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Abstract

Background: Nitrogen dioxide (NO_2) is a traffic-related air pollutant harmful to human health. Studies in Canada have demonstrated associations between low socioeconomic status and NO_2 exposure in several cities. To the authors' knowledge, no study has previously evaluated the presence of NO_2 exposure inequality at a national scale in Canada.

Data and Methods: Data on socioeconomic status from the 2021 Census and the Canadian Index of Multiple Deprivation (CIMD) were linked with a national model of NO_2 concentrations for 2019 at the dissemination area (DA) level. Associations between area-level socioeconomic variables and NO_2 exposure were evaluated across all census metropolitan areas (CMAs) using ordinary least squares, linear mixed-effects, and simultaneous autoregressive models.

Results: DA-level proportions of racialized and low-income populations are associated with higher NO^2 exposure. These findings remain consistent under different statistical modelling approaches and persist when stratified by individual urban area. The other socioeconomic variables exhibit small, negative or inconsistent associations with NO_2 exposure. Analysis using the CIMD also highlights that DAs with higher levels of residential instability and ethno-cultural composition were consistently associated with higher NO_2 exposure.

Interpretations: Results indicate the presence of national environmental inequalities in NO_2 exposure across Canadian CMAs. Areas characterized by higher proportions of racialized populations were associated with higher NO_2 exposure, consistent with results reported in many other high-income countries.

Keywords: nitrogen dioxide, environmental justice, socioeconomic status, race, air pollution

Authors

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What is already known on this subject?

- Air pollution exposure in Canada results in a considerable health burden, including thousands of attributable deaths annually.
- Previous studies have identified socioeconomic inequalities in exposure to transportation-related air pollution within Canada's most populous cities, especially in areas with a higher proportion of low-income groups and racialized populations.

What does this study add?

- This study provides the first nationwide evidence of environmental disparities related to socioeconomic status and nitrogen dioxide (NO_2) exposure in Canada.
- Areas with higher proportions of racialized and low-income populations and higher levels of ethno-cultural composition and residential instability were associated most strongly with higher NO_2 exposure.
- Evidence of disparities in NO_2 exposure, even in low-exposure municipalities, highlights meaningful opportunities for improving air quality management throughout Canada.

Introduction

Exposure to nitrogen dioxide (NO_2) is linked with several harmful health effects. Evidence concludes a likely causal relationship between long-term NO_2 exposure and respiratory morbidity and a likely causal relationship between short-term NO_2 exposure and total non-accidental, cardiopulmonary, cardiovascular and respiratory mortality.[1] Ambient NO_2 originates from direct emissions of NO_2 and atmospheric reactions of pollutants, notably nitrogen oxide (NO). NO and NO_2, which are co-emitted and reported as NO_x emissions, are a product of combustion, generated primarily from transportation, mobile equipment, and industrial sources. NO_x emissions are higher in urban areas, where key sources are concentrated. As NO_x pollutants react quickly in the atmosphere, NO_2 exhibits sharp spatial gradients within urban environments, resulting in large neighbourhood discrepancies in exposure.[1] Understanding how these exposure gradients intersect with the spatial distribution of urban demographics is critical for evaluating, and ultimately addressing, environmental inequality.

While NO_2 is unequally distributed by socioeconomic status across many high-income countries, the presence of national inequality in NO_2 exposure in Canada is not yet fully understood.[2–6] In Canada's largest cities, areas with higher proportions of individuals living in lower income (e.g., lower median income, low-income prevalence, deprivation measures incorporating income) experience significantly higher NO_2 exposure at the area level across many study designs.[7–13] The proportion of the population that is racialized, or the highly related linguistic isolation and presence of immigrants, is significantly associated with higher NO_2 exposure in Montréal.[8,11,12] However, in Vancouver and the Greater Toronto Area, there is more conflicting evidence for the direction and strength of association between the proportion of racialized populations and NO_2 exposure.[7,9–13] Many other subpopulation proportions (i.e., based on Indigenous identity, age, and education) tend to have less coherent evidence of environmental inequalities, with conclusions varying by location or statistical approach.[8,11,14,15] Furthermore, NO_2 exposure disparities are rarely characterized outside Canada's major cities.[13–15] This heterogeneity in environmental inequalities, coupled with the lack of research beyond Canada's major cities, makes it challenging to extrapolate conclusions on environmental inequalities to the country as a whole.

Assessing environmental inequality nationally requires a model of NO_2 concentrations with sufficient spatial resolution to resolve the sharp intraurban and urban–rural spatial gradients present in both NO_2 concentrations and demographics. Challenges in accurately modelling ambient NO_2 concentrations nationally also include the limited number of ground monitoring sites. To address these challenges, land-use regression models can incorporate satellite information alongside land-use information and ground-level monitoring observations to offer spatially continuous NO_2 concentrations, allowing for a greater spatial extent of analysis.[16,17]

This study seeks to assess associations between neighbourhood demographics and the distribution of ambient NO_2 concentrations across Canadian cities and, in particular, identify which population groups reside in areas with elevated NO_2 exposure. It evaluates associations between NO_2 exposure and area-based measures of socioeconomic status using, first, socioeconomic characteristics from the 2021 Canadian Census of Population and, second, the Canadian Index of Multiple Deprivation (CIMD). The results enhance the national and city-specific understanding of environmental inequalities in Canada and provide information on populations at greatest risk from air pollution.

Methods

Nitrogen dioxide exposure data

The NO_2 concentration data used in this analysis were developed previously using a hybrid land-use regression model of average annual NO_2 ambient concentrations across Canada for 2019.[16] The exposure model uses linear regression to combine land-use variables (e.g., roadway buffers, industrial land use buffers, population density, greenness) with ground-level NO_2 observations, weather variables (e.g., average daily precipitation, average daily maximum temperature), and satellite retrievals from the National Aeronautics and Space Administration Ozone Monitoring Instrument. The NO_2 exposure model was calibrated for 2019 with measurements from the National Air Pollution Surveillance program.[18] Predicted NO_2 concentrations from the land-use regression model correlated moderately well with observed concentrations using cross-validation (adjusted R-squared = 0.63), with an average deviation of 2.2 parts per billion (ppb) as measured by root mean square error.[18] Modelled NO_2 concentrations were developed at the dissemination-block level but were averaged to generate concentrations for dissemination areas (DAs), the study's spatial unit of analysis.

Demographic data

Demographic data were obtained from the 2021 Census of Population. Specific socioeconomic variables from the census were selected based on findings from previous studies of NO_2 exposure disparities in Canada.[7–12,14] These variables included the proportion of individuals in DAs who were aged 14 years and younger, aged 65 years and older, racialized, Indigenous, without a high school diploma in the population aged 15 years and older, living in private households, and living below the low income cut-off (LICO). The LICO is defined using after-tax incomes, family size, and place of residence, and it identifies families that are expected to spend 20% more of their after-tax income on their basic needs than the average census family.[19] In addition, the CIMD provides a complementary analysis by capturing the multifaceted dimensionality of deprivation in Canada.[13,20,21] The CIMD was derived using principal component analysis of several variables from the census to broadly categorize marginalization into scores across four dimensions: residential instability, ethno-cultural composition, economic dependency, and situational vulnerability.[21] Environmental health research uses indices to measure socioeconomic status, as they capture socioeconomic status more broadly than individual variables and address potential collinearity issues.[12,13] However, indices have some noteworthy disadvantages, including their limited interpretability and the possible incorporation of multiple variables with opposing associations into one index. These

benefits and drawbacks motivated the use of both approaches within this study. Every socioeconomic variable was transformed into a z-score using the distribution across all census metropolitan areas (CMAs) to better enable comparison between variables.

All demographic data were obtained at the DA level. DAs are small, relatively stable geographic units with an average population of 400 to 700 people and are the smallest geographic unit at which socioeconomic data are made readily available to the public.[19] For all analyses, the spatial extent was restricted to all CMAs to account for any potential unadjusted spatial differences between urban and rural areas in Canada. Rural populations were excluded from the final analyses. In Canada, 74% of the population resides in CMAs.

Statistical analysis

To assess a linear association between NO_2 exposure and socioeconomic status, ordinary least squares (OLS) regression modelling was used alongside standard regression diagnostics to evaluate multicollinearity. To account for the differences in exposure between CMAs, a linear mixed-effects model for each CMA was run with random intercepts to account for strong differences in NO_2 exposure between CMAs. If residuals of the OLS model showed spatial autocorrelation, as demonstrated by Moran's *I* statistic, the model's outputs may be inaccurate because of the underlying spatial patterns of the data.[22] To account for this spatial autocorrelation, a simultaneous autoregressive model (SAR) with a spatial lagged dependent variable was used (see Equation 1):

$$(1)\ y = \rho W y + X\beta + \varepsilon,$$

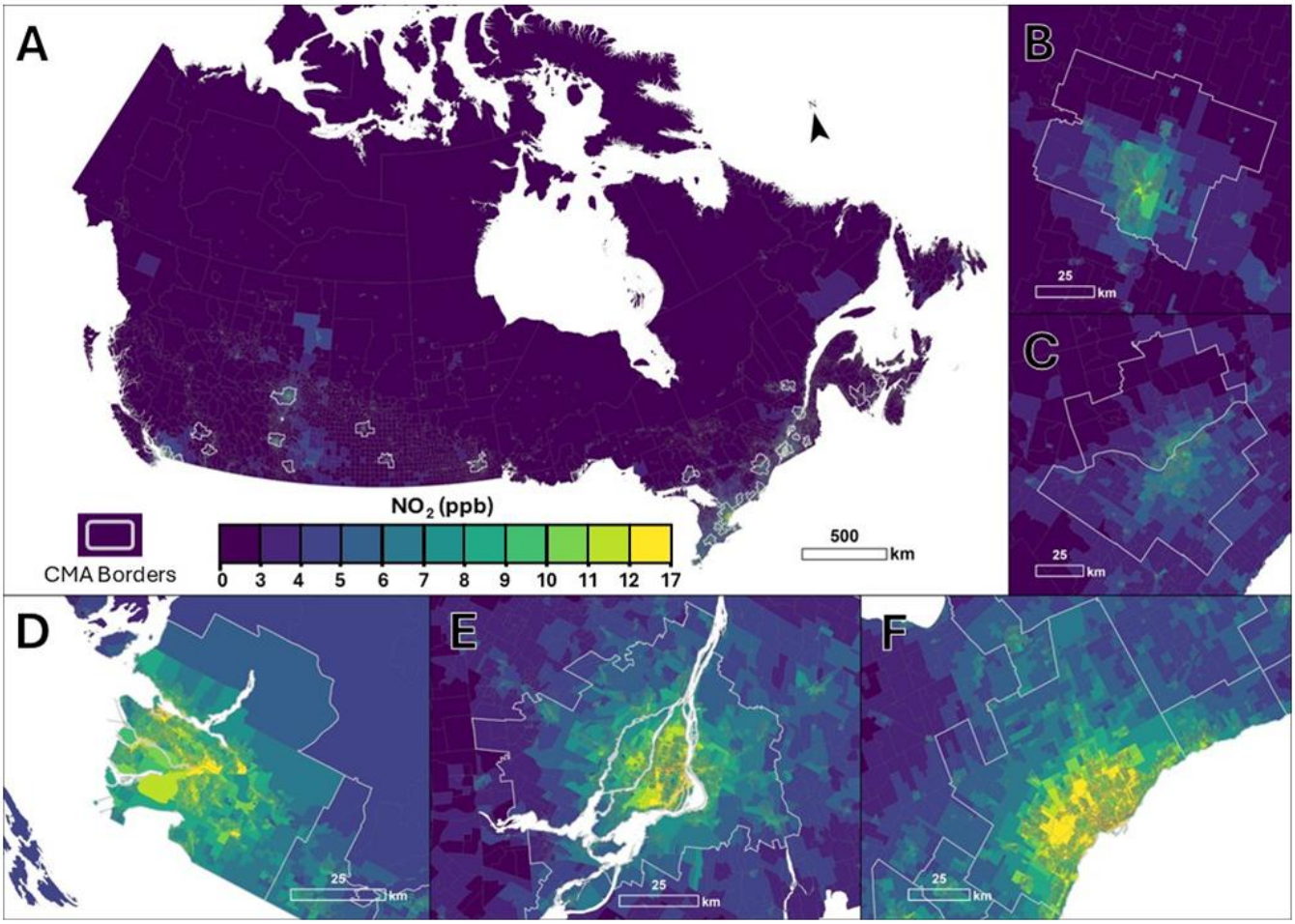
where y is the vector of NO_2 exposure at the DA level; ρ is the parameter of Wy, the spatially lagged dependent variable of neighbouring NO_2 exposure, of which W is a spatial weights matrix using first-order queen's contiguity; β is a vector of parameters for the matrix X of independent socioeconomic variables; and ε is a vector of error terms.[23] β is a direct (local) effect, operating net of spatial dependence, whereby any change in X also propagates indirectly through Wy. Equation 1 was modelled twice: first with X containing six socioeconomic census variables, and then second with X containing the four dimensions of the CIMD. As described by LeSage and Pace, coefficients in spatial autoregressive models cannot be interpreted directly because of the effects of the spatial lag of the dependent variable.[24] Instead, interpretation is based on direct, indirect, and total impacts. The direct impact measures the average effect of a change in a socioeconomic variable on the DA it originated in. The indirect impact measures the average effect of that change on other DAs. The total impact measures the sum of direct and indirect impacts, representing the average overall impact of a change in a socioeconomic variable.[24] RStudio with R 4.4.3 was used for the analysis, and ArcGIS Pro 3.2 was used for mapping. The SAR analysis was repeated using stratified CMA-specific analyses to investigate heterogeneity in associations of environmental inequalities across different municipalities.

Results

Nitrogen dioxide exposure

Annual NO_2 exposure concentrations averaged 7.2 ppb across the country in 2019. When restricted to populations only in CMAs, average exposure to NO_2 was 8.3 ppb, with a minimum exposure of 0.0 ppb, and a maximum exposure of 16.9 ppb. Canada's three most populous CMAs had the highest exposures, with population-weighted means of 11.0 ppb in Toronto, 9.7 ppb in Vancouver and 9.0 ppb in Montréal (see Figure 1).

Figure 1
Nitrogen dioxide exposure by dissemination area for A) Canada, with panels of the five most populous census metropolitan areas, in order of increasing population: B) Calgary, C) Ottawa–Gatineau, D) Vancouver, E) Montréal and F) Toronto



Source: Hystad P, Larkin A. *Updated Canadian NO_2 Land Use Regression Model for 2019 and Predictions of Canadian NO_2 Concentrations*. 2022.

Table 1 highlights NO_2 exposure patterns for each census variable. The strongest unidirectional gradients of NO_2 exposure are observed for the proportions of the population aged 14 and younger, living below the LICO, and identifying as racialized. Between the lowest and highest quintiles of each variable, median exposure varies from 9.3 ppb to 7.7 ppb, 6.8 ppb to 10.2 ppb, and 5.6 ppb to 10.4 ppb, respectively. Table 2 shows how NO_2 exposure varies across quintiles of the four dimensions of the CIMD. The strongest unidirectional gradient is observed for ethno-cultural composition, whereas the other CIMD dimensions exhibit nonuniform trends across quintiles. The median NO_2 exposure by ethno-cultural composition ranges from 5.5 ppb in the lowest quintile to 10.5 ppb in the highest.

Table 1
Distribution of nitrogen dioxide exposure in Canadian census metropolitan areas by quintile of socioeconomic characteristics

	Nitrogen dioxide exposure (parts per billion)		
Census variable quintiles	25th	50th (median)	75th
Proportion aged 14 years and younger			
1 (lowest)	7.1	9.3	11.4
2	6.6	8.6	10.6
3	6.5	8.3	10.2
4	6.2	8.0	9.8
5 (highest)	6.4	7.7	9.3
Proportion aged 65 years and older			
1 (lowest)	7.0	8.5	10.5
2	6.8	8.8	10.6
3	6.4	8.3	10.3
4	6.1	7.9	9.8
5 (highest)	6.1	7.6	9.6
Proportion of Indigenous people			
1 (lowest)	6.6	8.3	10.0
2	9.5	10.8	11.6
3	7.0	8.5	10.2
4	6.0	7.4	8.9
5 (highest)	5.3	6.6	8.0
Proportion without a high school diploma[1]			
1 (lowest)	6.8	8.7	11.0
2	6.3	7.9	9.9
3	6.4	8.0	9.9
4	6.5	8.2	10.2
5 (highest)	6.9	8.6	10.5
Proportion living below the low income cut-off[2]			
1 (lowest)	5.3	6.8	8.2
2	6.2	7.6	9.2
3	7.0	8.6	10.4
4	7.8	9.5	11.0
5 (highest)	8.2	10.2	11.6
Proportion of racialized population			
1 (lowest)	4.3	5.6	6.9
2	5.8	7.1	8.4
3	6.8	8.1	9.6
4	7.5	8.9	10.5
5 (highest)	9.1	10.4	11.4

1. Proportion aged 15 years and older without a high school diploma and living in private households.
2. The low income cut-off is defined using after tax incomes, family size and place of residence, and it identifies families that are expected to spend 20% more of their after-tax income on basic needs than the average census family.

Sources: Statistics Canada, 2021 Census of Population; and Hystad P, Larkin A, *Updated Canadian NO2 Land Use Regression Model for 2019 and Predictions of Canadian NO2 Concentrations* , 2022.

Table 2
Distribution of nitrogen dioxide in Canadian census metropolitan areas by quintile of dimensions of the Canadian Index of Multiple Deprivation

	Nitrogen dioxide exposure at specific subpopulation percentiles in Canada (ppb)		
Canadian Index of Multiple Deprivation quintiles	25th	50th (median)	75th
Economic dependency			
1	6.4	7.9	9.9
2	6.7	8.4	10.3
3	6.6	8.5	10.4
4	6.6	8.3	10.4
5	6.6	8.3	10.4
Situational vulnerability			
1	6.6	8.4	10.4
2	6.4	8.0	10.0
3	6.4	8.0	10.1
4	6.6	8.2	10.4
5	6.9	8.6	10.5
Residential instability			
1	6.2	8.0	10.0
2	5.9	7.6	9.5
3	6.2	7.7	9.4
4	6.8	8.4	10.4
5	7.7	9.6	11.5
Ethno-cultural composition			
1	4.3	5.5	6.8
2	5.9	7.0	8.2
3	6.9	8.1	9.6
4	7.6	9.0	10.5
5	9.2	10.5	11.4

Sources: Statistics Canada, 2021 Canadian Index of Multiple Deprivation; and Hystad P, Larkin A, *Updated Canadian NO2 Land Use Regression Model for 2019 and Predictions of Canadian NO2 Concentrations,* 2022.

Associations between nitrogen dioxide exposure and socioeconomic status

When assessing associations between census variables and NO_2 exposure, the OLS and linear mixed-effects models demonstrate the presence of spatial autocorrelation (see Table 3). The SAR model addresses this concern and does not demonstrate further spatial autocorrelation, according to Moran's *I* statistic. In this model, an increase of one standard deviation, or 25.6%, in the area-level racialized population was associated with a 0.09 ppb increase in NO_2, after adjusting for all other census variables included in the model, with additional indirect effects operating through neighbouring DAs as governed by ρ. As shown in Table 3, the SAR model demonstrates that DAs with higher proportions of racialized residents, individuals with less than a high school education and households with incomes below the LICO showed a statistically significant positive association with NO_2 exposure. Conversely, all models show that DAs with a higher proportion of the population aged 14 and younger and 65 years and older exhibited a negative association with NO_2 exposure. The proportion of Indigenous people showed mixed associations depending on the model. Although the presence of spatial autocorrelation limits the conclusions that can be drawn from the linear mixed-effects model, the similarity in the strongest positive and negative associations with NO_2 exposure tentatively suggest that within-CMA inequalities contribute to many of the observed associations.

Table 3
Associations between socioeconomic status and nitrogen dioxide exposure in Canadian census metropolitan areas

Model parameter	Ordinary least squares regression	Linear mixed-effects model with random intercept	Simultaneous autoregressive model (spatial lag)
Model fit			
Adjusted R-squared	0.42 ***	...	...
Log-likelihood	-71,120	-56,407	-34,358
AIC	142,257	112,832	68,734
Spatial autocorrelation			
Moran's *I*	0.80 ***	0.73 ***	-0.05 [1]
Socioeconomic characteristics (z-scores)			
Intercept			
Estimate	8.249 ***	6.658 ***	0.587 ***
Lower 95% CI	8.230	6.164	0.558
Upper 95% CI	8.270	7.152	0.616
Proportion aged 14 years and younger (SD = 5.1%)			
Estimate	-0.431 ***	-0.351 ***	-0.042 ***
Lower 95% CI	-0.457	-0.368	-0.050
Upper 95% CI	-0.404	-0.333	-0.034
Proportion aged 65 years and older (SD = 9.8%)			
Estimate	-0.261 ***	-0.196 ***	-0.033 ***
Lower 95% CI	-0.287	-0.213	-0.041
Upper 95% CI	-0.235	-0.179	-0.025
Proportion of Indigenous people (SD = 5.7%)			
Estimate	-0.702 ***	0.0577 ***	-0.037 ***
Lower 95% CI	-0.727	0.035	-0.045
Upper 95% CI	-0.677	0.080	-0.030
Proportion without a high school diploma[2] (SD = 8.4%)			
Estimate	0.102 ***	0.011	0.0281 ***
Lower 95% CI	0.081	-0.004	0.022
Upper 95% CI	0.123	0.025	0.035
Proportion living below the low income cut-off[3] (SD = 5.2%)			
Estimate	0.379 ***	0.440 ***	0.047 ***
Lower 95% CI	0.355	0.424	0.04
Upper 95% CI	0.402	0.455	0.055
Proportion of racialized population (SD = 25.6%)			
Estimate	1.099 ***	0.396 ***	0.094 ***
Lower 95% CI	1.077	0.378	0.086
Upper 95% CI	1.121	0.415	0.102

... not applicable

*** significantly different from reference category ($p < 0.001$)

1. *p*-value = 1

2. Proportion of the population aged 15 years and older without a high school diploma and living in private households.

3. The low income cut-off is defined using after tax incomes, family size and place of residence, and it identifies families that are expected to spend 20% more of their after-tax income on basic needs than the average census family.

Notes: AIC = Akaike information criterion. CI = confidence interval. SD = standard deviation.

Sources: Statistics Canada, 2021 Census of Population; and Hystad P, Larkin A, *Updated Canadian NO2 Land Use Regression Model for 2019 and Predictions of Canadian NO2 Concentrations, 2022.*

Table 4 outlines a similar suite of models used to assess the association between the dimensions of the CIMD and NO_2 exposure. After accounting for spatial autocorrelation, the necessary assumptions of linear regression modelling are met by the SAR model. For all models, residential instability and ethno-cultural composition at the DA level are positively and significantly associated with NO_2 exposure. Negative associations are observed between DA dimensions of economic dependency and situational vulnerability and NO_2 exposure (Table 4). An increase of one standard deviation in ethno-cultural composition was associated with a direct increase of 0.114 ppb in NO_2 exposure, with additional indirect impacts occurring through neighbouring DAs through ρ. In the analysis, the dimension of situational vulnerability includes the proportion of the population identifying as Indigenous and the proportion without a high school diploma, two variables that have opposing directions of association when modelled individually in the SAR model (Table 3). Average direct, indirect and total impacts of the SAR models are presented in Appendix Tables A1 and A2, where a change of a single standard deviation in the proportion of the racialized population, ethno-cultural composition, or residential instability is associated with an increase in NO_2 exposure greater than 1 ppb, accounting for both direct and spatial spillover effects.

Table 4
Associations between dimensions of the Canadian Index of Multiple Deprivation and nitrogen dioxide exposure in Canadian census metropolitan areas

Model parameter	Ordinary least squares regression	Linear mixed-effects model with random intercept	Simultaneous autoregressive model (spatial lag)
Model fit			
Adjusted R-squared	0.42 ***	...	...
Log-likelihood	-78,693	-61,154	-35,815
AIC	157,399	122,323	71,643
Spatial autocorrelation			
Moran's *I*	0.79 ***	0.69 ***	-0.06 [1]
Socioeconomic characteristics: z-scores of the dimensions of the CIMD			
Intercept			
Estimate	8.202 ***	6.577 ***	0.513 ***
Lower 95% CI	8.183	6.091	0.487
Upper 95% CI	8.221	7.063	0.539
Economic dependency			
Estimate	-0.030 **	-0.044 ***	-0.009 ***
Lower 95% CI	-0.050	-0.057	-0.015
Upper 95% CI	-0.011	-0.032	-0.004
Situational vulnerability			
Estimate	-0.421 ***	-0.089 ***	-0.022 ***
Lower 95% CI	-0.442	-0.103	-0.028
Upper 95% CI	-0.400	-0.075	-0.016
Residential instability			
Estimate	0.581 ***	0.677 ***	0.097 ***
Lower 95% CI	0.560	0.663	0.090
Upper 95% CI	0.601	0.691	0.103
Ethno-cultural composition			
Estimate	1.509 ***	0.527 ***	0.114 ***
Lower 95% CI	1.489	0.510	0.108
Upper 95% CI	1.528	0.543	0.121

... not applicable

** significantly different from reference category ($p < 0.01$)

*** significantly different from reference category ($p < 0.001$)

1. p-value = 1

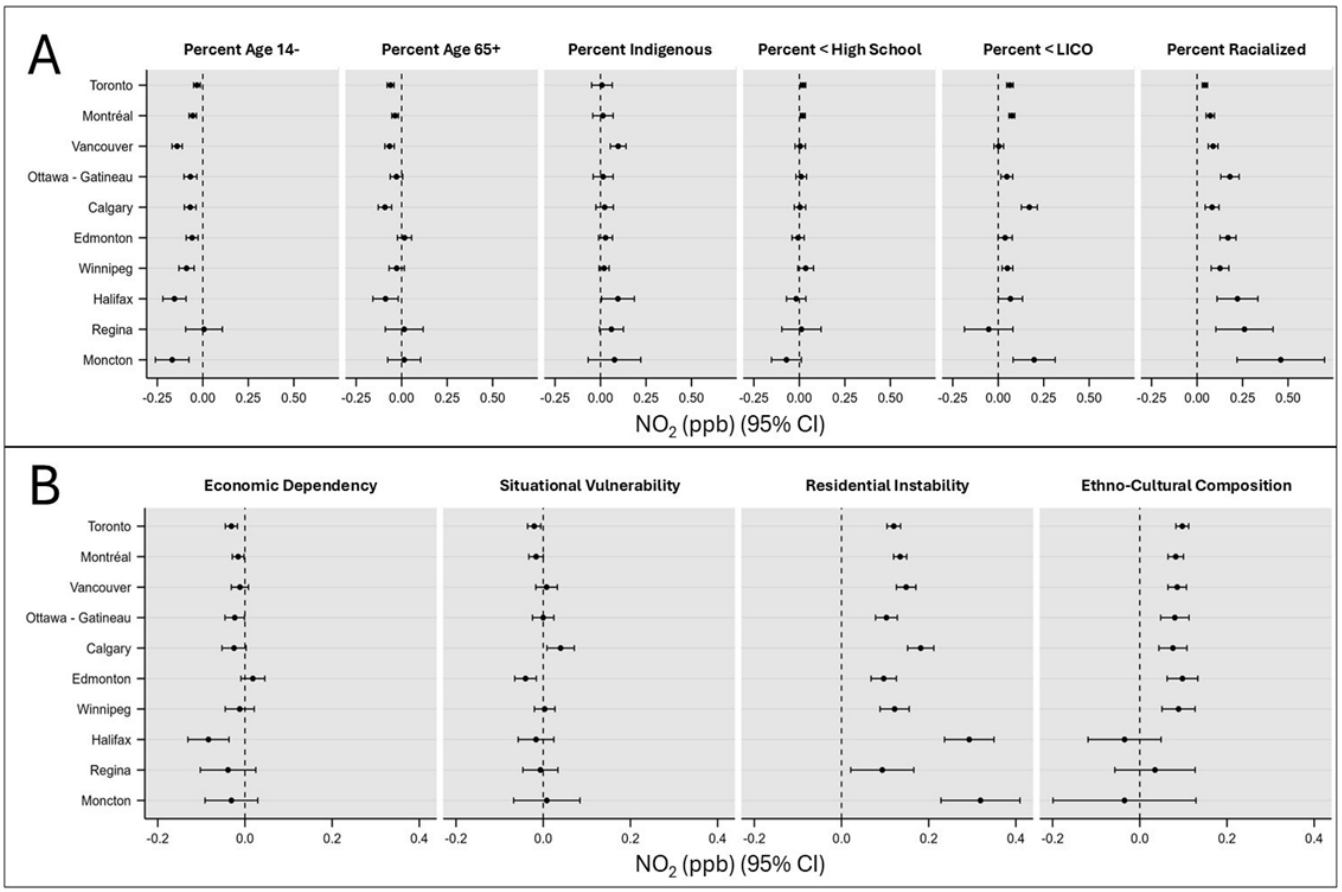
Notes: AIC = Akaike information criterion. CI = confidence interval. CIMD = Canadian Index of Multiple Deprivation.

Sources: Statistics Canada, 2021 Canadian Index of Multiple Deprivation; and Hystad P, Larkin A, *Updated Canadian NO2 Land Use Regression Model for 2019 and Predictions of Canadian NO2 Concentrations, 2022* .

The stratified CMA-specific analysis shows relatively uniform intraurban associations with similar directions of association as those observed in the national analysis. Figure 2 depicts patterns of association across selected populous CMAs (see Appendix Figure A1 for a depiction of all CMAs). The results of this study, notably the positive associations between the proportion of the racialized population and the ethno-cultural composition dimension (which measures the presence of immigrant-related traits of the census) and NO_2 exposure, offer evidence of environmental disparities for racialized populations

across the most populous CMAs in Canada. Residential instability is consistently positively associated with NO_2 exposure in all Canadian CMAs, significant in all but Red Deer, Alberta. Residential instability is a measure of neighbourhood transience and cohesiveness that combines the proportion of apartment dwellers, people living alone, non-homeowners, those who recently moved, unmarried people and median household income. The proportion of individuals living below the LICO shows positive associations with NO_2 exposure for 36 of 41 Canadian CMAs. For the age groups examined (14 years and younger and 65 and older), within-CMA associations with NO_2 exposure are generally negative for the most populous CMAs and insignificant in the remaining CMAs. The remaining socioeconomic characteristics have mixed results, with most CMAs showing insignificant associations and smaller magnitudes overall.

Figure 2
***β* coefficients of the simultaneous autoregressive model (spatial lag) associating an increase of one standard deviation in subpopulation proportions with differences in mean nitrogen dioxide concentrations across dissemination areas for 10 populous census metropolitan areas**



Notes: NO_2 = nitrogen dioxide. ppb = parts per billion. CI = confidence interval. LICO = low income cut-off. All β coefficients were derived from models that simultaneously adjusted for other dissemination area-level characteristics, including A) the remaining socioeconomic census variables and B) the other dimensions of the Canadian Index of Multiple Deprivation. For a depiction of all census metropolitan areas, see Appendix Figure A.1.
Sources: Statistics Canada, 2021 Census of Population and 2021 Canadian Index of Multiple Deprivation; and Hystad, P. and Larkin, A., 2022, *Updated Canadian NO_2 Land Use Regression Model for 2019 and Predictions of Canadian NO2 Concentrations.*

Discussion

This analysis provides evidence supporting the presence of broad environmental inequalities in air pollution exposure in Canada. It also reinforces a recurring finding of income-based inequalities in NO_2 exposure in Canada across a range of statistical approaches and spatial scales. An area's prevalence of

poverty, especially via low-income measures, is consistently associated with elevated NO_2 exposure among multicity studies,[12,14] in Vancouver,[9] in Toronto,[7] in Montréal[8,12,14] and in this national analysis of all Canadian urban areas. Pinault et al.,[11] however, did not find significant associations between the proportion of people living below the LICO and NO_2 exposure in Montréal, Vancouver, or Toronto, after accounting for indicators of social deprivation (i.e., living alone, being unmarried, living in a one-parent family, and experiencing linguistic isolation), many of which are correlated with measures of poverty.

Previous studies have reported mixed associations between NO_2 exposure and racialized populations, or related measures such as linguistic isolation or immigrant status, within Canadian cities. Negative or weak correlations have been observed in Toronto, Peel, and Vancouver,[7,9,12,13] and positive associations have been reported in Toronto and Montréal.[8,10–12] The results of this study, notably the positive associations between NO_2 exposure and racialized populations and ethno-cultural composition, offer evidence of environmental inequality for racialized populations that extends beyond a single Canadian city to a trend observed across CMAs nationwide. These associations align with the growing body of international evidence that racialized populations, or the often-correlated immigrant populations, are disproportionately exposed to NO_2 in high-income countries, including the United States,[2,25] England,[3] Germany,[26] the Netherlands,[3,27] and most Nordic countries.[5] The direction of association for other socioeconomic factors, such as age, income, and education, is less consistent across high-income countries.[2,3,5,27]

The overall uniformity in associations with NO_2 exposure observed in the stratified analysis highlights that when associations are stronger, either positive or negative, inequalities are consistently present in most CMAs and are not solely explained by interurban differences in demographics. Even when using similar statistical methods, associations with NO_2 exposure observed in this stratified analysis sometimes differ from previous work. For example, the findings from this study indicate a positive association between NO_2 exposure and areas with higher proportions of individuals without a high school diploma in Montréal, whereas previous research found the opposite relationship.[8,11] In Toronto, racialized populations were not significantly associated with NO_2 exposure in a previous study, unlike the association observed in the present analysis[7]. To better understand the sources of these differing findings, future research could examine how estimates of exposure disparities are influenced by the choice of NO_2 exposure model, the delineation of municipal boundaries, variable inclusion, and statistical approach, many of which vary across studies and may contribute to the inconsistencies observed in the literature.

Altogether, these results support a two-pronged understanding of NO_2 exposure inequality in Canada. DAs with higher proportions of racialized and low-income populations, and higher levels of residential instability, for example, are consistently associated with elevated NO_2 exposure across the country. In contrast, inequalities in NO_2 exposure associated with other socioeconomic variables show a less coherent national pattern, with weak and opposing associations when stratified by CMA, suggesting the presence of city-specific patterns. Consequently, findings from research on environmental inequality and exposure to air pollution should not necessarily extend beyond the spatial scale and socioeconomic variables examined in the study in question, even within the same country, until more is known about the underlying processes causing these environmental inequalities.

When determining the appropriate measures of socioeconomic status, the divergent directions of association between the proportion of the population identified as Indigenous and NO_2 exposure compared with the proportion of people without a high school diploma and NO_2, both of which are included in the situational vulnerability dimension of the CIMD, highlight the heterogeneity of environmental inequalities across different measures of socioeconomic indicators and some of the challenges associated with using indices. Conversely, the substantial and consistent association between NO_2 exposure and residential instability shows how the CIMD captures the multidimensionality of environmental inequality in ways that individual variables may not. Until the processes that drive

environmental inequality are better understood, it is helpful to use indices in tandem with individual socioeconomic variables.

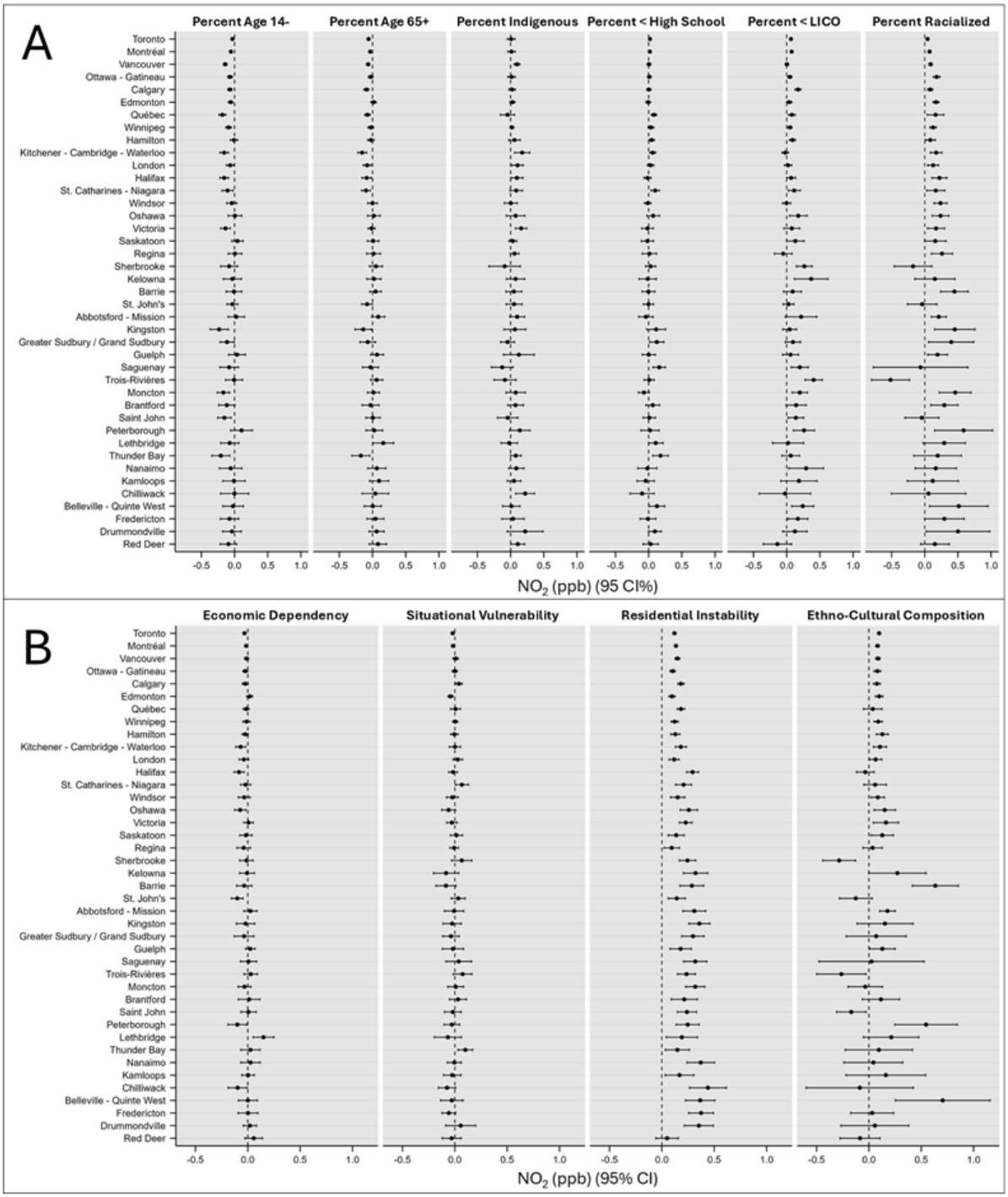
Future research that takes a national perspective is needed to further understand how environmental inequalities operate at different spatial scales in Canada. Previous research provides evidence that socially disadvantaged groups tend to live in greater proximity to traffic, a key source of urban NO_2 exposure.[18] Further work to determine the drivers of these inequalities would improve the understanding of possible mechanisms, including housing affordability, urban structure, urban planning decisions, and the settlement patterns of immigrant populations. While many of these factors have been proposed as contributors to environmental inequality, they have not been substantially evaluated in the Canadian literature.[11–13] Moreover, examining trends over time and for specific emission sectors could elucidate how air quality management measures influence environmental inequality. Even as the underlying causal mechanisms that link socioeconomic status and NO_2 exposure remain poorly understood, this research can inform mitigation efforts by identifying the populations with the highest exposure that could benefit from tailored risk management.

This study is limited by its use of area-level instead of individual-level socioeconomic conditions. Previous research suggests area-based socioeconomic conditions tend to have stronger associations with air pollution exposure.[28–30] Ambient outdoor exposure, already weakly correlated with personal exposure, may further bias results, as different socioeconomic groups have different labour, commuting or housing patterns, all of which affect the relationship between outdoor and personal exposure.[31–35] In addition, these findings apply to CMAs and cannot necessarily be extrapolated to rural populations, particularly for socioeconomic characteristics that are disproportionately concentrated in rural areas, such as Indigenous identity. Moreover, rural populations may be exposed to fewer yet more dominant sources of air pollution. For example, research conducted in a rural region of northern British Columbia with extensive oil and gas extraction has shown that Indigenous populations are inequitably overexposed to NO_2.[15] Additionally, while z-score standardization facilitates comparison of the magnitudes of observed associations, it may limit the validity of conclusions made for subpopulation proportions that are sparse or zero-heavy.

Despite these limitations, this study is the first to examine national associations between socioeconomic status and NO_2 exposure in Canada. In this study, NO_2 exposure was positively and significantly associated with several socioeconomic factors across Canadian CMAs. An area-level racialized population, household low-income status, and the CIMD dimensions of ethno-cultural composition and residential instability measured using the CIMD, demonstrate the largest inequalities in NO_2 exposure. Positive associations for these socioeconomic variables were consistent across statistical models and remained present in analyses stratified by CMA, even after accounting for the spatial structure of the data and other measures of socioeconomic status.

Appendix

Figure A.1
β coefficients of the simultaneous autoregressive model (spatial lag) associating an increase of one standard deviation in subpopulation proportions with differences in mean nitrogen dioxide concentrations across dissemination areas for all census metropolitan areas



Notes: NO_2 = nitrogen dioxide. ppb = parts per billion. CI = confidence interval. All β coefficients were derived from models that included the other dissemination area-level characteristics, including A) the remaining socioeconomic census variables and, subsequently, B) the other dimensions of the Canadian Index of Multiple Deprivation.
Sources: Statistics Canada, 2021 Census of Population and 2021 Canadian Index of Multiple Deprivation; and Hystad P, Larkin A, *Updated Canadian NO_2 Land Use Regression Model for 2019 and Predictions of Canadian NO_2 Concentrations, 2022.*

Table A1

Mean direct, indirect and total impacts of the simultaneous autoregressive model between socioeconomic status and nitrogen dioxide exposure

	Impact		
Census variable	Direct	Indirect	Total
Proportion aged 14 years and younger	-0.063 ***	-0.532 ***	-0.595 ***
Proportion aged 65 years and older	-0.050 ***	-0.417 ***	-0.467 ***
Proportion of Indigenous people	-0.056 ***	-0.470 ***	-0.526 ***
Proportion without a high school diploma[1]	0.042 ***	0.354 ***	0.396 ***
Proportion living below the low income cut-off[2]	0.071 ***	0.597 ***	0.667 ***
Proportion of racialized population	0.141 ***	1.188 ***	1.329 ***

*** significantly different from reference category ($p < 0.001$)

1. Proportion of the population aged 15 years and older without a high school diploma and living in private households.

2. The low income cut-off is defined using after tax incomes, family size and place of residence, and it identifies families that are expected to spend 20% more of their after-tax income on basic needs than the average census family.

Sources: Statistics Canada, 2021 Census of Population; and Hystad P, Larkin A, *Updated Canadian NO2 Land Use Regression Model for 2019 and Predictions of Canadian NO2 Concentrations, 2022* .

Table A2

Mean direct, indirect and total impacts of the simultaneous autoregressive model between dimensions of the Canadian Index of Multiple Deprivation and nitrogen dioxide exposure

	Impact		
Dimensions of the Canadian Index of Multiple Deprivation	Direct	Indirect	Total
Economic dependency	-0.014 ***	-0.138 ***	-0.152 ***
Situational vulnerability	-0.033 ***	-0.322 ***	-0.355 ***
Residential instability	0.144 ***	1.412 ***	1.555 ***
Ethno-cultural composition	0.170 ***	1.673 ***	1.844 ***

*** significantly different from reference category ($p < 0.001$)

Sources: Statistics Canada, 2021 Canadian Index of Multiple Deprivation; and Hystad P, Larkin A, *Updated Canadian NO2 Land Use Regression Model for 2019 and Predictions of Canadian NO2 Concentrations, 2022.*

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