

Ambient nitrogen dioxide exposure, socioeconomic deprivation, and low birth weight: A spatial epidemiological study of Toronto neighborhoods

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ABSTRACT

Background: Ambient air pollution, particularly nitrogen dioxide (NO₂), has been associated with adverse birth outcomes, though evidence on its relationship with low birth weight (LBW) remains mixed. This spatial ecological study examined the association between neighborhood-level NO₂ concentrations, socioeconomic deprivation, and LBW prevalence in Toronto, Canada.

Methods: We analyzed aggregate birth data from 2009 to 2011 across 140 Toronto neighborhoods (n = 90,871 births). LBW rates were linked with modeled ambient NO₂ and PM_{2.5} concentrations from the Canadian Urban Environmental Health Research Consortium. Socioeconomic indicators, including material deprivation and ethnic concentration, were derived from the Ontario marginalization index. Bayesian Poisson regression with conditional autoregressive priors was used to account for spatial autocorrelation.

Results: The average LBW rate was 7.35%, exceeding the provincial average of 6.5%. Neighborhood NO₂ concentrations ranged from 12 to 52 ppb. No statistically significant associations were observed between NO₂, PM_{2.5}, or ethnic concentration and LBW. However, a 1 ppb increase in NO₂ was associated with a relative risk (RR) of 1.002 (95% confidence interval [CI]: 0.996-1.008), and increased material deprivation was associated with a RR of 1.053 per standard deviation (95% CI: 0.977-1.125). Trends were consistent with findings from individual-level studies.

Conclusion: This study demonstrates the utility of Bayesian spatial modeling with neighborhood-level data for evaluating urban environmental health risks. While no significant associations were observed, modest trends suggest possible relationships between NO₂ exposure, socioeconomic deprivation, and LBW risk. To better assess causality, future research should incorporate individual-level data, improved spatial and temporal exposure alignment, and confounding control for maternal risk factors such as age, smoking, and comorbidities.

Keywords: nitrogen dioxide, low birth weight, socioeconomic deprivation, air pollution, Bayesian spatial modeling, urban environmental health

INTRODUCTION

Ambient air pollution is widely associated with adverse neonatal health outcomes [1-3]. However, the effects of nitrogen dioxide (NO₂) on neonatal outcomes, including low birth weight (LBW), have been less extensively studied, and existing findings remain inconclusive [4, 5]. Earlier research primarily focused on fine particulate matter (PM_{2.5}) or general air pollution metrics [6, 7]. More recently, studies have begun to examine NO₂—a traffic-related pollutant and common indicator of poor air quality—for its potential association with adverse birth outcomes [3, 8].

Several studies have reported statistical associations between NO₂ exposure and increased risk of LBW [5, 8], but most have not examined these patterns at the neighborhood

scale or accounted for socio-economic conditions that may confound or modify observed effects.

There are biologically plausible pathways by which NO₂ exposure could affect fetal growth. During pregnancy, oxygen and nutrient delivery to the fetus is essential for development. NO₂ has been hypothesized to impair maternal oxygen transport and reduce placental efficiency through mechanisms such as increased vascular resistance, oxidative stress, and systemic inflammation—potentially leading to restricted fetal growth.

Excluding multi-parity, LBW is most often caused by premature birth or intrauterine growth restriction (IUGR) [9]. Prematurity may result from infections, chronic maternal conditions such as diabetes, or a combination of environmental, behavioral, and genetic factors. IUGR is generally attributed to inadequate maternal-fetal circulation

or intrauterine infections, with maternal health, nutrition, and external exposures playing key roles.

We hypothesize that higher neighborhood-level NO₂ concentrations may be associated with an increased risk of LBW. This hypothesis is informed by the proposed biological mechanisms linking air pollution to fetal growth restriction.

A persistent challenge in environmental epidemiology is the spatial misalignment between pollution exposure data and health outcome data, particularly when using administrative boundaries. Prior research has explored this issue in the context of long-term pollution exposure and chronic disease outcomes [10-12]. In this study, we apply a previously established spatial analysis method to evaluate potential associations between ambient NO₂ levels and LBW outcomes across neighborhoods in Toronto, Canada.

METHODS

We conducted a spatial ecological study of 140 Toronto neighborhoods to investigate whether ambient air pollution was associated with neighborhood-level prevalence of LBW. Our analysis covered births occurring from January 1, 2009, through December 31, 2011, and incorporated open source environmental, demographic, and health data. The publicly available data was in aggregate and anonymous, with no prospect of data linkage to generate individual identifiable information. Access to environmental data (NO₂ and CO₂) to spatially model exposure was provided by the Canadian Urban Environmental Health Research Consortium (CANUE) [13].

Low Birth Weight Data

Neighborhood-level LBW counts, and three-year average rates were obtained from the Toronto Community Health Profiles Partnership's Mothers and Babies Program (Toronto Community Health Profiles Partnership 2013) [14]. LBW was defined as birth weight below 2,500 g, and the provincial average of 6.5% [15] was used to calculate expected LBW counts in each neighborhood. Fertility rates (births per 1,000 women aged 15-49) were extracted as a proxy for maternal age distribution. No neighborhoods had missing LBW or fertility data.

Neighborhood Boundaries

Neighborhood polygons were defined by Statistics Canada census tract boundaries, as adopted by the City of Toronto in the mid-1990s to support socio-economic planning. The 140 neighborhoods comprise contiguous census tracts and are provided in standard shapefile format. For spatial weighting, centroids of each polygon were calculated, and neighbors were designated as those polygons whose centroids fell within a specified radius or by queen contiguity criteria.

Nitrogen Dioxide Exposure

Our primary exposure, NO₂, was obtained from the CANUE's land-use regression model [13], which integrates 2006 national air pollution surveillance monitoring, satellite-derived NO₂, land-use covariates, and deterministic gradients to predict annual mean concentrations across Canada [16]. Modelled values for 2009-2011 were averaged at the postal-code level and then aggregated to neighborhood polygons in ArcGIS software [17]. Both mean and maximum NO₂ concentrations were calculated; the maximum served as the

primary metric to capture localized peaks near major roadways. Raster resolution was approximately 1,000 m × 1,000 m.

Fine Particulate Matter (PM_{2.5}) Confounder

To control for confounding by PM_{2.5}, we used annual concentration estimates derived from NASA's MODIS aerosol optical depth, the GEOS-Chem transport model, and geographically weighted regression [18]. The PM_{2.5} raster had a resolution of roughly 1 km × 1 km, with three-year running averages provided in the source data; we used the 2009-2011 mean ("2011").

Spatial Processing and Interpolation

Continuous NO₂ and PM_{2.5} rasters were interpolated using inverse distance weighting (power = 2) in QGIS [19], based on the principle that near points are more alike than far points. While kriging is more complex, IDW often yields competitive results when optimized and was selected for its simplicity and performance. Neighborhood summary statistics (mean PM_{2.5}; mean and maximum NO₂) were extracted via polygon overlays. Spatial patterns were visualized using choropleth and bivariate symbology in ArcGIS [17].

Statistical Analysis

We fitted Bayesian Poisson spatial regression models in R [20] (version 4.0.3) using the CARBayes package [21] (v5.0.0), specifying a Leroux conditional autoregressive (CAR) prior to model spatial random effects. The Leroux CAR combines spatially structured and unstructured random effects via a spatial dependence parameter (ρ), accommodating varying degrees of autocorrelation. The model offset was the log of expected LBW counts, based on the provincial 6.5% rate and neighborhood fertility. The primary model included maximum NO₂, PM_{2.5}, fertility rate, material deprivation [22], and ethnic concentration. A secondary model substituted mean NO₂ for maximum NO₂.

Full prior specifications included Gaussian priors for fixed effects ($\beta \sim N[0, 10^6]$) and inverse-gamma priors for variance components ($\sigma^2 \sim IG[1, 0.01]$). Expected counts served as an offset with a log link.

Model fit was compared using the deviance information criterion (DIC), effective number of parameters, and log marginal predictive likelihood. We assessed convergence via trace plots and Geweke diagnostics; residual spatial autocorrelation was tested with Moran's I [23]. Posterior estimates are reported as medians with 95% credible intervals. No additional sensitivity or secondary analyses were performed.

Software and Versions

Data processing and statistical modeling used R software version 4.0.3 [20], CARBayes 5.0.0 [21], package sf 0.9-7, and package spdep 1.1-5. Geoprocessing employed ArcGIS Desktop 10.6 [17] and QGIS 3.10 [19].

RESULTS

Descriptive Statistics

From January 1, 2009, to December 31, 2011, Toronto's 140 neighborhoods recorded 90,871 live births [24], of which 6,679

Table 1. LBW outcome and response variables used in the model by neighborhood areal unit for the 2009-2011 period

Variable	Mean (standard deviation)	Range (minimum-maximum)
LBW rate, Toronto (2009-2011)	7.35 (1.44)	3.40-11.00
Air pollution variables (140 Toronto neighborhoods, 2009-2011)		
NO ₂ (ppb): neighborhood mean	19.19 (1.76)	12.38-22.31
NO ₂ (ppb): neighborhood maximum	26.61 (5.63)	12.00-52.00
PM _{2.5} (µg/m ³): neighborhood mean	8.26 (0.40)	6.40-8.80
PM _{2.5} (µg/m ³): neighborhood maximum	8.63 (0.27)	7.85-9.30
Other exposure variables		
Fertility rate (births per 1,000 women aged 15-49)	43.41 (10.63)	18.40-84.80
Material deprivation score (standardized, 2011)	0.56 (0.83)	-0.78-3.03
Ethnic concentration score (standardized, 2011)	1.06 (0.82)	-0.32-3.44

Table 2. Effect estimates from primary spatial model of NO₂, PM_{2.5}, deprivation, ethnic concentration, and fertility on risk of LBW

	Effect estimate	Lower credible level (2.5%)	Upper credible level (97.5%)
Maximum NO ₂ (ppb)	1.00	1.00	1.01
Mean PM _{2.5} (ug/m ³)	0.95	0.86	1.04
Deprivation score	1.05	0.98	1.13
Ethnic concentration	1.00	0.94	1.07
Fertility rate	1.00	1.00	1.00

Note. DIC = 963.2076; pd = 42.05952; & LMPL = -486.81

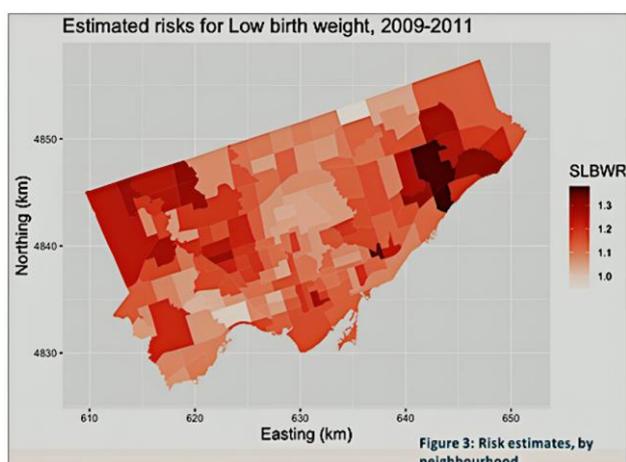


Figure 1. Estimated relative risks of LBW in Toronto neighborhoods, 2009-2011 (estimated relative risks of LBW, relative to Ontario average LBW: central north-south corridor of city and east-west midlines have lower risk of LBW, relative to elevated risks in the northwest and northeast corners of the city and downtown) (Source: Author’s own elaboration, using ArcGIS)

(7.35%) were classified as LBW. The citywide LBW rate exceeded Ontario’s 6.5% provincial average [15]. Ambient NO₂ levels varied broadly: neighborhood means ranged from 12.4 to 22.3 ppb (mean ± standard deviation: 19.2 ± 1.8 ppb), and maximum values spanned 12-52 ppb (26.6 ± 5.6 ppb). In contrast, PM_{2.5} was more homogeneous, with mean concentrations of 6.4-8.8 µg/m³ (8.3 ± 0.4 µg/m³). Fertility rates averaged 43.4 ± 10.6 births per 1,000 women (range: 18.4-84.8). Neighborhood material deprivation and ethnic concentration scores exceeded provincial benchmarks (0.56 ± 0.83 and 1.06 ± 0.82, respectively) (Table 1).

Effect Estimates (n = 140)

In the primary Bayesian Poisson spatial model, no covariate reached statistical significance at the 95% credible interval. Among 140 neighborhood units, each 1 ppb increase in maximum NO₂ was associated with a relative risk (RR) of 1.002 (95% confidence interval [CI]: 0.996-1.008), and each

one-standard deviation rise in material deprivation yielded an RR of 1.053 (95% CI: 0.977-1.125). PM_{2.5}, ethnic concentration, and fertility rate showed null associations. Substituting mean NO₂ for maximum produced a reversed but similarly non-significant effect (Table A1 in Appendix A). Model fit metrics were DIC = 963.21, p.d. = 42.06, and LMPL = -486.81 (Table 2).

Convergence diagnostics indicated satisfactory mixing for all parameters (Gelman-Rubin $\hat{R} < 1.05$; Geweke z-scores within ± 1.5).

The posterior median spatial dependence parameter (ρ) was 0.68 (95% CrI: 0.53-0.82), demonstrating moderate neighborhood-level autocorrelation.

Spatial Variation in Relative Risk

Standardized LBW ratios (SLBWR) revealed spatial heterogeneity in LBW risk across Toronto neighborhoods, ranging from 0.95 to 1.41 (mean = 1.15). Elevated risks clustered in the downtown core, along the central lakeshore, and in the city’s northwest and northeast sectors (Figure 1 and Figure A1 in Appendix A).

Visual and Spatial Patterns

Choropleth maps of LBW and NO₂ showed limited geographic overlap: high-pollution corridors (Highways 401, 407, Don Valley Parkway) did not consistently coincide with elevated LBW rates, nor did low-pollution areas uniformly demonstrate lower LBW (Figure 2). A bivariate map further illustrated this mismatch (Figure A2 in Appendix A). Global Moran’s I confirmed significant clustering of NO₂ (I = 0.624, p < 0.001) and LBW (I = 0.299, p = 0.002), validating the spatial modelling approach.

Interpolated Exposure Surfaces

Inverse distance-weighted surfaces [17] illustrated pronounced NO₂ gradients adjacent to major roadways, whereas PM_{2.5} was relatively uniform throughout Toronto neighborhoods (Figure A3 in Appendix A). The greater NO₂ heterogeneity—and the decision to model maximum rather than mean values—was intended to capture localized peak exposures that may influence perinatal outcomes.

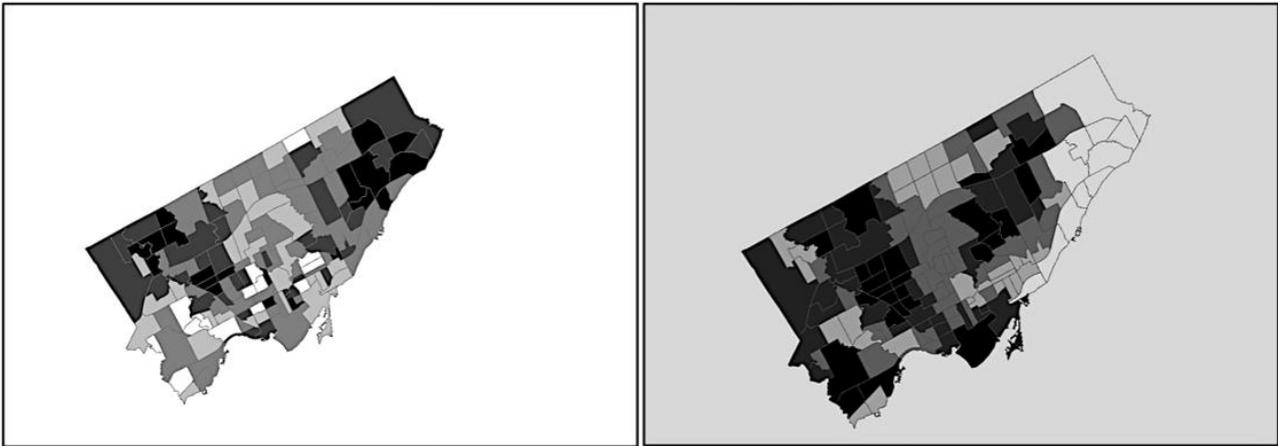


Figure 2. Choropleth gradients for average (left) LBW rates and (right) NO₂ concentrations across Toronto neighborhoods, 2009-2011 (shading intensity in both panels reflects variable magnitude, with **darker shades indicating higher values**: (left) **LBW**: neighborhoods with darker shading had higher proportions of LBW births (< 2,500 g), revealing elevated rates in the downtown core, northwest, and northeast areas & (right) **NO₂ concentrations**: darker shaded neighborhoods experienced higher modeled NO₂ levels (ppb), primarily clustered along major highways and arterial roads, indicating areas of intensified traffic-related air pollution) (Source: Author's own elaboration, using QGIS)

Interpretation of Results

The model's small, non-significant 0.2% increase in LBW risk per 1 ppb rise in maximum NO₂ suggests limited detectable effect at the neighborhood level. This modest association may reflect exposure misclassification or spatial misalignment between pollution gradients and administrative zones, as well as uniformly high exposure across most areas. No PM_{2.5}-LBW association was observed, consistent with PM_{2.5}'s narrow concentration range in 2009-2011. Material deprivation showed a non-significant 5% higher LBW risk per one-unit score increase, aligning with literature linking socioeconomic disadvantage to adverse birth outcomes [25-27]. Ethnic concentration and fertility rate were not significantly related to LBW, highlighting the limitations of aggregate proxies and potential unmeasured protective or risk factors (e.g., maternal health, nutrition, and smoking).

Overall, the findings imply that unmeasured individual-level variables [28-30] likely contribute to spatial LBW variability. Future research should integrate finer-scale and individual-level exposure data to better elucidate these relationships.

DISCUSSION

This study adds to the literature examining neighborhood-level NO₂ concentrations and LBW prevalence in urban settings. Through spatial modeling of publicly available data across 140 Toronto neighborhoods, the analysis characterizes intra-urban differences in exposure and outcome patterns. From 2009 to 2011, the majority of neighborhoods in Toronto had NO₂ concentrations above commonly referenced thresholds, particularly in proximity to major highways such as the 401, 407, and Don Valley Parkway. However, LBW prevalence did not display a spatial distribution consistent with that of NO₂. In adjusted models, the association between maximum NO₂ concentrations and LBW was small and not statistically significant. The magnitude and direction of this association are comparable to other studies using area-level designs [5, 31, 32]. The limitations inherent to spatial

averaging, temporal alignment, and pollutant homogeneity across neighborhoods may have affected the ability to detect stronger relationships, as noted in similar spatial epidemiological analyses [33-36].

The effect estimate observed in this study (RR 1.002 per ppb NO₂) falls within the range of previously reported associations. For example, it was identified an inverse association between NO₂ and term birth weight in a Canadian cohort [5], while the study in [2] reported a pooled odds ratio of 1.030 per 10 ppb NO₂ increase across multiple international studies. It was also reported that an adjusted odds ratio of 1.082 using advanced weighting methods [8]. These comparisons place the current findings within the broader context of global air pollution and birth outcome research.

The analysis also included area-level indicators of socioeconomic conditions. Material deprivation was positively associated with LBW in the model, although this association did not reach statistical significance. No clear relationship was observed for ethnic concentration. In contrast, previous research has reported effect modification by neighborhood-level economic deprivation [25-27]. The present study did not identify similar significant modification effects, which may relate to differences in population characteristics, measurement strategies, or exposure variability. No association was detected between PM_{2.5} and LBW in this study. The relatively narrow range of PM_{2.5} values across Toronto neighborhoods may account for this null result. Comparable findings have been reported in Southwestern Ontario, where other pollutants such as sulfur dioxide were more strongly linked to LBW [31]. Similarly, it was observed associations between NO₂ and LBW at a national scale in Spain, reinforcing the relevance of NO₂ as a traffic-related exposure metric in urban environments [4]. In Texas (United States), a study found that maternal residential proximity to industrial facilities emitting any of the fourteen identified pollutants during pregnancy were associated with LBW in offspring [36].

A key strength of this study is the use of open-access data and the application of Bayesian spatial modeling via the Leroux CAR framework, which allowed for adjustment of spatial autocorrelation and estimation of neighborhood-level risk. To

our knowledge, this represents one of the first applications of these methods to assess NO₂ and LBW associations within Toronto.

Limitations

Several methodological limitations must be acknowledged:

1. The ecological design precludes inference about individual-level associations and introduces potential bias through aggregation.
2. NO₂ exposure data, although high-resolution at the postal-code level, were aggregated to neighborhood boundaries, which may have obscured local exposure extremes.
3. Individual-level information on maternal characteristics and behaviours (e.g., age, smoking, and comorbidities) was not available, limiting confounding control.
4. The analysis focused on NO₂ and PM_{2.5} only; other pollutants relevant to birth outcomes were not included.

Although the associations observed were not statistically significant, the descriptive patterns in the data are consistent with previous research identifying NO₂ and material deprivation as relevant exposures in the context of perinatal outcomes. These findings underscore the value of neighborhood-level analyses in identifying spatial disparities and informing future study designs.

CONCLUSION

Ambient NO₂ concentrations in Toronto neighborhoods during the study period frequently exceeded guideline values. While this study did not identify statistically significant associations between NO₂ exposure, socioeconomic deprivation, and LBW, the results align with trends observed in prior research.

The use of spatial modeling and publicly available data provides a basis for evaluating intra-urban patterns of environmental and social conditions relevant to perinatal health. However, limitations related to spatial resolution, temporal alignment, and the absence of individual-level risk factors may have influenced the observed results.

Future research efforts would benefit from integrating individual-level birth records, temporally resolved exposure data aligned with gestational periods, and detailed covariates capturing maternal health and behavior. These enhancements are expected to improve the precision and interpretability of findings related to environmental exposures and birth outcomes

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AI statement: The author stated that AI tools were used only for grammar and phrasing improvements. All ideas, interpretations, and final content are the author's own and were fully reviewed for accuracy.

Declaration of interest: No conflict of interest is declared by the author.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the author.

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APPENDIX A

Table A1. Alternative model estimates using mean NO₂ in place of the maximum NO₂

	Median	Lower credible level (2.5%)	Upper credible level (97.5%)
Mean NO ₂	0.9839305	0.9641581	1.005817
Mean PM _{2.5}	0.9726801	0.8847944	1.069509
Deprivation	1.0565406	0.990644	1.126145
Ethnic concentration	0.9954106	0.9400709	1.060033
Fertility rate	0.9995001	0.9954106	1.003305

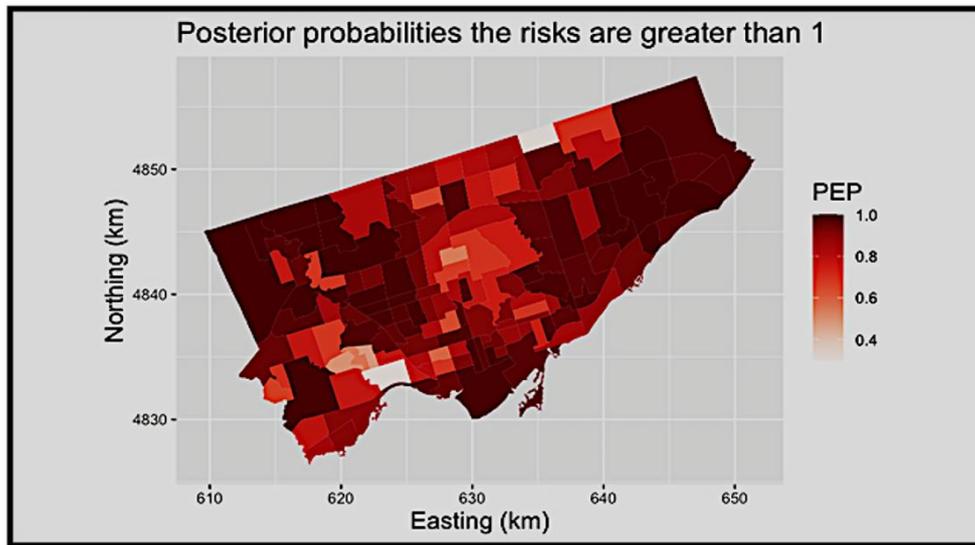


Figure A1. Posterior exceedance probabilities for LBW risk across neighborhoods of Toronto (this map shows the posterior exceedance probabilities (PEP) that the relative risk of LBW exceeds 1, based on the Bayesian spatial model; neighborhoods are shaded on a gradient from light red (lower PEP) to dark red (higher PEP), indicating increasing certainty that LBW risk is elevated above the provincial average; areas with PEP values approaching 1.0 reflect stronger evidence of elevated risk; & the spatial distribution highlights localized clusters of higher posterior risk, particularly in the downtown core and southern districts, supporting the utility of spatially explicit modeling in identifying areas of concern) (Source: Author’s own elaboration, using ArcGIS)

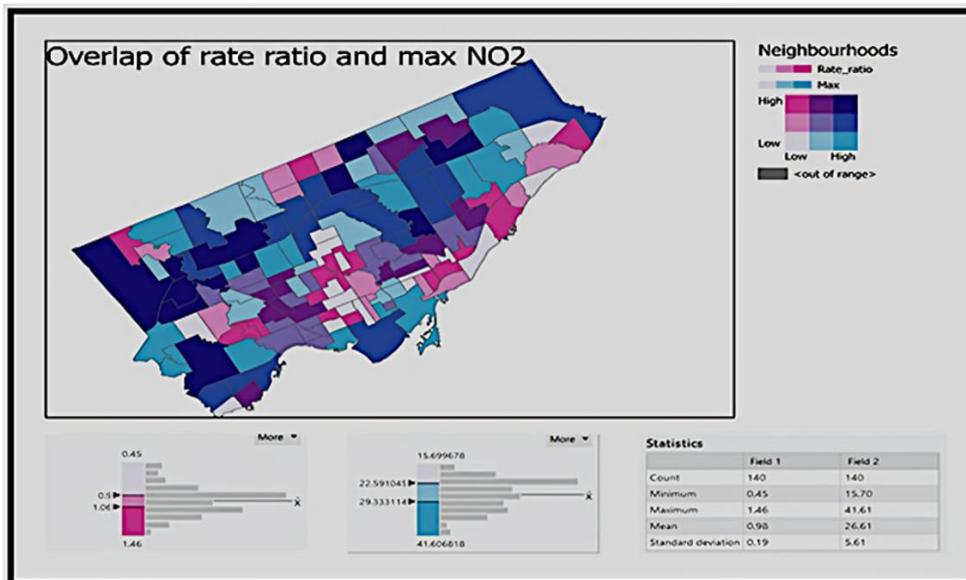


Figure A2. Bivariate overlap between low-birth-weight rate ratio and maximum nitrogen dioxide levels (it presents a bivariate choropleth map illustrating the spatial relationship between SLBWR ratios and maximum modeled NO₂ concentrations in 140 Toronto neighborhoods; shades of pink represent higher LBW rate ratios, blue indicates higher NO₂, and purple reflects concurrent elevation of both variables; grey areas denote missing or out-of-range data; summary statistics show a mean LBW rate ratio of 0.98 (range: 0.45-1.46) and a mean maximum NO₂ concentration of 26.61 ppb (range: 15.70-41.61); & it highlights limited geographic overlap between high LBW prevalence and high NO₂ exposure) (Source: Author’s own elaboration, using ArcGIS)

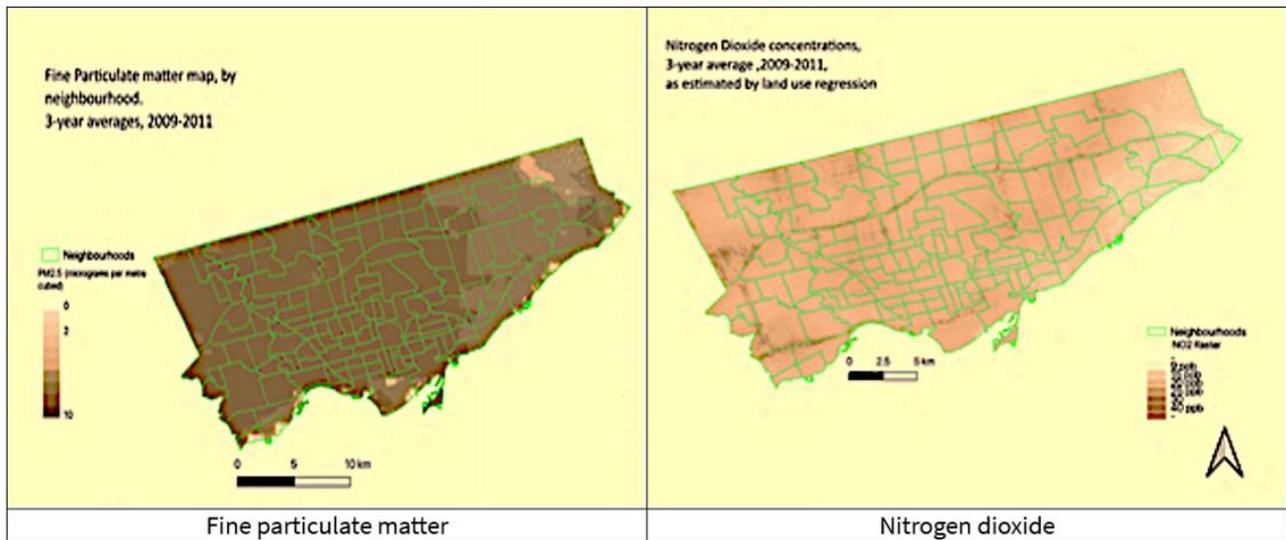


Figure A3. Map of inverse distance weight exposures for (left) PM_{2.5} and (right) NO₂ (interpolated exposure surfaces across Toronto neighborhoods, 2009-2011: (left) NO₂ concentrations show sharp gradients with higher values near major highways & (right) PM_{2.5} concentrations appear relatively uniform across the city; & surfaces were created using inverse distance weighting based on modeled estimates) (Source: Author's own elaboration, using QGIS)