

# Urban greenness and mortality in Canada's largest cities: a national cohort study

Dan L Crouse, Lauren Pinault, Adele Balram, Perry Hystad, Paul A Peters, Hong Chen, Aaron van Donkelaar, Randall V Martin, Richard Ménard, Alain Robichaud, Paul J Villeneuve



## Summary

**Background** Findings from published studies suggest that exposure to and interactions with green spaces are associated with improved psychological wellbeing and have cognitive, physiological, and social benefits, but few studies have examined their potential effect on the risk of mortality. We therefore undertook a national study in Canada to examine associations between urban greenness and cause-specific mortality.

**Methods** We used data from a large cohort study (the 2001 Canadian Census Health and Environment Cohort [2001 CanCHEC]), which consisted of approximately 1.3 million adult (aged  $\geq 19$  years), non-immigrant, urban Canadians in 30 cities who responded to the mandatory 2001 Statistics Canada long-form census. The cohort has been linked by Statistics Canada to the Canadian mortality database and to annual income tax filings through 2011. We measured greenness with images from the moderate-resolution imaging spectroradiometer from NASA's Aqua satellite. We assigned estimates of exposure to greenness derived from remotely sensed Normalized Difference Vegetation Index (NDVI) within both 250 m and 500 m of participants' residences for each year during 11 years of follow-up (between 2001 and 2011). We used Cox proportional hazards models to estimate associations between residential greenness (as a continuous variable) and mortality. We estimated hazard ratios (HRs) and corresponding 95% CIs per IQR (0.15) increase in NDVI adjusted for personal (eg, education and income) and contextual covariates, including exposures to fine particulate matter, ozone, and nitrogen dioxide. We also considered effect modification by selected personal covariates (age, sex, household income adequacy quintiles, highest level of education, and marital status).

**Findings** Our cohort consisted of approximately 1 265 000 individuals at baseline who contributed 11 523 770 person-years. We showed significant decreased risks of mortality in the range of 8–12% from all causes of death examined with increased greenness around participants' residence. In the fully adjusted analyses, the risk was significantly decreased for all causes of death (non-accidental HR 0.915, 95% CI 0.905–0.924; cardiovascular plus diabetes 0.911, 0.895–0.928; cardiovascular 0.911, 0.894–0.928; ischaemic heart disease 0.904, 0.882–0.927; cerebrovascular 0.942, 0.902–0.983; and respiratory 0.899, 0.869–0.930). Greenness associations were more protective among men than women (HR 0.880, 95% CI 0.868–0.893 vs 0.955, 0.941–0.969), and among individuals with higher incomes (highest quintile 0.812, 0.791–0.834 vs lowest quintile 0.991, 0.972–1.011) and more education (degree or more 0.816, 0.791–0.842 vs did not complete high school 0.964, 0.950–0.978).

**Interpretation** Increased amounts of residential greenness were associated with reduced risks of dying from several common causes of death among urban Canadians. We identified evidence of inequalities, both in terms of exposures to greenness and mortality risks, by personal socioeconomic status among individuals living in generally similar environments, and with reasonably similar access to health care and other social services. The findings support the development of policies related to creating greener and healthier cities.

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## Introduction

Globally, more than half of the world's population lives in cities, and in developed countries, this figure exceeds 75%.<sup>1</sup> In Canada, two-thirds of the population currently live in census metropolitan areas (that have populations greater than 100 000 individuals).<sup>2</sup> With more people moving to cities every year, there is interest in understanding how urban settings and aspects of the built-up environment affects health outcomes. Residents in large cities might be exposed regularly to environmental stresses, including

traffic congestion, heat island effects, poor air quality, and noise pollution, which might have adverse effects on their health. Natural environments, including green spaces, are recognised as features of the built-up environment with potential to mitigate some of these adverse effects by acting as visual amenities or as places that offer opportunities for social or physical activities.<sup>3</sup> Green spaces and indices describing the presence of green vegetation have been associated with reduced negative perception of noise,<sup>4</sup> urban heat,<sup>5</sup> concentrations of air

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Department of Sociology, University of New Brunswick, Fredericton, NB, Canada (D L Crouse PhD); New Brunswick Institute for Research, Data, and Training, Fredericton, NB, Canada (D L Crouse PhD); College of Public Health & Human Sciences, Oregon State University, Corvallis, OR, USA (P Hystad PhD); Public Health Ontario, Toronto, ON, Canada (H Chen PhD); Institute for Clinical Evaluative Sciences, Toronto, ON, Canada (H Chen); Dalla Lana School of Public Health, University of Toronto, Toronto, ON, Canada (H Chen); Department of Physics & Atmospheric Science, Dalhousie University, Halifax, NS, Canada (A van Donkelaar PhD, R V Martin PhD); Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA (R V Martin); Air Quality Research Division, Environment and Climate Change Canada, Dorval, QC, Canada (R Ménard PhD, A Robichaud MSc); and Department of Health Sciences, Carleton University, Ottawa, ON, Canada (P J Villeneuve PhD, P A Peters)

Correspondence to: Dr Dan L Crouse, Department of Sociology, University of New Brunswick, Fredericton, NB, E3B 5A3, Canada [dlcrouse@gmail.com](mailto:dlcrouse@gmail.com)

### Research in context

#### Evidence before this study

We searched the PubMed database for epidemiological studies of associations between mortality and exposure to natural environments, defined as “nature”, “parks”, “greenness”, “Normalized Difference Vegetation Index”, “NDVI”, “green space”, “greenspace”, and “presence of green vegetation”. We included peer-reviewed studies published up to May 1, 2017, regardless of location of study or language of publication. We also perused the bibliographies of relevant articles and of published reviews. Although several published studies had examined associations between natural environments and other outcomes, we identified only 12 articles that looked at associations with mortality. Most of these studies were ecological or cross-sectional in design; about half were done in Europe and about half in North America. Only two studies were national in scope, one of which was cross-sectional, and one of which had a small sample size and only included women. Despite the shortage of evidence, findings generally suggested that living in areas with higher amounts of green spaces was associated with reduced mortality, with the strongest association for deaths from cardiovascular disease. Findings from a review concluded that cohort studies that accounted better for socioeconomic status, among other issues, were needed to provide stronger evidence on this topic.

#### Added value of this study

We showed significant protective effects for several common causes of mortality associated with living in greener areas of cities. We also showed increasingly protective effects associated

with each increment of higher income and higher levels of education. The key strengths of our research compared with previous studies included the study design (a nationally representative prospective cohort study), the large sample size (nearly 1.3 million participants), and that we reported results for effect modification by several indicators of socioeconomic status. We also had the advantage of controlling our survival models for many personal and contextual covariates, including exposures to ambient fine particulate matter, ozone, and nitrogen dioxide.

#### Implications of all the available evidence

Within Canada and globally, more people are moving to cities and urban areas every year. There is great interest in understanding how urban settings and aspects of a built-up environment can change health outcomes. Residents in cities might be exposed regularly to environmental stresses such as traffic congestion, heat island effects, poor air quality, and noise pollution, with adverse results on their health; natural environments have been identified as having the potential to mitigate some of these adverse effects. Our findings suggest that increasing the amount of green vegetation in urban areas might have important benefits in reducing mortality. Given the potential benefits to health as reported here, findings from this study should be of interest to city planners, urban designers, landscape architects, and policy makers seeking evidence to support the development of policies related to creating greener and healthier cities.

pollution,<sup>6</sup> and psychological stress.<sup>7</sup> Overall, findings from reviews<sup>3,8</sup> have identified that interactions with natural spaces are associated with both physiological and psychological benefits to health.

Few studies, however, have examined the link between natural green spaces and mortality. Most of these have relied on cross-sectional or ecological study designs, and have produced inconsistent findings.<sup>9</sup> Despite limitations and differences in design among the previous studies, findings from a systematic review concluded that there is moderate to strong evidence for an association between green spaces and both all-cause and cardiovascular mortality.<sup>10</sup> For example, James and colleagues<sup>11</sup> reported lower mortality rates for non-accidental deaths among people living in areas with the highest quintile of green vegetation around their home compared with those in the lowest quintile, in a cohort of around 100 000 American women. A Canadian cohort study of approximately 575 000 adults in urban Ontario also showed significant reductions in cause-specific mortality associated with increased greenness around participants' residences.<sup>12</sup> However, no nationally representative cohort studies have been done in Canada or elsewhere examining the association between greenness and mortality. We therefore sought to examine the benefit of living in

greener areas on the health of urban Canadians in a large, national cohort study (the 2001 Canadian Census Health and Environment Cohort [2001 CanCHEC]). We looked at whether residential greenness was associated with reduced risk of dying from cause-specific mortality among urban, non-immigrant adults, while controlling for a wide range of individual and contextual covariates, and exposures to ambient fine particulate matter (PM<sub>2.5</sub>), nitrogen dioxide, and ozone. Additionally, we investigated whether associations between greenness and risk of mortality varied by selected personal characteristics.

## Methods

### Study cohort

2001 CanCHEC has been described in detail previously.<sup>13</sup> Briefly, it is a nationally representative sample of approximately 1.3 million individuals in 30 cities. The cohort consists of respondents to the mandatory 2001 Statistics Canada long-form census, and is linked by Statistics Canada to the Canadian mortality database and to annual income tax filings through 2011.<sup>13</sup> Individuals were eligible for the cohort if they were aged at least 19 years, were usual residents of Canada on the census day; were not long-term residents of an institution, and had filed a tax return during the follow-up period. The

long-form census included content related to education, income, and employment and family status, among many other topics. The linkage to the annual income tax files provided annual six-digit residential postal codes, which allowed us to include participants' annual residential mobility. In urban areas, postal codes often correspond to one side of a city block or to a single apartment building.

We excluded immigrants because they, especially those who immigrated recently, tend to have better health status and health behaviours than do the Canadian-born population, patterns which can persist for up to 20 years after immigration.<sup>14</sup> Immigrants might have had vastly different past environmental exposures than Canadian-born subjects, and were less likely to have chronic health conditions or disability because of the screening process that disqualifies people with serious medical conditions.<sup>15</sup> For these reasons, associations between greenness and health among immigrants would have required separate analyses. We also restricted this study to individuals living in the 30 largest census metropolitan areas according to population data from 2006 (the mid-point of our follow-up period).<sup>16</sup> Here we focused on urban environments to understand whether living in greener areas of cities moderated the effects of risks to health and wellbeing associated with urban living. We restricted our study to urban populations given that living in proximity to natural spaces in rural areas might not have the same relationship with health as it might in a city.

#### Assignment of exposures to greenness

We assigned estimates of exposure to greenness to the representative point of each participant's residential postal code for every year between 2001 and 2011. Missing postal codes, which could indicate that an individual had left Canada, moved to an institution, or that they had not filed a tax return that year, were imputed using a method based on reported postal codes for the years before and after a missing record.<sup>17</sup> This method led to the imputation of approximately 18% of all person-years nationally. Participants were coded as having missing exposure data for the years in which their postal code was located outside one of the 30 cities.

Our estimates of greenness were derived from the remotely sensed Normalized Difference Vegetation Index (NDVI). The NDVI is the most widely used satellite-derived indicator of the quantity of green vegetation on the ground<sup>18</sup> and has been used as a marker for exposure to greenness and green spaces in many previous epidemiological studies.<sup>11,12,19</sup> Theoretically, NDVI values have a range of -1 to 1, with negative values representing water, values around zero representing bare soil, and higher positive values representing dense green vegetation. Here we restricted our data to values greater than 0 (ie, 0.01 to 1.00) to disentangle the effects of greenness from the potential effects of living near water.

We used images from the moderate-resolution

imaging spectroradiometer from NASA's Aqua satellite, which are available across Canada at a spatial resolution of 250 m as 16-day averages, as far back as 2002. We calculated annual maximum greenness values averaged over the summer months for each year from 2002 to 2011 (and therefore excluded observations from winter months when much of the ground would be covered by snow, and which would have provided incomplete or inaccurate information about the presence of vegetation). In this way, our estimates of greenness described the levels of vegetation when plants are fully developed and in peak bloom, rather than the average level of vegetation throughout the year. Next, we calculated long-term mean values over this 10-year period. In the absence of comparable data for earlier periods, we assumed that the 10-year mean values represented the longer-term historical patterns of greenness and assigned exposure to those values to participants' residential postal codes for each year of follow-up. Thus, variation in estimates of exposure for each participant in each year of follow-up was attributed solely to residential mobility patterns. We assigned to each participant the 10-year mean NDVI values within both 250 m and 500 m of their residence.

#### Statistical analysis

We rounded counts of individuals randomly to the nearest five for institutional confidentiality. We used Cox proportional hazards models to estimate associations between residential greenness (as a continuous variable) and mortality. We estimated hazard ratios (HRs) stratified by sex, by 5-year age groups from age 25 to 89 years (due to potential inaccuracies in record-linkages among older individuals), and by census metropolitan area. We censored participants at date of death or if they were lost to follow-up because of the end of study period, or if they had moved away from one of the study cities.

We adjusted our models for the following individual-level covariates at baseline: Aboriginal identity, visible minority status, marital status, highest level of education, employment status, and household income adequacy quintiles. Visible minorities were deemed as individuals (other than Aboriginal people) who were non-white in race or colour. Income adequacy quintiles were calculated from the ratio between the pre-tax income of economic families to the Statistics Canada low-income cutoff for family and community size, adjusted for regional economical differences. Area-based income adequacy ratios adjust for regional differences in family economic status, such as housing costs.<sup>13</sup> We also calculated time-varying, contextual variables at the census division-level from the closest census year (ie, either 2001, 2006, or 2011) describing the proportion of unemployed adults aged at least 25 years, the proportion of adults aged at least 25 years who had not completed high school, and the proportion of individuals in low-income families (ie, below the Statistics Canada low-income cutoff). Canadian census divisions are roughly

the size of a large city or county. To capture living in a denser, urban core, as opposed to living in more suburban

areas of a city, we calculated a time-varying log of population density (individuals per km<sup>2</sup>) at the scale of dissemination areas from the closest census year. Dissemination areas are typically equivalent in size to one or more adjacent city blocks and have populations of approximately 400–700 individuals.

Finally, we adjusted our models for exposures to ambient air pollution, which is a known negative stress upon health in urban areas.<sup>20</sup> For this adjustment, we used estimates from existing models and observations of PM<sub>2.5</sub>, ozone, and nitrogen dioxide. Each of these datasets have been described previously (PM<sub>2.5</sub>,<sup>21</sup> ozone,<sup>22</sup> and nitrogen dioxide<sup>23</sup>), and used in previous epidemiological analyses.<sup>24</sup> Briefly, the PM<sub>2.5</sub> data were satellite-derived annual estimates at a spatial resolution of 1 km×1 km. For ozone calculations we used the 8-h average daily maximum concentrations obtained from model-observation data fusion at a resolution of approximately 21 km×21 km in the warm seasons from 2002 to 2009. The nitrogen dioxide data were derived from a national 2006 land-use regression model developed from observations from fixed-site stations and incorporating satellite-derived nitrogen dioxide estimates and land-use predictors. Ozone and nitrogen dioxide estimates were year-adjusted using ground-based time-series measurements from 1981 to 2012. Following a similar approach to what we have implemented elsewhere,<sup>24</sup> we assigned these exposures as 3-year moving windows of previous exposures, with a single-year lag, with the intention of describing past exposures to these pollutants.

We developed hazard models for six common causes of mortality including: all non-accidental causes (10th revision of the International Statistical Classification of Diseases and Related Health Problems [ICD-10] A to R); cardiovascular plus diabetes (ICD-10 I10 to I69, E10 to E14); cardiovascular diseases (ICD-10 I10 to I69); ischaemic heart disease (ICD-10 I20 to I25); cerebrovascular disease (ICD-10 I60 to I69); and non-malignant diseases of the respiratory system (ICD-10 J00–J99). We calculated HRs per increment of the IQR in exposure to greenness in 0.15 units.

We tested for effect modification by selected characteristics with non-accidental mortality. Specifically, we used Cochran's *Q* statistic<sup>25</sup> to test heterogeneity in HRs by age, sex, income, education, and marital status. We examined models in which we considered the mean amount of greenness within 500 m of each participant's residence to examine whether this factor would strengthen or attenuate the associations.

Given that 2001 CanCHEC did not include information on smoking or other health behaviours, we developed models adjusted identically to our fully adjusted models with participants in the smaller Canadian Community Health Survey (CCHS) mortality cohort, which does contain such information.<sup>26</sup> These models allowed us to observe the effect of adjusting additionally for smoking, body-mass index (BMI), and consumption of alcohol,

	n (%)	HR (95% CI)	Exposure to greenness within 250 m (mean [SD])
All participants	1 265 515 (100%)	NA	0.58 (0.11)
Age (years)			
25–34	271 680 (21.5%)	NA	0.57 (0.11)
35–64	776 905 (61.4%)	NA	0.58 (0.11)
65–74	125 345 (9.9%)	NA	0.58 (0.11)
≥75	91 580 (7.2%)	NA	0.57 (0.11)
Sex			
Male	598 065 (47.3%)	NA	0.58 (0.11)
Female	667 445 (52.7%)	NA	0.58 (0.11)
Visible minority status			
No	1 241 430 (98.1%)	1.24 (1.16–1.32)	0.58 (0.11)
Yes	24 085 (1.9%)	1.00 (1.00–1.00)	0.55 (0.11)
Aboriginal identity			
Yes	25 070 (2.0%)	1.00 (1.00–1.00)	0.52 (0.11)
No	1 240 445 (98.0%)	0.68 (0.65–0.72)	0.58 (0.11)
Marital status			
Never married and not currently common law	205 880 (16.3%)	1.12 (1.10–1.15)	0.55 (0.11)
Common law	150 910 (11.9%)	0.91 (0.87–0.94)	0.58 (0.12)
Legally married and not separated	715 840 (56.6%)	0.78 (0.77–0.80)	0.59 (0.11)
Legally married but separated and not currently common law	34 020 (2.7%)	1.08 (1.04–1.13)	0.56 (0.11)
Divorced and not currently common law	86 205 (6.8%)	1.10 (1.07–1.13)	0.55 (0.11)
Widowed and not currently common law	72 660 (5.7%)	1.00 (1.00–1.00)	0.57 (0.11)
Highest level of education			
Did not complete high school	280 840 (22.2%)	1.62 (1.58–1.66)	0.56 (0.11)
Some post-secondary education	443 465 (35.0%)	1.35 (1.32–1.39)	0.58 (0.11)
Diploma	268 790 (21.2%)	1.16 (1.13–1.19)	0.58 (0.11)
Degree or more	272 420 (21.5%)	1.00 (1.00–1.00)	0.59 (0.11)
Income quintile			
Lowest	188 640 (14.9%)	1.30 (1.27–1.33)	0.55 (0.11)
Lower middle	237 555 (18.8%)	1.19 (1.16–1.21)	0.57 (0.11)
Middle	265 285 (21.0%)	1.08 (1.06–1.11)	0.58 (0.11)
Middle upper	281 485 (22.2%)	1.03 (1.01–1.06)	0.58 (0.11)
Highest	292 545 (23.1%)	1.00 (1.00–1.00)	0.60 (0.11)
Labour force status			
Employed	848 720 (67.1%)	0.52 (0.51–0.54)	0.58 (0.11)
Unemployed	40 240 (3.2%)	0.78 (0.74–0.83)	0.56 (0.12)
Not in labour force	376 550 (29.8%)	1.00 (1.00–1.00)	0.57 (0.11)

Data are descriptive statistics of participants at baseline and fully adjusted hazard ratios (HR) for risk factors included in the survival models for all non-accidental causes of death. HRs and 95% CIs for associations between green space and non-accidental mortality; HRs computed per IQR (0.15). All models were adjusted for visible minority status, Aboriginal identity, marital status, highest level of education, income quintile, and labour force status; models stratified by 5-year age groups, sex, and by census metropolitan area. Models were also adjusted for three variables calculated at the census division level with data from the most recent census year: (1) unemployed—the proportion of adults (aged ≥25 years) who were unemployed in the census division. This does not include individuals who were not in the labour force.

(2) Education—the proportion of adults (aged ≥25 years) who had not graduated from high school or its equivalent.

(3) Income—the proportion of individuals of any age in low-income families (using low-income cutoff definition). Models were also adjusted for population density, and exposures to ambient fine particulate matter, ozone, and nitrogen dioxide. NA—not applicable.

**Table 1: Baseline characteristics of cohort**

fruits, and vegetables, all of which are associated with mortality and are available in the CCHS. The CCHS-mortality cohort includes respondents enrolled between 2000 and 2008 and followed up for mortality until the end of 2011. We excluded individuals aged less than 25 years and more than 90 years at baseline, and immigrants who immigrated during the previous 20 years.<sup>27</sup> We explored models only for non-accidental deaths because restricting this cohort to respondents in the 30 cities reduced the sample size too greatly to consider other causes reliably.

Lastly, we examined the shape of the concentration-response curve for greenness on non-accidental mortality. For this, we used a class of shape-constrained health-effect functions,<sup>28</sup> which fitted several different shapes of association as variations on sigmoidal functions, the ensemble of which was created by a weighted average of all shapes considered with weights defined by the likelihood function values.

### Role of the funding source

There was no funding source for this study. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

### Results

Our cohort consisted of approximately 1 265 000 individuals at baseline who contributed a total of 11 523 770 person-

years (table 1). 106 180 individuals died during the 10·6 years of follow-up (table 2). Overall, mean exposure to greenness (ie, mean NDVI score within 250 m) was 0·58 (SD 0·11); exposures ranged from 0·13 to 0·96 (IQR 0·15). There were modest gradients of increasing exposures to greenness associated with increasing incomes and education levels: individuals in the lowest income quintile had a mean exposure of 0·55 compared with those in the highest who had a slightly higher average of 0·60. We also examined correlations between exposures assigned in each year and identified Pearson coefficients of more than 0·8 between values in each case, which suggested that there was little spatial variation in greenness values among these locations over this 10-year period.

Estimates of residential greenness were  $r=-0\cdot24$  with nitrogen dioxide among participants in these 30 cities. We noted significant protective effects of greenness for each cause of death (table 2); controlling for personal characteristics attenuated the associations, but controlling for the contextual covariates had negligible effects. Adjustment for population density reduced HRs by approximately 4% in all cases. Among the three pollutants, controlling for ozone had no effect on HRs, PM<sub>2·5</sub> reduced them slightly, and nitrogen dioxide reduced them by approximately 4–6% in all cases.

In our fully adjusted models we noted significant decreased risks of mortality with all causes of death examined. We found the most protective effects for deaths from respiratory diseases and the weakest effects

Model description	Non accidental (n=106 180)	Cardiovascular plus diabetes (n=34 005)	Cardiovascular (n=30 855)	Ischaemic heart disease (n=17 885)	Cerebrovascular (n=5955)	Respiratory (n=9465)
Model 1 Stratified by 5-year age groups and sex	0·923 (0·915–0·930)	0·914 (0·901–0·927)	0·919 (0·906–0·933)	0·898 (0·881–0·916)	0·992 (0·958–1·027)	0·892 (0·868–0·916)
Model 2 Model 1 plus stratified by census metropolitan area	0·917 (0·909–0·925)	0·912 (0·898–0·927)	0·924 (0·909–0·939)	0·899 (0·880–0·919)	0·997 (0·959–1·035)	0·889 (0·863–0·916)
Model 3 Model 2 plus adjusted for personal covariates*	0·994 (0·985–1·003)	0·998 (0·982–1·014)	1·004 (0·987–1·021)	0·995 (0·973–1·017)	<u>1·047</u> (1·008–1·088)	0·982 (0·952–1·012)
Model 4 Model 3 plus adjusted for contextual covariates†	0·988 (0·979–0·998)	0·993 (0·977–1·010)	0·999 (0·982–1·016)	0·988 (0·966–1·011)	<u>1·042</u> (1·002–1·083)	0·977 (0·948–1·008)
Model 5 Model 4 plus adjusted for population density	0·957 (0·948–0·967)	0·960 (0·943–0·976)	0·961 (0·944–0·979)	0·949 (0·927–0·972)	1·004 (0·963–1·047)	0·941 (0·911–0·972)
Model 6 Model 5 plus adjusted for PM <sub>2·5</sub>	0·940 (0·931–0·949)	0·941 (0·925–0·958)	0·943 (0·925–0·960)	0·932 (0·910–0·955)	0·982 (0·942–1·024)	0·924 (0·894–0·955)
Model 7 Model 5 plus adjusted for ozone	0·959 (0·949–0·968)	0·960 (0·943–0·977)	0·961 (0·944–0·979)	0·951 (0·928–0·974)	1·00 (0·959–1·042)	0·939 (0·908–0·970)
Model 8 Model 5 plus adjusted for nitrogen dioxide	0·917 (0·908–0·926)	0·913 (0·897–0·929)	0·912 (0·895–0·930)	0·906 (0·884–0·929)	0·944 (0·904–0·985)	0·902 (0·872–0·933)
Model 9 Model 5 plus adjusted for PM <sub>2·5</sub> , ozone and nitrogen dioxide	0·915 (0·905–0·924)	0·911 (0·895–0·928)	0·911 (0·894–0·928)	0·904 (0·882–0·927)	0·942 (0·902–0·983)	0·899 (0·869–0·930)

Data are hazard ratios computed per IQR (0·15) and 95% CIs for cause-specific mortality associated with greenness within 250 m of participants' residence. Underlined text indicates significant associations. PM<sub>2·5</sub>=ambient fine particulate matter. \*Visible minority status, Aboriginal identity, marital status, highest level of education, income quintile, and labour force status. †Three contextual covariates were calculated at the census division level with data from the most recent census year: (1) unemployed—the proportion of adults (aged ≥25 years) who were unemployed in the census division. This does not include individuals who are not in the labour force. (2) Education—the proportion of adults (aged ≥25 years) who had not graduated from high school or its equivalent. (3) Income—the proportion of individuals of any age in low-income families (using low-income cutoffs definition).

Table 2: Cause-specific mortality associated with greenness in different model designs

See Online for appendix

	Hazard ratio* (95% CI)	p value
No characteristic selected	0.915 (0.905–0.924)	
Current age (years)		0.001
25–34	0.982 (0.846–1.140)	
35–64	<u>0.866 (0.846–0.886)</u>	
65–74	<u>0.861 (0.842–0.880)</u>	
≥75	<u>0.954 (0.941–0.967)</u>	
Sex		0.001
Men	<u>0.880 (0.868–0.893)</u>	
Women	<u>0.955 (0.941–0.969)</u>	
Income quintile		0.001
Lowest	0.991 (0.972–1.011)	
Middle low	<u>0.960 (0.941–0.979)</u>	
Middle	<u>0.872 (0.851–0.894)</u>	
Middle upper	<u>0.863 (0.840–0.886)</u>	
Highest	<u>0.812 (0.791–0.834)</u>	
Highest level of education		0.001
Did not complete high school	<u>0.964 (0.950–0.978)</u>	
Some post secondary	<u>0.897 (0.880–0.914)</u>	
Diploma	<u>0.860 (0.834–0.887)</u>	
Degree or more	<u>0.816 (0.791–0.842)</u>	
Marital status		0.001
Never married and not currently common law	<u>0.919 (0.893–0.946)</u>	
Legally married or common law, and not separated	<u>0.880 (0.868–0.893)</u>	
Separated, widowed, or divorced, and not common law	0.970 (0.953–0.986)	

Data show associations between mortality from non-accidental deaths and greenness within 250 m of participants' residences, and effect modification by selected characteristics. Underlined text indicates significant associations. \*Results are from fully-adjusted models as described in model 9 (table 2); hazard ratios computed per IQR (0.15). p values are for Q statistic (test for effect modification)

**Table 3: Mortality from non-accidental deaths and greenness: effect modification by selected characteristics**

for deaths from cerebrovascular disease. We showed a decreased risk of dying of approximately 9–10% per IQR in exposure to greenness with all other causes of death examined in these models.

We noted stronger protective associations among men and among individuals aged 35–74 years compared with both younger and older individuals (table 3). We showed increasingly protective effects among individuals in each increasing income quintile (and no association among those in the lowest quintile, and in individuals according to each level of increased educational attainment. We also showed more protective effects among those who were married or in common-law relationships compared with individuals who were separated, widowed, or divorced. In models using the amount of greenness within 500 m as the exposure of interest, we showed slightly stronger, more protective associations with all six causes of death (appendix).

	Not adjusted for health behaviours	Adjusted for smoking	Adjusted for smoking, body-mass index, fruit and vegetable consumption, and alcohol consumption
-2 log-likelihood	62 829	62 459	62 413
Hazard ratio* (95% CI)	0.980 (0.941–1.021)	0.986 (0.947–1.027)	0.984 (0.944–1.025)

Data show associations between non-accidental mortality and greenness within 250 m of participants' residences among participants in the Canadian Community Health Survey (7200 deaths, 123 200 participants). \*Results are from fully adjusted models as described in model 9 (table 2); hazard ratios computed per IQR (0.15).

**Table 4: Associations between non-accidental mortality and greenness in the Canadian Community Health Survey**

We showed weaker associations between greenness and mortality with the CCHS survey (table 4). However, we showed that additional adjustments for smoking, BMI, and consumption of alcohol, fruit, and vegetables improved model fit, but had no appreciable effect on the effect estimate. Lastly, the shape of the relationship between greenness and non-accidental death was slightly non-linear (figure).

### Discussion

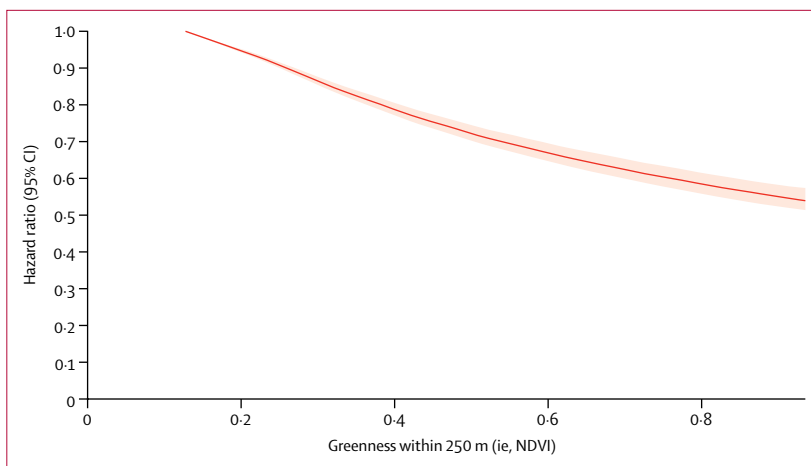
The findings from our study showed that living in urban areas characterised by increased amounts of greenness appears to reduce the risk of mortality from several common causes of death. This is the first study to examine the relationship between exposure to greenness and mortality across Canada. In this large, nationally representative cohort of urban Canadian non-immigrant adults we showed a significant decreased risk of dying from several causes of death associated with increased estimates of greenness within both 250 m and 500 m of participants' residences. Controlling for exposures to ambient nitrogen dioxide strengthened the associations substantially. We showed significantly more protective effects among men and among participants with higher incomes and more education. Moreover, we showed no association among individuals in the lowest income quintile. The increased protective effects among individuals in categories of higher income and education were commensurate with increased estimates of exposure among individuals in these groups as well—ie, some more affluent populations have not only greater exposures to greenness, but also increased benefits to their health, compared with those in less-affluent groups. The finding of greater exposures to greenness among more affluent groups is consistent with those reported in an English population-based study,<sup>29</sup> and those from an earlier Canadian study based on individuals in Ontario,<sup>12</sup> but few others have reported on differences in exposures to greenness by income or by socioeconomic status. The

finding of increased benefits to health among more affluent groups, however, is largely inconsistent with results from previous studies that have considered associations between greenness or greenspace and several health outcomes, including mortality.<sup>3,30</sup> One hypothesis to explain the stronger effects elsewhere among more deprived populations is that such populations tend to have poorer health status and higher levels of stress, such that they stand to benefit more from a restorative environment. Here we propose that more affluent populations might have more true leisure time, and tend to spend more time outside and enjoying their property at weekends or during other time off from work compared with lower-income populations and those who are unemployed or unable to work.<sup>31</sup> Furthermore, the quality of the greenspaces around the homes of more affluent populations might be different from those around people in more deprived populations, which is a factor that we were unable to assess or describe with our existing datasets.

Our finding of strongest protective associations among individuals aged 35–74 years suggests that among adults, middle age might be an aetiological important window during which living close to greenness might yield the largest benefits to health. Results of effect modification by sex and age in the context of greenspace and health have been inconsistent in the scientific literature (with some studies showing stronger effects for women, others for men, and others no differences; the same is true for different age groups of adults).<sup>3,30</sup> There have been several potential explanations for these differences by sex and age, including differing daily health behaviours and exposure patterns (which might be partly determined by employment status and child-rearing responsibilities), perceptions of nature, and the kinds of activities done while in natural environments.

Few other studies have examined the potential link between mortality and exposure to natural environments. A systematic review<sup>9</sup> identified only 12 such studies, seven of which had ecological study designs. Despite the shortage of evidence, the investigators concluded that increased exposure to green space appears to be associated with a reduced risk of cardiovascular mortality. In our study, we showed associations that were more protective than those reported in the only previous Canadian study.<sup>12</sup> For non-accidental mortality, those investigators reported HR 0.95 (95% CI 0.94–0.97) per IQR increase in NDVI within 500 m of participants' residences. They also adjusted their models for estimates of ambient nitrogen dioxide, but, unlike our results, they showed that it had no effect on their risk estimates.

Our findings of associations with non-accidental mortality among women were more attenuated than those reported in a cohort study<sup>11</sup> of American women that also examined associations between mortality and greenness measured within 250 m of participants' homes. Those investigators reported HR 0.88 (95% CI



**Figure:** Concentration–response plot for mortality and greenness

Data are hazard ratios (dark red line) and 95% CIs (light pink shading) for mortality association with greenness within 250 m of participants' residences from model 9 (as described in table 2). NDVI= Normalized Difference Vegetation Index.

0.82–0.94) per increment of 0.10 in exposure for non-accidental deaths, compared with HR 0.96 (95% CI 0.94–0.97) from our most comparable model.

2001 CanCHEC is a very large, broadly representative national cohort. In addition to age and sex, we also stratified our survival models by census metropolitan area, which ensured that participants were compared only with others living in the same urban communities, and thus also in areas with similar climates, and with similar access to health care and other services. We were able to track participants' residential mobility patterns with annual postal codes, which have high positional accuracy in urban areas, thus minimising exposure misclassification. A key strength of our study is that we were able to adjust our survival models additionally for potential exposures to ambient air pollution. Controlling for other environmental exposures, nitrogen dioxide in particular, improved our models and had substantial effects on our effect estimates. We know from earlier studies that estimates of intraurban concentrations of nitrogen dioxide are associated with mortality,<sup>32</sup> and the estimates of nitrogen dioxide that we used were also associated with our estimates of residential greenness. It is therefore not unexpected that adjusting for this confounding variable strengthened the associations. We believe that nitrogen dioxide had a stronger effect on our results than did either PM<sub>2.5</sub> or ozone because of the higher spatial resolution of that model compared with those for the other two pollutants.

Another strength of our study was that we were able to collect and assign exposures that were temporally consistent with our cohort follow-up period. A key limitation of the NDVI is that it describes only the presence and amount of vegetation, and not its quality or accessibility. That is, the index does not allow differentiation between a park, woodlot, or agricultural field, or identification of whether it represents private or

public space. Nonetheless, after adjusting for many individual-level and community-level covariates, NDVI has been shown<sup>12,19,33</sup> to be associated with higher levels of physical activity, and with several health outcomes.

Although we were unable to adjust directly for smoking or other personal health behaviours in our main analysis, our results with the CCHS data suggest that although those variables are important predictors of mortality, they do not appear to affect the association between greenness and mortality. The small size of the CCHS cohort restricted our ability to detect significant associations between greenness and mortality in this sample. Residential self-selection is another issue that we could not consider—namely that some people, perhaps those who are more active or more educated (or generally healthier than others), might choose (and be able to afford) to live in greener neighbourhoods. It is important to consider the potential influence on our findings of the social gradient in health—ie, that individuals of higher socioeconomic position tend to have better health than those of lower socioeconomic position.<sup>34</sup>

The fact that we found stronger associations with greenness within 500 m of participants' homes suggests that metric possibly better reflects subjects' typical activity spaces where important exposures or interactions with natural environments might take place. Future studies could explore associations within different buffer sizes with the purpose of identifying relevant exposure areas for different health benefits, along with exploring different exposure time-windows and lag periods.

Our results broadly describe associations only with living in a greener area. Furthermore, we did not consider participants' potential daily activities and exposures within and beyond their home neighbourhoods. Our results therefore did not allow us to identify whether the observed reductions in mortality were related to corresponding reductions in noise, heat, or air pollution associated with greener areas, or if exposure to greener, more natural environments produced an overall restorative, stress-reducing effect that ultimately contributed to improved cardiovascular health. Future research should seek to understand which kinds of natural environments contribute the greatest benefits to health, and should also consider issues related to access, sight lines, and time actually spent in these environments.

Living in urban areas characterised by increased amounts of greenness seems to reduce the risk of mortality from several common causes of death. We identified evidence of inequalities both in terms of exposures to greenness, and in terms of benefits to longevity, by personal socioeconomic status among subjects living in generally similar environments, and with reasonably similar access to health care and other social services. Given the potential benefits to health, findings from this study should be of interest to planners

and policy makers seeking evidence to support the creation of greener and healthier cities.

#### Contributors

DLC, LP, PH, and PJV contributed to the study design. DLC, AB, and LP prepared and cleaned the data. AvD, RVM, RM, AR, and PH contributed to the exposure assessment. DLC, LP, AB, PAP, and HC contributed to the data analyses. DLC took the lead in writing the manuscript. All authors contributed to the interpretation of data and findings, provided critical revisions to the manuscript, and approved the final draft.

#### Declaration of interests

We declare no competing interests.

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