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Residential mobility and multi-domain environmental exposures in Canada: Development of the Residential Mobility Exposome File

by Toyib Olaniyan

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Abstract

Background: Residential mobility influences cumulative environmental exposures over the life course, yet few national datasets capture these dynamics across multiple exposure domains. This paper describes the development of the Residential Mobility Exposome File (ReMEF) and the cohort profile.

Data and Methods: The ReMEF integrates individual-level residential histories from linked census and administrative data with annually resolved spatial measures of ambient air pollution, built and green environment characteristics, and ambient temperature. Annual k-means clustering was applied within each domain to classify exposures into three levels (low, medium, or high), followed by a temporal dominance rule to derive five-year exposure biographies. The analytical cohort included individuals aged 25 to 89 years with stable pre-baseline residence, enabling assessment of residential mobility patterns and exposure trajectories.

Results: The ReMEF framework offers a scalable approach for leveraging residential mobility as a quasi-experimental feature of observational data. The standardized trichotomy (low, medium, high) applied across domains allows for comparability between different types of exposures. Residential mobility varied substantially by population group and socioeconomic characteristics. Certain racialized populations had relatively higher mobility, while First Nations and Inuit individuals were less likely to move. Distinct exposure biographies were observed across environmental domains, with racialized and immigrant populations more frequently residing in higher ambient air pollution clusters.

Interpretations: The ReMEF provides a resource analytical file and is useful for natural experiments that aim to leverage residential mobility to examine cumulative, multi-domain environmental exposures and disparities over time. The analytical file creation code is available upon request, and it can be recreated using the source data following approval.

Keywords: Residential mobility, exposome, environmental disparities, environmental justice, air pollution, climate exposure, built and green environment

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What is already known on this subject?

- Residential mobility shapes cumulative environmental exposures across the life course and can contribute to differential environmental risk.
- Population-based Canadian cohorts, such as the Canadian Census Health and Environment Cohort, provide rich sociodemographic and health-linked data for studying environmental determinants of health.
- Understanding how environmental exposures change as individuals move—and how these changes vary across social, racialized, and socioeconomic groups—is critical for advancing research on environmental inequality, environmental justice, and climate-related health impacts.

What does this study add?

- This study introduces the Residential Mobility Exposome File (ReMEF), a novel national analytical file that links longitudinal residential postal code histories with annually resolved, multi-domain environmental exposures in Canada.
- By integrating ambient air pollution, built and green environment, and ambient temperature data, the ReMEF provides dynamic exposure biographies that capture both residential mobility and temporal environmental change.
- The ReMEF cohort profile reveals distinct and socially patterned environmental exposure profiles, with racialized and immigrant populations more frequently residing in higher ambient air pollution exposure clusters.
- The ReMEF framework enables life-course and intersectional analyses of cumulative environmental exposures and provides a scalable platform for future research on environmental inequality, environmental justice, and climate–health relationships.
- The analytical file is extensible to additional years and environmental domains, and the methodological framework is adaptable to other research contexts where residential mobility and time-varying environmental exposures are of interest.

Introduction

Environmental exposures such as air pollution, extreme temperatures, and limited access to green space are major contributors to health inequities in Canada and globally.[1-4] Yet these exposures are rarely static: individuals move across neighbourhoods with distinct environmental profiles, while environmental and social conditions evolve over time.[5-7] Despite this dynamic reality, most population-based environmental epidemiology studies rely on static, multi-pollutant snapshots and single-domain or cross-sectional exposure assignments, limiting insight into how exposure inequalities accumulate and change over the life course.[7-9] In addition, while most environmental epidemiological studies capture health effects related to an individual's exposure—often from a single domain—a growing interest is the synergy between climatic extremes and the built or natural environments that modify those exposures.[10-12] Integrating these domains is essential for a true exposome framework, yet the complexity of tracking such multifaceted, time-varying interactions has historically limited national-scale analyses.[13-16]

Furthermore, a little-known but critical perspective in this field is the divergence between "apparent" and "unperceived" exposures during relocation.[17,18] While individuals may often self-select into environments based on apparent features such as green space or urban density, they are simultaneously assigned "unperceived" exposures, such as fine particulate matter or ozone, which act as quasi-random environmental assignments during a move.[17,19] Leveraging residential relocation as a natural experiment requires a dataset capable of distinguishing these preferences from exogenous environmental shifts. Thus, the Residential Mobility Exposome File (ReMEF) addresses these needs by linking historical Canadian postal codes with multi-domain environmental data, to enable the assessment of how multi-domain environmental exposures change as people move—and how these dynamics differ across sociodemographic and geographic groups. This study describes the creation of the ReMEF and characterizes its profile through residential mobility patterns and exposure biographies (clusters) across three domains: ambient air, the built and green environment, and ambient temperature. For the purposes of this study, the term "residential mobility" is used to refer to voluntary annual changes in residential address, distinct from the term "residential relocation," which, within the Canadian context, carries historical connotations of forced displacement—particularly for Indigenous Peoples.

Methods

Data sources and study population

The ReMEF was created by integrating longitudinal historical residential postal codes primarily obtained from annual tax files available from the Canadian Census Health and Environment Cohort (CanCHEC) with time-varying environmental data from multiple sources. Details of the CanCHEC cohort profile are described elsewhere,[20] and information on each of the environmental data sources is described below and summarized in Table 1. Briefly, the CanCHEC includes respondents to the 1991, 1996, and 2001 Census long-form questionnaires linked to annual income tax, mortality, and postal code data (1986 to 2016) via Statistics Canada's Social Data Linkage Environment.[20] Individuals aged 25 years and older at cohort entry were followed from the respective census date until death or December 31, 2016. Of the original 9,077,170 individuals from the 1991 (2.6 million), 1996 (3.2 million), and 2001 (3.2 million) censuses, 2.8 million individuals were excluded because they responded to multiple long-form census questionnaires—and only their earliest census questionnaire was included. Furthermore, of the remaining 6,320,800 individuals, 2,344,830 who moved in the five years before cohort entry were further excluded. This was done to ensure that the cohort being assessed onwards from the baseline for residential mobility is comparable, and the exposures are not attributable to environments outside Canada, as is the case for recent immigrants. Furthermore, it is important to have a comparative counterfactual group (i.e., non-movers during follow-up) to limit the bias caused by self-selection, since residential mobility does not exist randomly.[10,18,21,22] The five-year pre-baseline is denoted as Time 0 (T_0), with 3,975,970 individuals—from which 2,489,200 individuals moved in any year during the follow-up period (T_1 to T_5). An overview of the study design is depicted in Figure 1. Three external exposome domains of the environment were considered in this analytical file based on depth of evidence linking them to health outcomes.[3,7,19,23-25]

Table 1
Summary of key analytical variables by data source and spatiotemporal scale

Key variables	Data source	Spatiotemporal scale: Resolution	Spatiotemporal scale: Time
Postal code	Tax files attached to CanCHEC	Postal code centroid	Annual
Ambient air pollution			
$PM_{2.5}$	Previous exposure on CanCHEC	1 x 1 km	Annual
NO_2	Previous exposure on CanCHEC	30 X 30 m	Annual
O_3	Previous exposure on CanCHEC	21 X 21 km	Annual
O_x	Previous exposure on CanCHEC	Postal code centroid[1]	Annual
Built and green environment			
NDVI	CANUE	250 m buffer	Annual[2]
% dense urban	CANUE	1 x 1 km	Closest census year (1991, 1996, 2001, 2006, 2011, 2016)
% natural land cover	CANUE	1 x 1 km	Closest census year (1991, 1996, 2001, 2006, 2011, 2016)
Ambient temperature			
Annual highest temperature	CANUE	10 X 10 km	Annual[3]
Annual lowest temperature	CANUE	10 X 10 km	Annual[3]
Average daily maximum temperature	CANUE	10 X 10 km	Annual[3]
Average daily minimum temperature	CANUE	10 X 10 km	Annual[3]
Sociodemographic variables			
Population group	Census	Individual	Census time (baseline)
Racialized population	CanCHEC	Individual	Census time (baseline)
Immigrant status	CanCHEC	Individual	Census time (baseline)

1. O_x was derived from a redox-weighted average of NO_2 and O_3 at the postal code centroid.

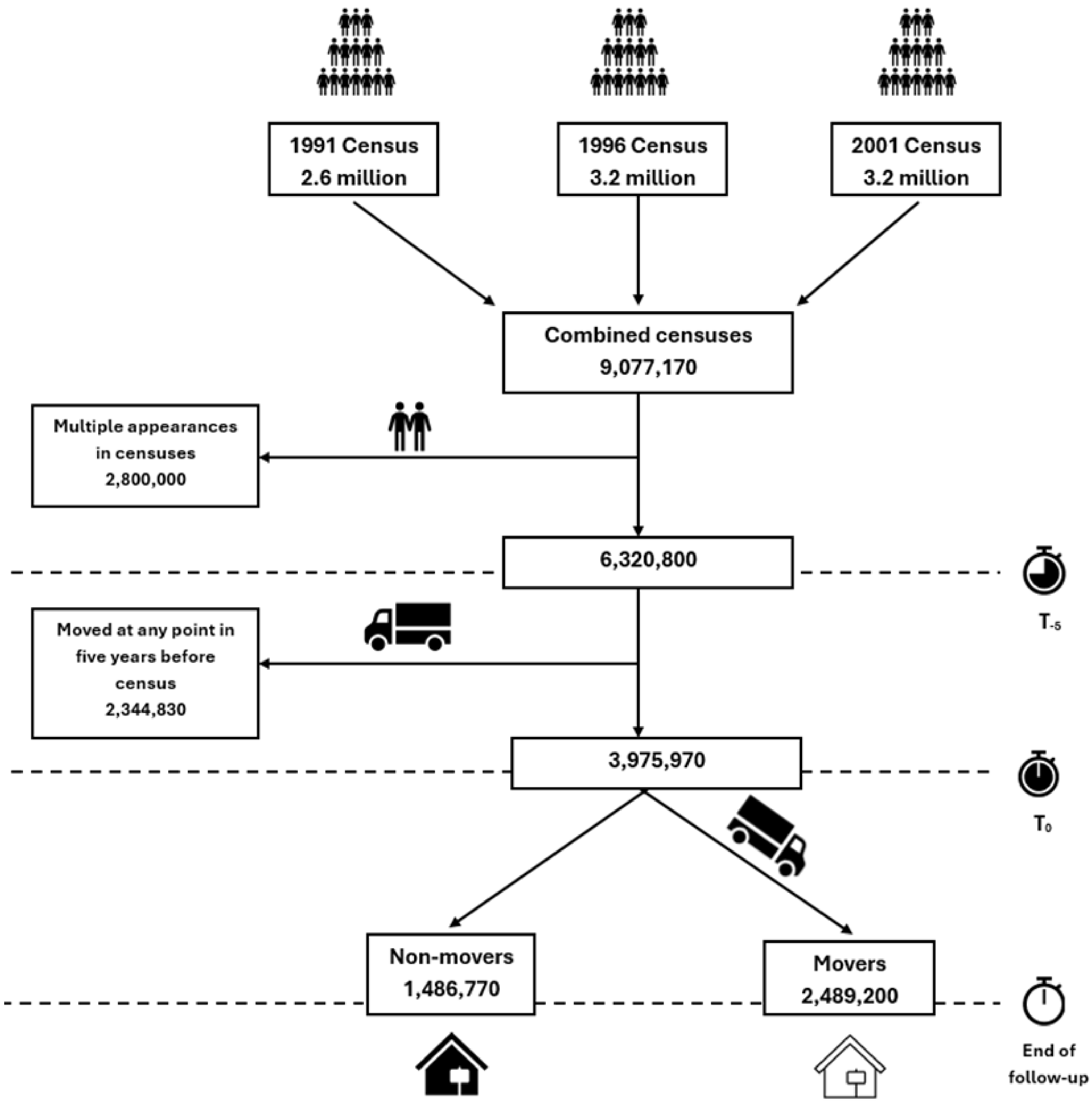
2. The annual data were not available for 2012 and were derived from the average of 2011 and 2013 values.

3. Climate data were not available for 2016 and were derived from the three-year moving average for 2013, 2014, and 2015.

Notes: CanCHEC = Canadian Census Health and Environment Cohort; NDVI = Normalized Difference Vegetation Index; CANUE = Canadian Urban Environmental Health Research Consortium.

Sources: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001. and the Canadian Urban Environmental Health Research Consortium (CANUE) database

Figure 1
Overview of the study design



Sources: Statistics Canaada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

External exposome domains

Ambient air pollution

Annual exposures to particulate matter of 2.5 μm in diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), warm-season ground-level ozone (O_3), and oxidant capacity (O_x) were assigned at the six-character postal-code level. Details of the estimation procedures have been published elsewhere.[7,26] Briefly, $PM_{2.5}$ (1 km^2 resolution) was estimated via satellite aerosol optical depth and GEOS-Chem models calibrated with ground measurements via geographically weighted regression.[7,26] NO_2 (30 m resolution) was derived from a national land-use regression model incorporating spatial predictors such as road density and industrial emissions.[26] Warm-season ground-level O_3 concentrations were derived from a national Canadian surface generated using a chemical transport model, which provided gridded estimates at a 21 km^2 resolution based on modelled warm-season (photochemical) maximum concentrations—the period of peak photochemical O_3 formation in Canada (May 1 to October 31). These modelled surfaces were subsequently calibrated against historical observations from fixed-site monitors of Canada's National Air Pollution Surveillance Program network using linear regression, to align model output with measured ambient concentrations.[26] O_x was calculated as a redox-weighted average to represent the combined oxidative burden: $O_x = [(NO_2 \times 1.07) + (O_3 \times 2.075)]/3.145$.[24]

Built and green environment

Greenness and urban form indicators were sourced from the Canadian Urban Environmental Health Research Consortium (CANUE) database.[27] Greenness was characterized by the Normalized Difference Vegetation Index (NDVI) at 250 m buffers, derived from Landsat imagery via Google Earth Engine. NDVI annual data were not available for 2012 and thus were derived from the average of 2011 and 2013 values.[28] Urban form and grey space intensity were quantified using local climate zones, specifically the percentage of dense urban area and natural land cover within a 1 km^2 radius.[29] These metrics capture landscape-level influences on surface temperature and heat island effects.[29,30]

Ambient temperature

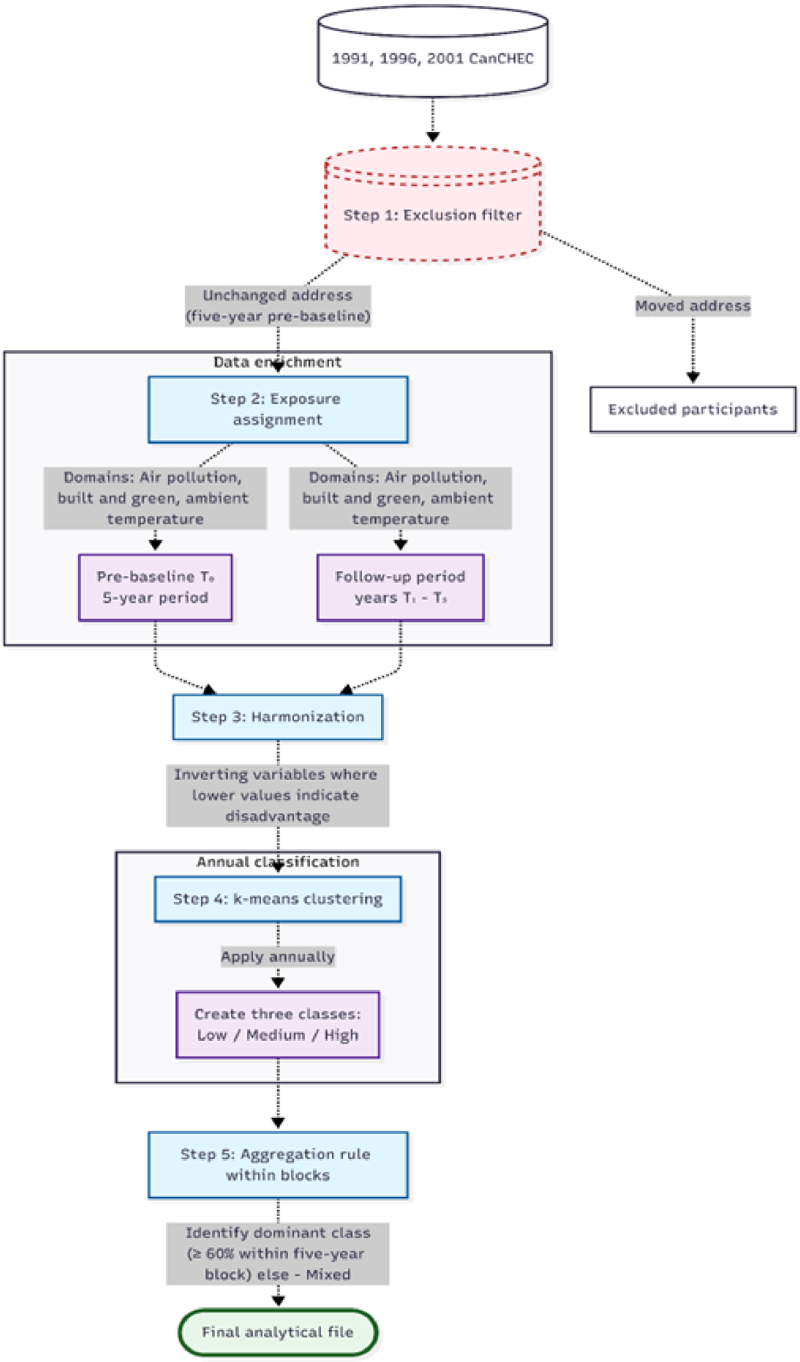
Ambient temperature was characterized using four annual metrics from CANUE: the annual highest temperature, annual lowest temperature, annual average daily maximum temperature, and annual average daily minimum temperature. These were derived from the ANUSPLIN gridded climate dataset—a national, station-based interpolated product generated using a thin plate smoothing spline method from Environment and Climate Change Canada climate station observations—at a native spatial resolution of 10 km, with values subsequently assigned to each residential postal code by CANUE for linkage with health data.[31] To address missing annual 2016 data, values were derived from a three-year moving average (2013 to 2015).

Derivation of external exposome cluster and residential mobility assignment

Harmonization of exposure scales

To facilitate comparisons across domains, all exposures were oriented such that higher values represented more adverse conditions (Figure 2). This was done by inverting variables where lower values indicate disadvantage (e.g., annual lowest temperature, annual daily minimum temperature, natural land cover, and NDVI greenness).

Figure 2
Analytical file creation steps



Sources: a Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001. and the Canadian Urban Environmental Health Research Consortium (CANUE) database.

Exposure clustering and block-level assignment

Year-specific k-means clustering (k=3) was applied to standardized variables in each domain, producing 'Low, Medium, and High' exposure categories.[32] The number of clusters (i.e., three) within each domain was selected *a priori* to facilitate comparison and reduce the number of dimensions. Besides the ambient temperature domain, where a U-shaped relationship has been reported with health outcomes,[23] high exposure denotes a relatively poor (i.e., harmful) exposure classification, and vice versa for low exposure. Since both cold and heat extremes are associated with adverse health outcomes, the annual lowest and annual average daily minimum temperatures were inverted prior to clustering, such that higher values consistently reflected greater thermal stress, regardless of direction. All variables were standardized (mean = 0, standard deviation = 1) before applying k-means clustering, yielding three clusters representing low, medium, and high thermal stress environments. The resulting 'Low cluster'—characterized by mild temperatures and minimal extremes at either end—will be used as the reference category in subsequent analyses, since it most closely approximates the thermally neutral environment associated with minimum temperature-attributable mortality risk.

For each cohort member, dominant exposure categories were determined within consecutive five-year blocks, with the final block extended to six years (to accommodate the final follow-up year—2016). The rationale for a five-year block is based on previous research using the CanCHEC, which found a five-year window to be sufficient for assessing changes in ambient air pollution following residential mobility associated with mortality outcomes in Canada.[7] Within each block, individuals were assigned a dominant exposure category for each domain (ambient air pollution, ambient temperature, and built and green space) using a 60% or greater majority rule. More specifically, if 60% or more (i.e., three years or more in a five-year window) of annual cluster assignments within a block fell into the same category, that category was assigned to the block. If no category reached this threshold (i.e., no category has three years or more in a five-year window), the block exposure was deemed to have no dominant exposure levels and thus set to the 'Mixed' category. The 60% dominance rule was implemented under the assumption of an unweighted, additive contribution of annual exposures within each five-year block. This threshold identifies the exposure level most representative of an individual's environment during the period, assuming that the cumulative health impact is driven by most time spent in a specific exposure cluster. For individuals who did not meet this threshold, a 'Mixed' category was created to preserve the distinction of spatial instability.

Residential mobility procedure

Mobility was defined as moving out of the pre-baseline (previous five years) postal code at any time during follow-up. Individuals with an unchanged pre-baseline residence were those with the same postal code for all five pre-cohort years. Within each block, individuals were classified as non-movers if they remained at the same postal code for four years or more of the five years (four years or more of the six in the final block). This cut-off was to account for short-term moves captured in the historical postal code from the annual tax file. Long-term residential changes are of interest, and researchers looking for transient changes may apply another cut-off that meets their analytical needs. Conversely, for overall residential mobility status, those who moved at least once to a different postal code in any year during follow-up were classified as movers. Both block-level and overall mover status indicators were derived.

Statistical methods for characterizing the cohort profile

Descriptive characteristics were summarized for the analytical cohort across various individual and sociodemographic indexes. This was stratified by five-year pre-baseline residential stability (i.e., unchanged and changed) and residential mobility status at follow-up (i.e., movers and non-movers). The distribution of the exposure cluster within each domain was also assessed across the follow-up time blocks (T_0 to T_5) by the sociodemographic indexes of interest.

Predicted probabilities of residential mobility any time across the follow-up period were estimated using logistic regression models adjusting for individual and contextual covariates available from the CanCHEC.[20] These include sex; age group; marital status; educational attainment; labour force status;

income quintile; cohort cycle; and area-level Canadian marginalization indexes such as material deprivation, dependency, social instability, and ethnic concentration. This was estimated across various population groups (Black, Chinese, Indigenous, White, and others not included elsewhere). These population group categories were based on harmonization with the 1991 Census. The racialized population is defined as people, other than Indigenous people, who are non-Caucasian in race or non-White in colour, as reported on the respective census, regardless of their birthplace or citizenship. Indigenous identity was defined using the self-reported Aboriginal identity questions from the 1996 and 2001 censuses, classifying respondents as First Nations, Métis, or Inuit. For 1991, where no direct Aboriginal identity question was available, Indigenous identity was approximated using ethnic origin responses. It is acknowledged that Indigenous identity is subject to change across census cycles for a variety of reasons, including shifts in self-identification, differences in question design, and varying social and political contexts surrounding identity disclosure—resulting in a non-trivial proportion of individuals reporting different identities over time. To account for potential non-comparability across census years arising from these methodological and conceptual differences, all analyses were adjusted for cohort (i.e., census year of cohort entry), and findings pertaining to Indigenous identity should be interpreted with this limitation in mind. The predicted probabilities were also estimated across sociodemographic indexes (such as racialized population and immigrant status). An additional indicator—low socioeconomic status—was operationalized and defined as individuals in the lowest two income quintiles whose highest educational attainment was a high school education or less. For this indicator, both income quintile and educational attainment were omitted from the model.

The analytical file creation and analyses were conducted in R 4.2.3, SAS 9.4, and Stata 18.0.

Results

Cohort characteristics and selection

The final analytical cohort consisted of 3,975,970 individuals characterized by an unchanged five-year pre-baseline residential history. This population included 2,489,200 movers and 1,486,770 non-movers (Figure 1). Demographic and sociodemographic distributions were comparable between movers and non-movers. The characteristics of the analytical cohort were largely analogous to those of the individuals excluded from the file because of changes in five-year pre-baseline residence, with one notable exception regarding age (Table 2). Individuals aged 25 to 34 years represented a relatively larger proportion among those excluded (39.3%) compared with the population with an unchanged five-year pre-baseline residence (14.7%).

Table 2
Cohort descriptive statistics and characteristics of analytical cohort

	Full cohort (pre-baseline)		Unchanged (mover status)	
	Changed	Unchanged	Movers	Non-movers
	number			
Cohort participants	2,344,830	3,975,970	2,489,200	1,486,770
	percent			
Sex				
Female	50.3	50.6	49.9	51.7
Male	49.7	49.4	50.1	48.3
Age group (years)				
25 to 34	39.3	14.7	15.9	12.5
35 to 44	27.9	25.3	22.4	30.3
45 to 54	15.7	23.3	19.4	29.8
55 to 64	8.9	16.7	15.8	18.2
65 to 74	5.5	12.9	15.8	7.9
75 to 84	2.4	6.3	9.3	1.2
85 and older	0.3	0.9	1.4	0.1
Population group				
Black	1.1	0.8	0.9	0.8
Chinese	1.4	1.7	1.5	1.9
Indigenous	3.3	2.8	2.5	3.2
First Nations	2.4	2.1	1.9	2.4
Métis	0.9	0.6	0.6	0.7
Inuit	0.1	0.1	0.1	0.1
Multiple Indigenous identities	0.1	0.1	0.1	0.1
Other, not included elsewhere	7.2	6.4	6.9	5.6
White	87.1	88.4	88.3	88.5
Racialized population				
Yes	9.6	8.9	9.2	8.3
No (White)	87.1	88.4	88.3	88.5
No (Indigenous)	3.3	2.8	2.5	3.2
Immigrant status				
Immigrant	14.2	18.1	18.2	18.0
Non-immigrant	85.8	81.9	81.8	82.0
Marital status				
Never married and not common-law	14.5	10.5	12.0	8.0
Common-law	14.2	6.1	5.8	6.4
Married	57.4	70.7	66.3	77.9
Separated	3.6	1.7	2.0	1.3
Divorced	6.9	4.4	5.1	3.3
Widowed	3.4	6.7	8.8	3.2
Educational attainment				
No high school diploma	25.5	34.1	36.3	30.4
High school diploma or equivalency	37.2	35.6	34.6	37.4
Trades, college or university credential below bachelor's degree	20.0	16.8	16.1	17.9
Bachelor's degree or higher	17.3	13.5	13.0	14.4
Labour force status				
Employed	71.5	62.4	57.3	70.8
Unemployed	6.3	4.3	4.2	4.5
Not in the labour force	22.3	22.3	38.5	24.7

Notes: Because of rounding, percentages may not add up to 100%. Cohort charcteristics are as of the baseline. CanCHEC = Canadian Census Health and Environment Cohort.

Source: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

Table 2
Cohort descriptive statistics and characteristics of analytical cohort (continued)

	Full cohort (pre-baseline)		Unchanged (mover status)	
	Changed	Unchanged	Movers	Non-movers
	percent			
Income quintile				
1 (lowest)	18.6	15.0	16.7	12.1
2	19.0	19.2	20.3	17.3
3	20.4	20.9	20.4	21.9
4	20.8	22.1	20.8	24.1
5 (highest)	21.2	22.9	21.8	24.6
Dependency				
1 (lowest)	20.0	15.9	16.6	15.2
2	20.2	18.3	18.5	18.1
3	18.2	17.8	18.0	17.4
4	21.0	22.8	22.6	22.8
5 (highest)	19.5	25.2	24.1	26.5
Deprivation				
1 (lowest)	18.8	25.4	24.4	27.2
2	25.5	26.1	26.2	26.1
3	22.0	18.9	19.7	17.8
4	16.8	14.6	14.9	14.0
5 (highest)	15.8	15.0	14.7	14.9
Residential instability				
1 (lowest)	22.1	23.3	21.8	26.0
2	22.7	26.4	24.9	28.8
3	20.0	21.1	21.1	20.9
4	18.0	17.8	18.7	16.0
5 (highest)	16.1	11.4	13.3	8.3
Ethnic concentration				
1 (lowest)	21.2	20.5	18.9	23.2
2	20.2	18.7	18.4	19.2
3	18.3	16.7	17.2	15.9
4	19.6	20.0	20.8	18.7
5 (highest)	19.5	24.1	24.6	23.1
CanCHEC cycle				
1991	34.4	29.1	32.8	22.9
1996	35.6	37.7	38.5	36.3
2001	30.0	33.3	28.7	40.8

Notes: Because of rounding, percentages may not add up to 100%. Cohort charcteristics are as of the baseline. CanCHEC = Canadian Census Health and Environment Cohort.

Source: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

Derivation and characterization of exposure profiles

The analytical file contains longitudinal exposure profiles for three external exposome domains: ambient air pollution, built and green space, and ambient temperature. Initial annual classifications used k-means cluster analysis (k=3) to categorize cohort members into 'Low', 'Medium', or 'High' exposure classes based on standardized input variables (Figure 2).

Long-term exposure was defined through five-year block windows (except for the last block, which was six years) using a 60% majority rule (presence in three or more of the five years).

Blocks lacking a dominant class were categorized as mixed. The 'High' air pollution cluster represented elevated standardized concentrations of four assessed pollutants ($PM_{2.5}$, NO_2, O_3, and O_x), accounting for the upper tier of cumulative environmental and health burden. In the built and green space domain, 'High' exposure denoted environments with relatively more grey space and relatively less vegetation (low greenness), typical of dense urban settings. For ambient temperature, the 'High' and 'Medium' clusters represented thermal stress, while the 'Low' cluster represented mild temperatures and minimal extremes at either end of the temperature spectrum (i.e., hot summers and cold winters).

Residential mobility and environmental profiles

The predicted probability of residential mobility during the follow-up period varied by sociodemographic group. The probability of moving was relatively larger among Black cohort members (65.0%) compared with other population groups. A relatively lower predicted probability of moving was observed among First Nations (55.2%) and Inuit (42.5%) cohort members. Racialized populations had a larger predicted probability of moving compared with non-racialized populations, while probabilities were comparable across socioeconomic status (Table 3).

Table 3
Predicted probability of residential mobility across various population group indexes, sociodemographic indexes, and geographical indicators

	Predicted probability (%)	95% confidence interval	
		from	to
Population group			
Black	65.0	64.6	65.5
Chinese	58.8	58.4	59.2
Indigenous	56.1	55.8	56.3
First Nations	55.2	54.9	55.5
Métis	61.2	60.6	61.8
Inuit	42.5	41.0	44.0
Multiple Indigenous identities	64.2	60.0	68.4
Other, not included elsewhere	64.2	64.0	64.3
White	62.7	62.6	62.8
Racialized population			
Yes	63.2	63.1	63.4
No (White)	62.7	62.6	62.8
No (Indigenous)	56.1	55.8	56.3
Immigrant status			
Immigrant	61.4	61.3	61.5
Non-immigrant	62.8	62.7	62.9
Low socioeconomic status[1]			
Yes	62.4	62.2	62.6
No	62.6	62.5	62.7

1. Low socioeconomic status was defined as individuals in the lowest two income quintiles whose highest educational attainment was a high school education or less. Therefore, income quintile and educational attainment were omitted from the model.

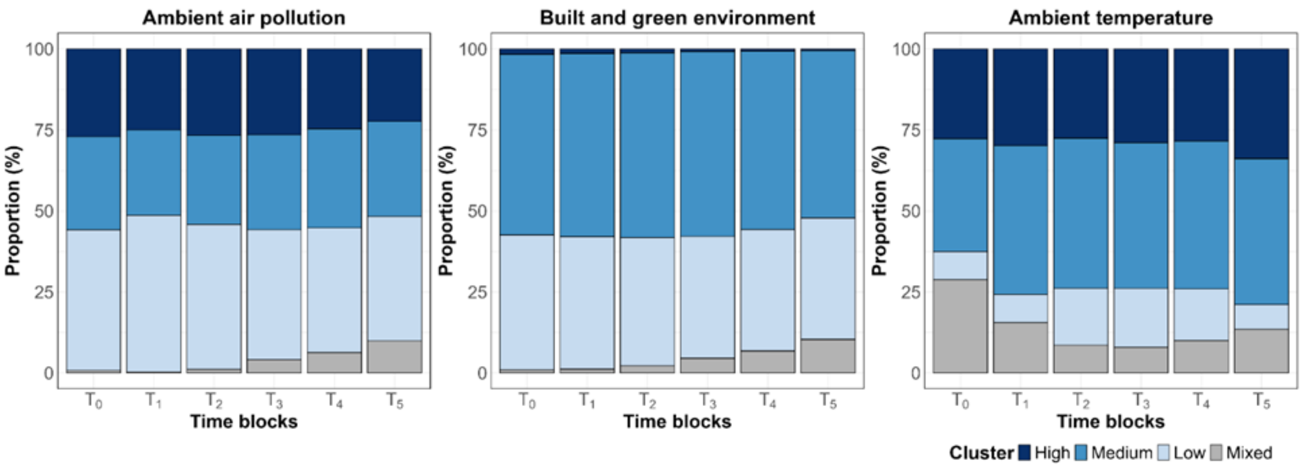
Notes: This table shows predicted probabilities with associated 95% confidence intervals. Each index adjusted for the following: sex; age group; marital status; educational attainment; labour force status; income quintile; and area-level Canadian marginalization indexes such as material deprivation, dependency, social instability, ethnic concentration, and cohort cycle. Residential mobility is defined as any change in residential address in the follow-up period among those with an unchanged pre-baseline residential history (that is, five years before the baseline, T0).

Source: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

Ambient air pollution

Approximately one in four cohort members was classified within a high air pollution cluster during the follow-up period. Across each time block, the share of the cohort in the high air pollution cluster decreased from 27.1% at T_0 to 22.4% at T_5 (Figure 3). Irrespective of the time blocks, the proportion of high air pollution exposure was relatively larger among Black cohort members (61.0%) compared with Chinese (44.0%) and White (24.6%) members. Furthermore, approximately 50% of the immigrant population resided in a high air pollution cluster, compared with 20% of non-immigrants (Table 4). The prevalence of the 'Mixed' air pollution category increased from 0.7% at T_0 to 9.9% at T_5 (Figure 3).

Figure 3
Proportional distribution of cluster levels across the three external environments over time blocks (T0 to T5)



Source: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

Table 4
Distribution of ambient air pollution cluster across study period, T_0 to T_5

	People (N)	Person-block (NB)	percent			
			Low	Medium	High	Mixed
Overall	3,975,970	17,642,600	43.3	28.3	26.0	2.4
Mover status						
Movers	2,489,200	10,545,180	41.6	29.2	26.1	3.1
Non-movers	1,486,770	7,097,420	45.8	27.0	25.7	1.5
Population group						
Black	32,805	146,880	13.1	23.5	61.0	2.5
Chinese	66,015	296,105	27.8	25.6	44.0	2.7
Indigenous	109,980	513,880	77.5	13.4	6.4	2.7
First Nations	82,720	390,130	77.3	13.5	6.6	2.6
Métis	23,430	105,560	76.1	14.7	6.1	3.2
Inuit	3,410	16,470	92.6	3.1	2.3	2.0
Multiple Indigenous identities	420	1,720	64.8	20.6	12.5	2.0
Other, not included elsewhere	254,370	1,229,500	27.1	27.2	42.7	3.0
White	3,512,800	15,456,240	44.0	29.0	24.6	2.4
Racialized population						
Yes	353,190	1,672,480	26.0	26.6	44.5	2.9
No (White)	3,512,800	15,456,240	44.0	29.0	24.6	2.4
No (Indigenous)	109,980	513,880	77.5	13.4	6.4	2.7
Immigrant status						
Immigrant	721,515	3,123,580	22.5	27.3	47.7	2.6
Non-immigrant	3,254,460	14,519,020	47.8	28.5	21.3	2.4
Low socioeconomic status[1]						
Yes	1,119,880	4,614,355	46.0	26.3	25.2	2.4
No	2,856,090	13,028,245	42.3	29.0	26.2	2.4

1. Low socioeconomic status was defined as individuals in the lowest two income quintiles whose highest educational attainment was a high school education or less.

Notes: Because of rounding, percentages may not add up to 100%. "People" is the number per sociodemographic covariate, while "person-blocks" is the number of people per category within the time block T0 to T5 who were alive. The proportions are based on the distribution of ambient air pollution across T0 to T5 for people who were alive. Hence, the denominator is the person-block.

Source: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

Built and green environment

More than 90% of the cohort resided in either a medium (56.2%) or a low (39.6%) built and green environment cluster. Approximately 1.2% of the population resided in a high cluster, while 3.1% were categorized as mixed (Table 5). While exposure to the high cluster was relatively similar across most demographics, Chinese cohort members represented a relatively larger share in this category (3.2%) compared with other groups (approximately 1%). Like the air pollution environment, the 'Mixed' category increased from approximately 1.0% at T_0 to 10.4% at T_5 (Figure 3).

Table 5

Distribution of built and green environment cluster across study period, T_0 to T_5

	People (N)	Person-blocks (NB)	percent Low	Medium	High	Mixed
Overall	3,975,970	17,642,600	39.6	56.2	1.2	3.1
Mover status						
Movers	2,489,200	10,545,180	37.2	57.3	1.4	4.1
Non-movers	1,486,770	7,097,420	43.1	54.5	0.8	1.5
Population group						
Black	32,805	146,880	12.3	83.7	0.9	3.0
Chinese	66,015	296,105	6.8	87.3	3.2	2.7
Indigenous	109,980	513,880	55.0	40.0	0.8	4.3
First Nations	82,720	390,130	59.1	35.6	0.8	4.5
Métis	23,430	105,560	46.4	48.9	0.8	3.8
Inuit	3,410	16,470	12.4	83.9	0.2	3.5
Multiple Indigenous identities	420	1,720	41.6	53.8	1.7	2.9
Other, not included elsewhere	254,370	1,229,500	20.5	74.9	1.4	3.2
White	3,512,800	15,456,240	41.5	54.4	1.1	3.0
Racialized population						
Yes	353,190	1,672,480	17.4	77.9	1.7	3.1
No (White)	3,512,800	15,456,240	41.5	54.4	1.1	3.0
No (Indigenous)	109,980	513,880	55.0	40.0	0.8	4.3
Immigrant status						
Immigrant	721,515	3,123,580	20.4	75.2	1.5	2.9
Non-immigrant	3,254,460	14,519,020	43.7	52.1	1.1	3.1
Low socioeconomic status[1]						
Yes	1,119,880	4,614,355	38.9	56.5	1.3	3.2
No	2,856,090	13,028,245	39.8	56.1	1.1	3.0

1. Low socioeconomic status was defined as individuals in the lowest two income quintiles whose highest educational attainment was a high school education or less.

Notes: Because of rounding, percentages may not add up to 100%. "People" is the number per sociodemographic covariate, while "person-blocks" is the number of people per category within the time block T0 to T5 who were alive. The proportions are based on the distribution of the built and green environment across T0 to T5 for people who were alive. Hence, the denominator is the person-block.
Source: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

Ambient temperature

Approximately 13% of the cohort resided in an optimal (low) ambient temperature cluster. Apart from the pre-baseline block (T_0), temporal changes in these proportions were minimal through T_5 (Figure 3). Métis (5.3%) and Inuit (2.7%) cohort members accounted for a relatively smaller share in the optimal temperature cluster compared with the White (12.2%) or Black (14.6%) populations. Overall, the mixed category for temperature comprised approximately 15% of the cohort (Table 6).

Table 6
Distribution of ambient temperature cluster across study period, T_0 to T_5

	People (N)	Person-blocks (NB)	percent Low	Medium	High	Mixed
Overall	3,975,970	17,642,600	13.1	43.2	28.7	14.9
Mover status						
Movers	2,489,200	10,545,180	13.4	42.5	27.1	17.0
Non-movers	1,486,770	7,097,420	12.7	44.3	31.2	11.8
Population group						
Black	32,805	146,880	14.6	53.1	9.0	23.3
Chinese	66,015	296,105	41.1	26.9	16.0	16.1
Indigenous	109,980	513,880	8.6	18.2	64.0	9.2
First Nations	82,720	390,130	9.8	20.2	59.8	10.3
Métis	23,430	105,560	5.3	12.3	76.3	6.0
Inuit	3,410	16,470	2.7	7.0	85.7	5.6
Multiple Indigenous identities	420	1,720	11.3	23.0	57.3	8.4
Other, not included elsewhere	254,370	1,229,500	19.2	37.1	23.9	19.8
White	3,512,800	15,456,240	12.2	44.8	28.4	14.6
Racialized population						
Yes	353,190	1,672,480	22.7	36.7	21.2	19.4
No (White)	3,512,800	15,456,240	12.2	44.8	28.4	14.6
No (Indigenous)	109,980	513,880	8.6	18.2	64.0	9.2
Immigrant status						
Immigrant	721,515	3,123,580	22.0	41.3	15.7	21.0
Non-immigrant	3,254,460	14,519,020	11.2	43.7	31.6	13.6
Low socioeconomic status[1]						
Yes	1,119,880	4,614,355	11.9	42.0	30.8	15.4
No	2,856,090	13,028,245	13.5	43.7	28.0	14.8

1. Low socioeconomic status was defined as individuals in the lowest two income quintiles whose highest educational attainment was a high school education or less.

Notes: Because of rounding, percentages may not add up to 100%. "People" is the number per sociodemographic covariate, while "person-blocks" is the number of people per category within the time block T0 to T5 who were alive. The proportions are based on the distribution of ambient temperature across T0 to T5 for people who were alive. Hence, the denominator is the person-block.

Source: Statistics Canada, Canadian Census Health and Environment Cohort, 1991, 1996, and 2001.

Discussion

This study provides a national portrait of residential mobility and dynamic, multi-domain external environmental exposures in Canada through the development of the ReMEF. By integrating individual-level residential histories with spatially and temporally resolved measures of ambient air pollution, the built and green environment, and ambient temperature, the ReMEF represents a novel analytical file designed to characterize environmental exposures as time-varying processes rather than static attributes of a place. The ReMEF advances current understanding by explicitly operationalizing exposure biographies—longitudinal summaries of environmental conditions experienced as individuals move through space and time. Unlike traditional exposure assessment approaches that implicitly assume residential stability or environmental constancy, the ReMEF framework captures how both people and environments change, and how these dynamics intersect with sociodemographic stratification.

This dynamic framing aligns with emerging exposome paradigms that emphasize cumulative, time-dependent, and socially patterned exposures across the life course.[11,22,33,34] Beyond its scientific contribution, this work also aligns with the objectives of Bill C-226, the *National Strategy Respecting Environmental Racism and Environmental Justice Act*, by providing an empirical foundation for examining how race, socioeconomic position, and place jointly structure environmental risk in Canada. The primary contribution of this study is twofold: first, to describe the creation of a harmonized, longitudinal analytical file (the ReMEF), and second, to profile the cohort with respect to residential mobility patterns and clustered environmental exposures across three external environment domains. The analytical framework employs annual k-means clustering within each domain, followed by a temporal dominance rule, to reduce high-dimensional, spatiotemporal exposure data into interpretable, longitudinal exposure profiles.

Importantly, the ReMEF standardizes the exposure classification into a common trichotomous scale (Low, Medium, High) across each environmental domain. For all three domains, the ‘Low’ cluster serves as the reference category, representing the least adverse exposure environment. Within the ambient air pollution domain, the ‘Low’ cluster reflects areas with the lowest concentrations of $PM_{2.5}$, NO_2, O_3, and O_x, while the ‘High’ cluster captures areas with the greatest pollutant burden across these indicators. Within the built and green space domain, the NDVI was inverted prior to clustering such that higher values reflect reduced greenness. Accordingly, the ‘Low’ cluster represents areas characterized by greater vegetation cover, lower density of urban fabric, and higher proportions of natural land, while the ‘High’ cluster reflects greater urbanization, reduced green space, and the dominance of dense built environments. Within the ambient temperature domain, cold-side variables—annual lowest and annual average daily minimum temperatures—were similarly inverted prior to clustering so that higher values consistently reflect greater thermal stress regardless of direction. As a result, the ‘Low’ cluster represents areas with mild thermal conditions and minimal temperature extremes, while the ‘High’ cluster captures areas with the greatest thermal burden, encompassing both heat and cold extremes. Across all domains, the ‘Medium’ cluster reflects intermediate exposure conditions. Researchers using the ReMEF are therefore encouraged to use the ‘Low’ cluster as the referent in downstream analyses, allowing ‘Medium’ and ‘High’ clusters to be interpreted as escalating levels of environmental burden within each domain.

However, some important analytical caveats are worth noting. The disproportionately small proportion of cohort members classified into the 'High' built and green environment cluster—representing approximately 1% of the cohort across all time blocks (T_0 to T_5)—reflects the residential geography of the Canadian population rather than an artifact of the classification process, since highly urbanized, low-green environments are genuinely rare in this context. Researchers using this dataset should be aware that such sparse cluster membership can result in unstable effect estimates, wide confidence intervals, and reduced statistical power in downstream epidemiological analyses. Users are therefore advised to interpret associations involving the 'High' built and green environment cluster with caution and consider sensitivity analyses that collapse sparse categories or stratify by adequate sample size where feasible.

From a methodological perspective, the ReMEF framework offers a scalable approach for leveraging residential mobility as a quasi-experimental feature of observational data. The ReMEF’s value lies in its potential for quasi-experimental research. To strengthen causal interpretation, individuals with residential moves in the five years preceding the baseline were excluded to support the natural experiment assumption. When paired with propensity score methods or other quasi-experimental designs, this restriction enhances the plausibility of counterfactual comparisons and mitigates the self-selection bias inherent in residential mobility research.

Before further examining the methodological assumptions underlying the analytical file, it is important to situate these findings within the context of the cohort profile. The demographic composition of the analytical cohort was broadly representative of the source population (CanCHEC), supporting the generalizability of ReMEF-based analyses. The restriction of the analytical file to individuals aged 25 to 89 years at baseline was intentional, aimed at reducing—though not eliminating—the residential instability more common in younger age groups. Consistent with this rationale, the primary demographic difference between included and excluded individuals was age, with those aged 25 to 34 disproportionately excluded because of residential mobility five years before the baseline. This pattern reflects well-documented life-course mobility dynamics among younger adults.[18] Furthermore, residential mobility varied substantially across population groups and sociodemographic strata. Black cohort members were relatively more likely to move during follow-up, whereas First Nations and Inuit individuals were less likely to change residence. These patterns are consistent with prior literature suggesting that mobility is shaped by, but not limited to, socioeconomic opportunity, educational attainment, health status, life satisfaction, and cultural and historical ties to land and community.[21-23,35,36] Higher predicted probabilities of mobility among racialized populations may also reflect heterogeneous mobility drivers, including both opportunity-seeking and constraint-driven relocation.[22,37]

The ReMEF cohort profile further reveals distinct environmental exposure patterns across racialized and immigrant populations, particularly within the ambient air pollution domain. Certain population groups were disproportionately represented in higher-exposure clusters, highlighting persistent environmental inequities consistent with prior Canadian and U.S. studies linking racialization, immigrant status, residential sorting, and proximity to emission sources.[21-23,35,36] Notably, the increasing prevalence of “mixed” exposure biographies over time suggests that environmental classifications are not static; rather, they evolve through both residential mobility and secular environmental change.

Several design choices merit consideration. First, the selection of environmental domains reflects current epidemiologic evidence, yet the framework is intentionally modular and extensible to additional spatial–temporal exposures. Second, the reliance on annual tax file postal codes captures long-term residence but may miss short-term or seasonal mobility. However, it is important to note that the analytical file focuses on isolating sustained exposures (long term)—thus, a residential stability criterion (presence in four or more of five years) was applied. Third, the use of a five-year exposure window, consistent with prior Canadian mortality research,[7] provides a flexible building block for longer cumulative exposure assessments (e.g., 10-, 15-, or 20-year windows). Lastly, the clustering strategy—k=3 with a 60% temporal dominance rule—prioritizes parsimony and interpretability. However, this approach assumes that each exposure year contributes equally to long-term health risk. This assumption may not hold in contexts where acute or extreme exposures exert disproportionate biological effects. In such cases, non-dominant exposure years may outweigh the dominant classification. Future applications of the ReMEF may therefore benefit from weighted cumulative exposure models, which allow time-varying exposures to be weighted according to recency and latency via flexible functions, such as cubic splines.[38] Additionally, the identification of a “mixed” exposure category presents a unique opportunity to investigate the health implications of environmental instability itself, which may reflect cumulative stressors or synergistic effects beyond additive exposure models.

Among its key strengths, the ReMEF is a population-based, nationally representative analytical file that integrates long-term residential histories with multi-domain environmental data at a fine spatial resolution. It addresses a central challenge in exposome research: accounting for human mobility while preserving the temporal ordering of exposures. By harmonizing census, tax, vital statistics, and environmental data, the ReMEF provides a reproducible platform for examining environmental inequality, climate–health relationships, and cumulative exposures across the life course. Its scale enables stratified analyses across population groups and socioeconomic strata, while its design supports advanced methods such as trajectory modelling, matching approaches, and multi-domain exposure profiling.

Several limitations warrant consideration. Exposure assignment at the postal-code centroid may not fully capture within-neighbourhood heterogeneity; however, Canadian six-character postal codes generally provide fine spatial resolution, particularly in urban areas. Annual exposure assignment does not capture short-term variability, but this design choice aligns with the study’s focus on chronic and cumulative exposure processes. While k-means clustering necessarily simplifies exposure gradients, this trade-off enhances interpretability and cross-domain comparability. Finally, residential mobility may be influenced by unmeasured self-selection factors such as employment or health status; nonetheless, longitudinal design features and pre-baseline stability criteria reduce potential bias.

In conclusion, this study demonstrates the feasibility and value of the ReMEF as a national analytical resource. By linking individual residential trajectories with dynamic, multi-domain environmental exposures, the ReMEF enables a life-course perspective on environmental risk and inequality. As such, it provides a critical foundation for future epidemiological, methodological, and policy-relevant research aimed at understanding how mobility, the environment, and social stratification jointly shape population health in a changing climate.

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