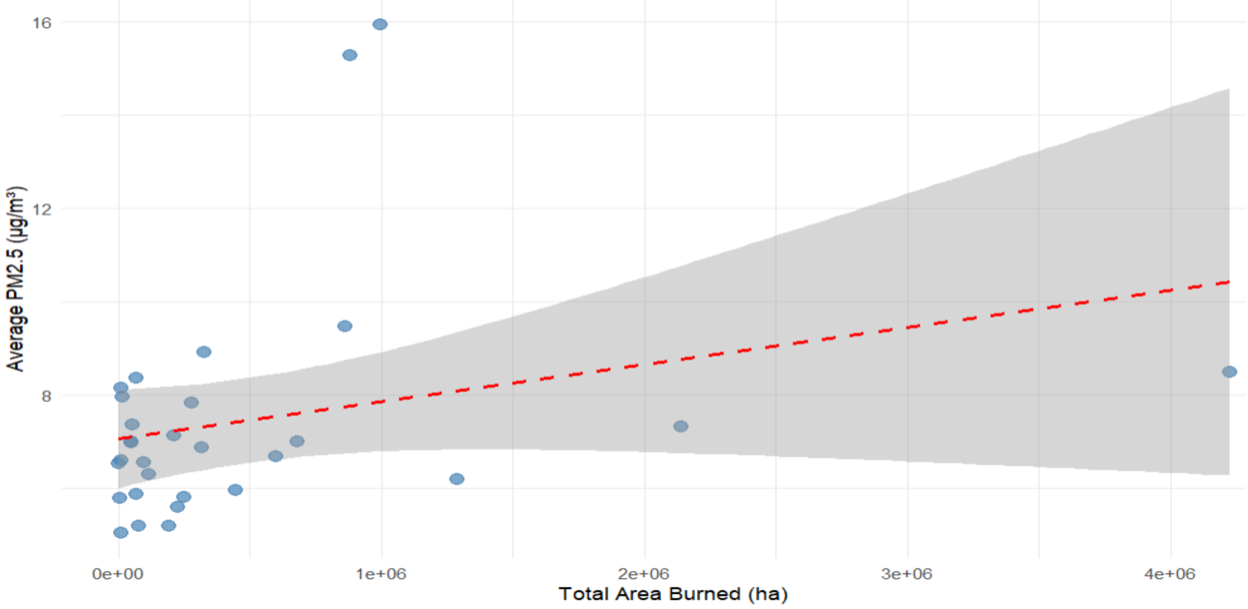

Figure 7: Scatter plot of the Total Area Burned versus Average $PM_{2.5}$ in all Provinces (2010-2023)

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Discussion

This study demonstrates that wildfire activity across Canadian provinces exhibits a highly dynamic and heterogeneous spatiotemporal pattern where substantial interannual variability was observed in both fire frequency and total area burned. Alberta, British Columbia, and Quebec experienced marked increases in burned area, culminating in the extreme 2023 wildfire season, whereas Saskatchewan showed a modest decline and Ontario displayed a gradual upward trajectory. These patterns align with previous research which shows the combined influence of climatic variability and anthropogenic factors on wildfire events [5]. The high wildfire activity in 2023 corresponds with nationally reported wildfire emergencies that suggested transboundary smoke plumes and widespread regional air quality deterioration [15], underscoring the multifactorial drivers of wildfire behavior. The extreme 2023 season could be due to emerging climate-driven fire behavior characterized by prolonged burning periods, rapid spread, and extensive smoke production.

Temporal trends revealed consistent fluctuations in total burned area over the study period. Burned area declined substantially between 2010 and 2012; these fluctuations could be attributed to meteorological conditions or improved monitoring. However, this event was followed by a gradual increase in subsequent years. A notable decline in 2022 was immediately succeeded by an unprecedented surge in 2023, where burned area exceeded 1.6 million hectares, indicating the episodic yet intensifying nature of recent wildfire regimes. Higher fire frequencies were observed in provinces with greater human activity, consistent with evidence linking anthropogenic presence to ignition patterns [5]. Subjective argument is that the cross-provincial smoke transport could have contributed to regional air quality impacts, particularly in Ontario, which may have been affected by emissions originating from Quebec and other provinces.

$PM_{2.5}$ concentrations increased across all provinces, although the magnitude of emission varied regionally. Alberta experienced the greatest increase in emissions, while British Columbia and Ontario showed more moderate increases. Saskatchewan's $PM_{2.5}$ levels rose substantially, reflecting heightened vulnerability to wildfire smoke exposure, whereas Quebec maintained relatively stable concentrations despite severe fire seasons. These findings suggest that wildfire activity is a major determinant of air quality deterioration, particularly in heavily forested regions, although industrial emissions and meteorological processes also influence this pollutant dispersion. This observation is consistent with prior studies emphasizing the role of topography and urban proximity in influencing $PM_{2.5}$ exposure patterns and spread [15,16].

Patterns of high-risk air quality days also differed across provinces. Ontario and British Columbia experienced marked increases, while Alberta and Saskatchewan exhibited more irregular fluctuations. The sharp rise in 2023 reflects the compounded impacts of severe wildfire seasons and prolonged smoke events. Notably, the weak association between wildfire frequency and air quality indicators suggests that fire intensity, duration, and scale are more critical determinants of exposure than a standalone event.

Alberta's substantial rise in $PM_{2.5}$ concentrations likely reflects the combined effects of recurrent large wildfires and concurrent industrial emissions, which may exacerbate cumulative exposure burdens [17]. Despite the presence of advanced air monitoring networks and satellite-based surveillance systems [18], the 2023 wildfire season generated persistent smoke plumes that elevated particulate pollution locally and transboundary [18]. In contrast, British Columbia recorded comparatively lower $PM_{2.5}$ concentrations despite high wildfire activity, possibly due to population concentration in coastal regions less directly affected by interior fires [19], although interior communities experienced elevated exposures [9].

Saskatchewan demonstrated a sharp rise in $PM_{2.5}$ during peak wildfire periods, consistent with its climatic conditions, extensive forest cover, and susceptibility to prolonged fire seasons [16]. However, the province reported relatively fewer high-risk air quality days overall, which may reflect differences in monitoring coverage or atmospheric dispersion patterns. These findings reinforce evidence of regional inequities in

$PM_{2.5}$ exposure and reductions across Canada, disproportionately affecting socioeconomically vulnerable populations [20]. In Ontario, high-risk air quality days increased substantially over the study period; this could be a result of the combined influence of transported wildfire smoke and local industrial and agricultural emissions. Rapid urbanization could further amplify exposure risk by intensifying interactions between anthropogenic emissions and biomass smoke [21].

The study found no statistically significant association between total area burned and $PM_{2.5}$ concentrations. This indicates that larger burned areas do not consistently translate into proportional increases in particulate pollution. These findings suggest that wildfire intensity, combustion characteristics, and duration are more influential determinants of air quality outcomes than fire frequency alone. Large-scale, high-intensity "mega-fires" may disproportionately drive population-level exposure compared to smaller or more frequent events. Moreover, meteorological conditions, wind patterns, and regional topography modulate pollutant transport and accumulation, reinforcing the multifactorial nature of wildfire-related air pollution [22].

Overall, the results revealed a complex, non-linear relationship between wildfire activity and smoke exposure across Canadian provinces. Increasing wildfire severity, combined with climatic variability and anthropogenic influences, is likely to intensify regional disparities in air quality and health risk.

Study Strengths and Limitations

This study provides a comprehensive spatiotemporal assessment of wildfire activity and smoke exposure across provinces in Canada. By integrating wildfire indicators with air quality metrics, it offers a multidimensional evaluation of environmental and public health risks associated with evolving wildfire activities. The use of longitudinal provincial data enabled the identification of temporal trends and regional heterogeneity, while advanced statistical visualization and time-series analysis strengthened the interpretation of wildfire and air quality dynamics.

However, some limitations are hereby acknowledged in the course of the study. Firstly, the ecological study design and use of aggregated provincial-level data limit causal inference, may mask localized exposure variability, and risk of ecological fallacy. Additionally, reliance on $PM_{2.5}$ as a proxy for wildfire smoke exposure, although widely accepted, does not distinguish wildfire emissions from other pollution sources such as industrial activities or transportation. Furthermore, variations in monitoring network density across provinces may have introduced measurement bias and influenced estimates of high-risk air quality days. Finally, meteorological variables and atmospheric transport processes were not explicitly modeled, which may have affected the interpretation of cross-provincial smoke dispersion patterns.

Future research should integrate high-resolution satellite data, atmospheric modeling, and population-level exposure assessments to better capture localized variability and strengthen causal interpretation, and also adjust for meteorological confounders in future work.

Conclusion

Overall, the analysis reveals that wildfire activity and associated air quality impacts across Canadian provinces are characterized by substantial spatial and temporal variability. While provinces such as Alberta, British Columbia, and Quebec experienced pronounced increases in wildfire severity, particularly during the extreme 2023 season, others, including Saskatchewan and Ontario, exhibited more moderate or divergent trends. Concurrently, $PM_{2.5}$ concentrations increased across all provinces between 2010 and 2023, with Alberta and Saskatchewan showing the most pronounced rises, reflecting heightened exposure to wildfire-related air pollution. The growing number of high-risk air quality days, especially in Ontario and British Columbia, further underscores the cumulative effects of recent extreme wildfire seasons. Importantly, the weak correlation between wildfire frequency and air quality indicators suggests that the intensity, scale, and persistence of fires play a more critical role in shaping pollution exposure than the number of fire events alone. Furthermore, these findings highlight the complex interplay between climatic, environmental, and human influences in driving wildfire dynamics and their public health implications across Canada.

Recommendations

Regional disparities in wildfire patterns and air pollution underscore the need for province-specific mitigation and preparedness strategies. Provinces with recurrent severe fire activity and industrial emissions may face compounded environmental health risks, while transboundary smoke transport further amplifies exposure beyond fire zones. These findings emphasize the importance of integrated wildfire surveillance systems, enhanced air quality monitoring infrastructure, and climate-adaptive public health interventions, and leveraging advanced technologies such as remote sensing, artificial intelligence, and geospatial modeling for early detection and prediction of wildfire smoke exposure. This should be complemented by strengthened public health education and risk communication strategies to raise awareness of air pollution risks and promote protective measures, including the use of air filtration systems and personal protective equipment.

As climate change continues to intensify wildfire activities globally, understanding spatiotemporal wildfire dynamics and smoke exposure patterns is critical for informing evidence-based policy, strengthening emergency preparedness, and protecting vulnerable populations. Coordinated strategies that integrate environmental monitoring, urban planning, and climate-resilient health systems will be essential to mitigate the growing public health burden of wildfire smoke.

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