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Healthy built environment: Spatial patterns and relationships of multiple exposures and deprivation in Toronto, Montreal and Vancouver

Dany Doiron[a,*], Eleanor M. Setton[b], Kerolyn Shairsingh[c], Michael Brauer[d], Perry Hystad[e], Nancy A. Ross[f], Jeffrey R. Brook[c,g]

[a] Respiratory Epidemiology and Clinical Research Unit, Research Institute of the McGill University Health Centre, Montreal, Quebec, Canada
[b] Geography Department, University of Victoria, Victoria, British Columbia, Canada
[c] Southern Ontario Centre for Atmospheric Aerosol Research, Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, Canada
[d] School of Population and Public Health, University of British Columbia, Vancouver, British Columbia, Canada
[e] College of Public Health and Human Sciences, Oregon State University, Corvallis, USA
[f] Department of Geography, McGill University, Montreal, Quebec, Canada
[g] Dalla Lana School of Public Health, University of Toronto, Toronto, Canada

A R T I C L E I N F O

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A B S T R A C T

Background: Various aspects of the urban environment and neighbourhood socio-economic status interact with each other to affect health. Few studies to date have quantitatively assessed intersections of multiple urban environmental factors and their distribution across levels of deprivation.
Objectives: To explore the spatial patterns of urban environmental exposures within three large Canadian cities, assess how exposures are distributed across socio-economic deprivation gradients, and identify clusters of favourable or unfavourable environmental characteristics.
Methods: We indexed nationally standardized estimates of active living friendliness (i.e. "walkability"), NO_2 air pollution, and greenness to 6-digit postal codes within the cities of Toronto, Montreal and Vancouver. We compared the distribution of within-city exposure tertiles across quintiles of material deprivation. Tertiles of each exposure were then overlaid with each other in order to identify potentially favorable (high walkability, low NO_2, high greenness) and unfavorable (low walkability, high NO_2, and low greenness) environments.
Results: In all three cities, high walkability was more common in least deprived areas and less prevalent in highly deprived areas. We also generally saw a greater prevalence of postal codes with high vegetation indices and low NO_2 in areas with low deprivation, and a lower greenness prevalence and higher NO_2 concentrations in highly deprived areas, suggesting environmental inequity is occurring. Our study showed that relatively few postal codes were simultaneously characterized by desirable or undesirable walkability, NO_2 *and* greenness tertiles.
Discussion: Spatial analyses of multiple standardized urban environmental factors such as the ones presented in this manuscript can help refine municipal investments and policy priorities. This study illustrates a methodology to prioritize areas for interventions that increase active living and exposure to urban vegetation, as well as lower air pollution. Our results also highlight the importance of considering the intersections between the built environment and socio-economic status in city planning and urban public health decision-making.

1. Introduction

Globally, it's expected that two out of every three individuals will live in cities by 2050(United Nations 2019). In Canada, 82% of individuals lived in urban and suburban areas in 2016(Statistics Canada 2017) and by 2050, almost nine in ten Canadians (87.3%) will be urban dwellers(United Nations 2018). A mounting body of evidence suggests that aspects of the urban environment can affect people's health and health-related behaviours in a number of different ways (Nieuwenhuijsen 2016; Northridge et al. 2003), as outlined below. In recent years, there has also been a renewed focus on the importance of city planning and urban interventions to face the major global health challenges of the 21st century(Giles-Corti et al. 2016). Urban design features such as land use mix, population density, transportation

* Corresponding author at: Research Institute of the McGill University Health Centre, 5252 de Maisonneuve Ouest, Suite 3D.10, Montreal, Quebec H4A 3S5, Canada.
E-mail address: dany.doiron@mail.mcgill.ca (D. Doiron).

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infrastructure, vegetation and tree planting, public facilities, and mobility options contribute to environmental factors such as air quality, neighbourhood greenness, and the extent to which individuals can conveniently walk and cycle to their destinations (i.e. active transportation). In turn, such urban environmental factors have both positive and negative impacts on health, at the individual- and population-levels. A large body of literature has associated neighbourhood walkability(Hajna et al. 2018; McCormack and Shiell 2011; Wasfi et al. 2016), exposure to air pollution(Anderson et al. 2012; Brunekreef and Holgate 2002), and greenness(Fong et al. 2018; James et al. 2015) with health behaviours, chronic health conditions and mortality. Most studies to date have however considered these exposures in isolation and evidence shows that various aspects of the urban environment interact with each other in both synergistic and competing ways(Hankey and Marshall 2017). For instance, studies have shown that areas of high walkability are sometimes characterized by poorer air quality(Cowie et al. 2016; Marshall et al. 2009). Evidence also suggests that greenness may attenuate the harmful health effects of air pollution(Crouse et al. 2019; Dadvand et al. 2015), while environmental noise can exacerbate the impacts of air pollution on chronic health conditions(Tzivian et al. 2017). Further, the pathways linking some exposures to health may be behaviourally mediated, for example walkability, whereas others such as air pollution may have more direct effects. Finally, evidence shows that worse income and socioeconomic status are correlated with suboptimal environmental conditions, which in turn negatively affects health outcomes(Evans and Kantrowitz 2002). Areas with high socioeconomic deprivation and poor built environments may therefore be of high priority for interventions while in turn, interventions targeted towards only one aspect may be less successful in improving population health.

The ubiquitous and modifiable nature of urban environmental exposures makes them promising targets for public health policies, regulations and urban interventions(Giles-Corti et al. 2016; Nieuwenhuijsen 2016). However, a better understanding of how different aspects of the urban environment interact with each other in influencing health across different populations is required to design appropriate policy responses. Planners and policy makers therefore need tools and evidence that are based on small-scale variations of comparable environmental factors across cities. The Canadian Urban Environmental Health Research Consortium (CANUE) is addressing this need with a data platform of harmonized postal code-level environmental exposure metrics characterizing multiple aspects of urban living for all of Canada(Brook et al. 2018). Additionally, CANUE's data holdings, which continue to evolve and incorporate more environmental factors, are being integrated directly into the databases of multiple prospective cohorts and other health research platforms (Doiron et al. 2018; Dummer et al. 2018; Raina et al. 2009; Subbarao et al. 2015) to facilitate environmental health research.

In this study, we leverage urban environmental factors held and distributed by CANUE to explore their spatial patterns within the three principal municipalities of Canada's largest metropolitan areas: Toronto, Montreal and Vancouver. Standard postal code-indexed metrics of neighbourhood walkability, nitrogen dioxide (NO_2) air pollution, satellite-based greenness, and material deprivation are used to: (1) explore their spatial distribution and intersection within cities, (2) assess how environmental factors are distributed across socio-economic deprivation gradients, and (3) identify potentially favorable environments (high walkability, low NO_2, high greenness) and those most in need of interventions (low walkability, high NO_2, and low greenness). NO_2 is used as a measure of air quality given it typically shows larger within-city variation, especially that related to motor vehicle traffic, relative to other commonly-measured pollutants such as fine particulate matter mass concentrations ($PM_{2.5}$)(Levy et al. 2014). Further, a material deprivation index composed of education, employment and income measures was employed since it provides a broader picture of how health determinant intersect with environmental attributes than more commonly used metrics such as mean neighbourhood household income.

Few studies to date have quantitatively assessed intersections of multiple urban environmental factors and their distribution across levels of deprivation. These analyses allow identification of areas in each city with health-promoting environmental characteristics as well as areas with a confluence of characteristics potentially detrimental to health. This study thereby illustrates a methodology for municipalities to prioritize areas for interventions that increase active living and exposure to urban vegetation, as well as lower air pollution. It also more generally demonstrates the potential for environmental data platforms to address questions important in the quest for healthier cities.

2. Materials and methods

2.1. Study area

We explored the spatial distribution of neighbourhood active living friendliness (i.e. "walkability"), NO_2 air pollution, greenness and deprivation within the cities of Toronto, Montreal and Vancouver. These cities were selected as they represent the core population of Canada's three largest metropolitan areas, which encompass over one-third (35.5%) of the Canadian population(Statistics Canada 2017). The DMTI Spatial (Desktop Mapping Technologies Inc.) Municipal Amalgamation File (MAF) was used to define 2016 municipal boundaries(DMTI Spatial Inc. 2015). Study areas excluded many suburban zones in metropolitan areas that are administered by other municipal governments. The geographic coverage of Toronto, Montreal, and Vancouver are 630.20 km^2, 365.65 km^2 and 114.97 km^2, with a 2016 population density of 4334.4, 4662.1 and 5492.6 people per km^2, respectively (Statistics Canada 2019). Housing type varied considerably across cities; single-detached houses represented 7% (Montreal), 15% (Vancouver), and 24% (Toronto) and apartment buildings made up 59% (Toronto), 62% (Vancouver), and 72% (Montreal) of all occupied private dwellings in 2016(Statistics Canada 2019). About half of individuals in each city commuted to work by car while public transit modal share was 37% in Toronto and Montreal and 30% in Vancouver. In Toronto and Montreal, 12% and 13% of the employed labour force walked or biked to get to work, respectively, whereas active transportation modal share was 21% in Vancouver(Statistics Canada 2019).

2.2. Data preparation

All environmental exposures and deprivation scores were provided by CANUE, indexed to all single-link DMTI Spatial Inc. 6-digit postal codes in each of the three study areas. Single-link postal codes are located at the geographic coordinates that best represent where the majority of the population lives within the postal code zone. In Canadian urban areas, postal codes correspond to one side of a city block, or even a single large apartment building. Deprivation scores, walkability and greenness metrics were for the year 2016. While NO_2 estimates were for 2012, studies have demonstrated temporal stability in the spatial patterns of NO_2 and other air pollutants over ~10 years(Wang et al. 2013).

In order to restrict our analyses to inhabited areas, we excluded 18 137 out of 102 076 postal codes in the three municipalities made up exclusively of business points of call (i.e. postal codes with no apartments or houses). The presence of residences within each single-link postal code was determined using the Enhanced Postal Point file included in the DMTI Spatial Inc. *CanMap Content Suite*(DMTI Spatial Inc. 2015).

Material deprivation scores and walkability were originally estimated for dissemination areas, which are geographic units composed of one or more adjacent city blocks. To facilitate co-analyses with NO_2 and greenness metrics indexed to postal code single-link locations, all postal codes within a dissemination area were assigned the same deprivation and walkability scores. Population counts were obtained from the

Canadian Census at the level of the dissemination block, which are generally smaller units of geography relative to DAs that are bounded by roads or natural boundaries. The total population for a dissemination block was distributed equally across all single-link postal codes within each dissemination block. Across all three cities there was a mean population of 60 individuals per postal code. Figure S1 in supplementary materials shows the relationship between dissemination areas, dissemination blocks and single link postal code locations in Canada.

2.3. Active transportation/active living

We used the Canadian Active Living Environments (Can-ALE) index to explore the spatial distribution of neighbourhood active transportation(Herrmann et al. 2019; Ross et al. 2018). The Can-ALE index is the sum of z-scores of four built environment measures associated with walking rates and active transportation: intersection density, dwelling density, points of interest and transit stops. Each measure was calculated from one-kilometer circular buffers based on centroids of 2016 dissemination areas (DAs). The summed Can-ALE score indicates the distribution of active-living friendliness in a given DA relative to all DAs in Canada, with negative values representing below average walkability, and positive values representing above average walkability. A Can-ALE score of around zero indicates that a location is near the Canadian average for the quality of the active living environment. Higher values of the Can-ALE index have been shown to predict higher than average walk-to-work and active-transportation-to-work (i.e. walking and cycling) rates across Canada (Herrmann et al. 2019). As mentioned above, all single link postal code locations within a DA were assigned the same Can-ALE value.

2.4. Nitrogen dioxide air pollution

Annual average NO_2 concentrations in parts per billion (ppb) at each single-link postal code location were estimated using a national land use regression (LUR) model for the year 2006 and adjusted for the year 2012 using air quality monitoring station data(Hystad et al. 2011; Weichenthal et al. 2017). The LUR model included road length within 10 km, 2005–2006 satellite NO_2 estimates, area of industrial land use within 2 km, and summer rainfall as predictors of regional NO_2 variation, and deterministic gradients were used to model local scale variation related to roads (i.e., traffic). The final NO_2 model showed good performance, explaining 73% of the variation in measurements from different types of monitoring sites (general exposure, regional background, local-source influenced) in the national air pollution surveillance (NAPS) network, with a root mean square error (RMSE) of 2.9 parts per billion (ppb).

2.5. Greenness

Exposure to greenness was estimated using normalized difference vegetation index (NDVI) derived from the U.S. Geological Surveys' Landsat 8 satellite images. We used Google Earth Engine functions to create cloud free annual growing season composites. Water features were masked in order to exclude water pixels in NDVI calculations. We then exported the resulting Top of Atmosphere (TOA) reflectance band data(Gorelick et al. 2017). The 2016 annual mean NDVI within a 500-meter buffer around each single-link postal code location were used in analyses.

2.6. Neighbourhood socioeconomic status (SES)

To assess how environmental exposures were distributed across levels of socioeconomic status, we used the material component of the 2016 Material and Social Deprivation Index (MSDI)(Pampalon et al. 2012). The MSDI was derived using principal component analyses in each city with DA-level indicators of education, employment and income obtained from the Canadian Census. The distribution of material deprivation values observed in each city were then divided into deprivation quintiles (groups making up 20% of the population), thereby allowing us to explore variations within cities. As with the Can-ALE score, all postal codes within a dissemination area were assigned the same material deprivation values.

2.7. Statistical analyses

We first generated descriptive statistics and correlation coefficients for walkability, NO_2, and greenness exposures. To explore variations of urban environmental exposures across socioeconomic gradients, we compared the distribution of within-city exposure tertiles across quintiles of material deprivation, similar to the method used by Marshall *et al.* (Marshall et al. 2009) and Cowie *et al.* (Cowie et al. 2016). For this exercise, we divided the prevalence rate (proportion) of postal codes falling in low exposure tertiles within each quintile of deprivation by the overall prevalence of postal codes in low tertiles of exposures. This process was repeated for prevalence rates of postal codes falling in high exposure tertiles across deprivation quintiles. A ratio of 1.0 indicated that the prevalence of an exposure tertile in a given deprivation category was the same as its overall prevalence when considering all postal codes within a city. A score of less than 1.0 indicated a lower prevalence compared to overall, and vice versa. Methods employed by Marshall *et al.* (Marshall et al. 2009) and Cowie *et al.* (Cowie et al. 2016) were also adapted to classify postal codes into "*sweet*" and "*sour spots*". Briefly, exposure tertiles were overlaid with each other in order to identify postal codes of high walkability, low NO_2, *and* high greenness (i.e. "*sweet spots*") and postal codes characterized by low walkability, high NO_2, *and* low greenness (i.e. "*sour spots*"). To allow comparison with the two previous studies having used this methodology to intersect walkability and traffic related air pollution, we also overlaid walkability tertiles with tertiles of NO_2. The intersection between walkability tertiles and tertiles of greenness exposure were also explored. Finally, we calculated the population distribution across high and low exposure tertiles and for "*sweet spot*" and "*sour spot*" postal codes within each city using linked Canadian Census data.

All statistical analyses were performed using the R statistical package, version 3.6.0(R Core Team 2019).

3. Results

After exclusion of postal codes without any residential addresses, a total of 41 200, 28 558, and 14 181 postal codes for Toronto, Montreal and Vancouver respectively were used in analyses. Descriptive statistics for walkability, NO_2, and greenness exposure are shown in Table 1. Maps showing the spatial distribution of each exposure for each city are provided in supplemental materials (Figures S2, S3 and S4). The mean Can-ALE index was highest in Montreal (4.17 ± 4.01 standard deviation (SD), *no units*) and lowest in Vancouver (3.43 ± 4.62 SD, *no units*). Mean NO_2 was comparable across cities, ranging from 16.0 ppb (± 3.71 SD) annual average in Montreal to 16.6 ppb (± 2.70 SD) in Toronto. Finally, mean annual NDVI greenness within 500 m around each postal code was also similar across cities, ranging from 0.33 (± 0.09 SD, *no units*) in Vancouver to 0.40 (± 0.09 SD, *no units*) in Toronto. In all 3 cities, greenness was negatively correlated with both walkability (r = −0.51 to −0.63) and NO_2 (r = −0.40 to −0.61), while walkability showed a positive correlation with NO_2 (r = 0.09–0.50) (Table 2).

Table 3 shows the relative prevalence of postal codes in the lowest and highest tertiles of exposure across material deprivation quintiles. Low material deprivation areas in Toronto, Montreal and Vancouver had a 68%, 70% and 114% higher prevalence of highly walkable postal codes compared to city-wide prevalence. Conversely, in all three cities postal codes favouring active living (i.e. highly walkable) were around half as common in the highest deprivation quintiles compared to city-

Table 1
Descriptive statistics for walkability, NO_2, and greenness.

	Mean ± SD	Median	Min	1st tertile	2nd tertile	Max	N	Missing
Walkability (no unit)								
Toronto	3.85 ± 5.76	2.12	−3.43	1.11	3.61	47.83	41 199	1
Montreal	4.17 ± 4.01	3.35	−3.50	2.06	4.80	19.34	28 558	0
Vancouver	3.43 ± 4.62	2.14	−3.55	1.40	3.23	28.88	14 181	0
NO_2 (ppb)								
Toronto	16.6 ± 2.70	16.4	8.7	15.6	17.3	35.9	40 977	223
Montreal	16.0 ± 3.71	16.1	6.3	14.8	17.4	36.0	28 407	151
Vancouver	16.1 ± 3.57	15.7	5.7	14.6	17.1	39.2	14 006	175
Greenness (no unit)								
Toronto	0.40 ± 0.09	0.40	0.03	0.36	0.44	0.71	41 200	0
Montreal	0.35 ± 0.09	0.35	0.05	0.30	0.38	0.77	28 558	0
Vancouver	0.33 ± 0.09	0.33	0.03	0.30	0.36	0.75	14 181	0

Table 2
Pearson's correlation coefficients for walkability, NO_2, and greenness.

	Walkability	NO_2	Greenness
Toronto			
walkability	1	0.09	−0.51
NO_2	–	1	−0.40
greenness	–	–	1
Montreal			
walkability	1	0.50	−0.62
NO_2	–	1	−0.61
greenness	–	–	1
Vancouver			
walkability	1	0.26	−0.63
NO_2	–	1	−0.54
greenness	–	–	1

wide prevalence. High material deprivation areas were also less likely to experience low NO_2 concentrations in all three cities, and 23% and 38% more likely to experience high NO_2 exposure in Vancouver and Toronto, respectively. We observed a consistent deprivation-greenness relationship for the city of Toronto; low greenness postal codes were 44% more prevalent in highly deprived areas and 34% less prevalent in low deprivation areas, compared to city wide prevalence. Conversely, high greenness values in Toronto were 58% more prevalent in the lowest deprivation postal codes, and 55% less prevalent in high deprivation areas. Finally, in Montreal and Vancouver, relatively high greenness was 49% and 57% less common in highly deprived postal codes, respectively.

Figs. 1, 2 and 3 shows the spatial distribution of "*sweet*" and "*sour spots*" in Toronto, Montreal and Vancouver, respectively, as well as examples of what these locations look like using randomly selected Google Street View and satellite images. Toronto had the highest proportion of both "*sweet spots*" (1.9% of postal codes) - i.e. high walkability, low NO_2, *and* high greenness - and "*sour spots*" (4%) – i.e. low walkability, high NO_2, *and* low greenness (Table 4). Montreal had the lowest proportion of both "*sweet*" (0.6%) and "*sour spot*" (2%) postal codes. In all three cities, we observed spatial clustering of "*sweet"* and "*sour*" spots (Figs. 1, 2 and 3). High walkability/low NO_2 postal codes made up 8.6%, 7.4%, and 1.8% of postal codes in Toronto, Vancouver and Montreal, respectively. The prevalence of postal codes with a low walkability score and high NO_2 concentrations was 4.4%, 7.9% and 8.9% in Montreal, Vancouver and Toronto, respectively. Finally, postal codes characterized by relatively high walkability and high greenness

Table 3
Walkability, NO_2, and greenness tertiles: relative postal code prevalence rate by quintiles of material deprivation*.

	All postal codes	Low walk.	Low NO_2	Low green	High walk.	High NO_2	High green
Proportion of all postal codes (%)	100	33.3	33.3	33.3	33.3	33.3	33.3
Toronto (prevalence rate)							
1 (low deprivation)	1.0	0.59	0.80	0.66	1.68	0.70	1.58
2	1.0	0.92	1.14	0.77	1.17	0.76	1.26
3	1.0	1.17	1.22	0.92	0.87	0.90	1.03
4	1.0	1.16	1.03	1.17	0.72	1.24	0.69
5 (high depr.)	1.0	1.19	0.82	1.44	0.50	1.38	0.45
Montreal (prevalence rate)							
1 (low depr.)	1.0	0.79	0.74	1.13	1.70	1.26	1.11
2	1.0	1.00	1.12	0.94	1.30	1.08	1.29
3	1.0	1.25	1.28	0.75	0.75	0.89	1.27
4	1.0	1.09	1.18	0.90	0.71	0.78	0.87
5 (high depr.)	1.0	0.87	0.65	1.23	0.57	0.95	0.51
Vancouver (prevalence rate)							
1 (low depr.)	1.0	0.59	1.47	1.82	2.14	0.88	0.69
2	1.0	1.39	1.77	0.53	1.06	0.61	1.59
3	1.0	1.18	1.12	0.62	0.68	0.99	1.33
4	1.0	1.15	0.48	0.68	0.51	1.21	0.97
5 (high depr.)	1.0	0.74	0.20	1.25	0.55	1.23	0.43

* A ratio of 1.0 indicates that the prevalence of low/high exposure tertiles in a deprivation category is the same as its overall prevalence in a given city, while a ratio below 1.0 indicated a lower prevalence compared to overall, and vice versa. For example, a value of 1.58 for *high greenness* in Toronto's lowest deprivation quintile indicates an 58% higher than expected prevalence of *high greenness* in low deprivation postal codes compared to *high greenness* across all deprivation categories. Further, a value of 0.66 for *low greenness* in Toronto's lowest deprivation quintile represents a 44% lower prevalence of *low greenness* in the least deprived postal codes compared to all deprivation categories.

Fig. 1. "Sweet" and "sour spots" postal codes in the city of Toronto.

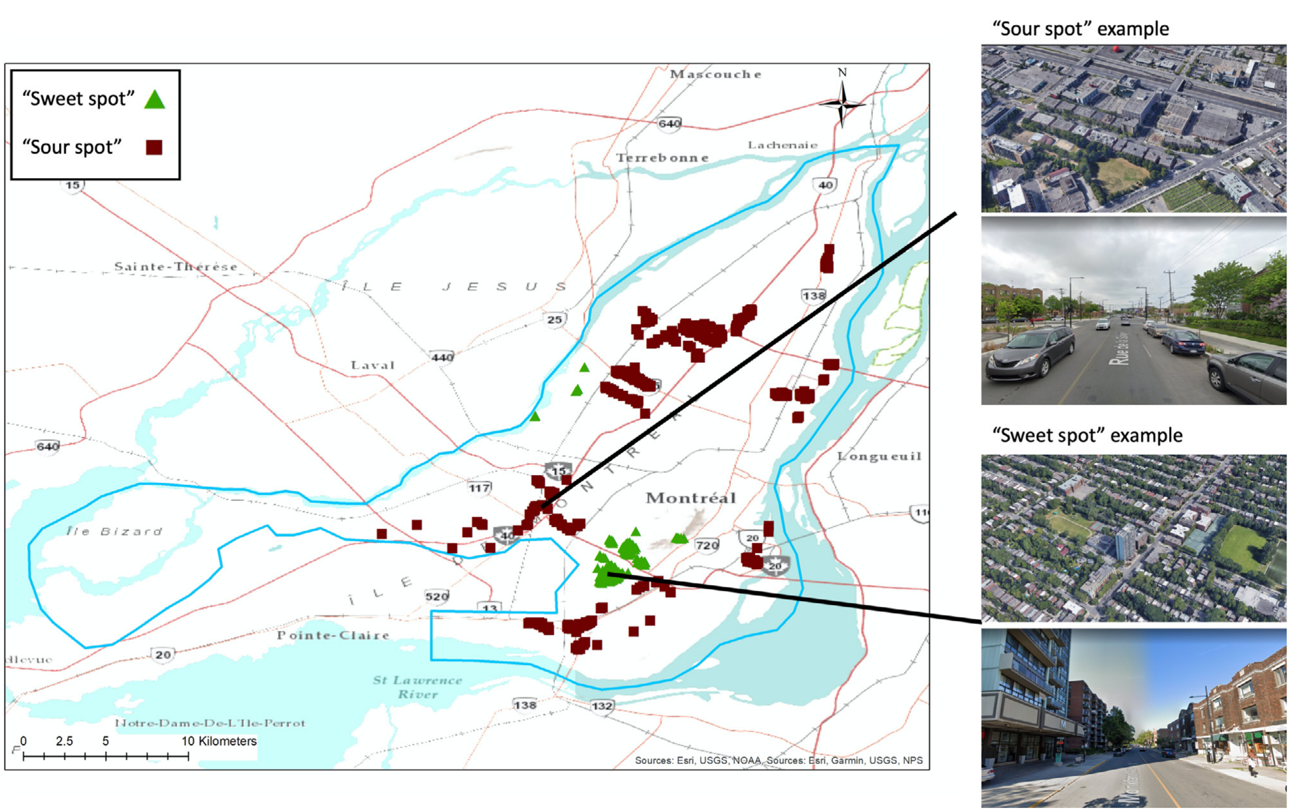

Fig. 2. "Sweet" and "sour spots" postal codes in the city of Montreal.

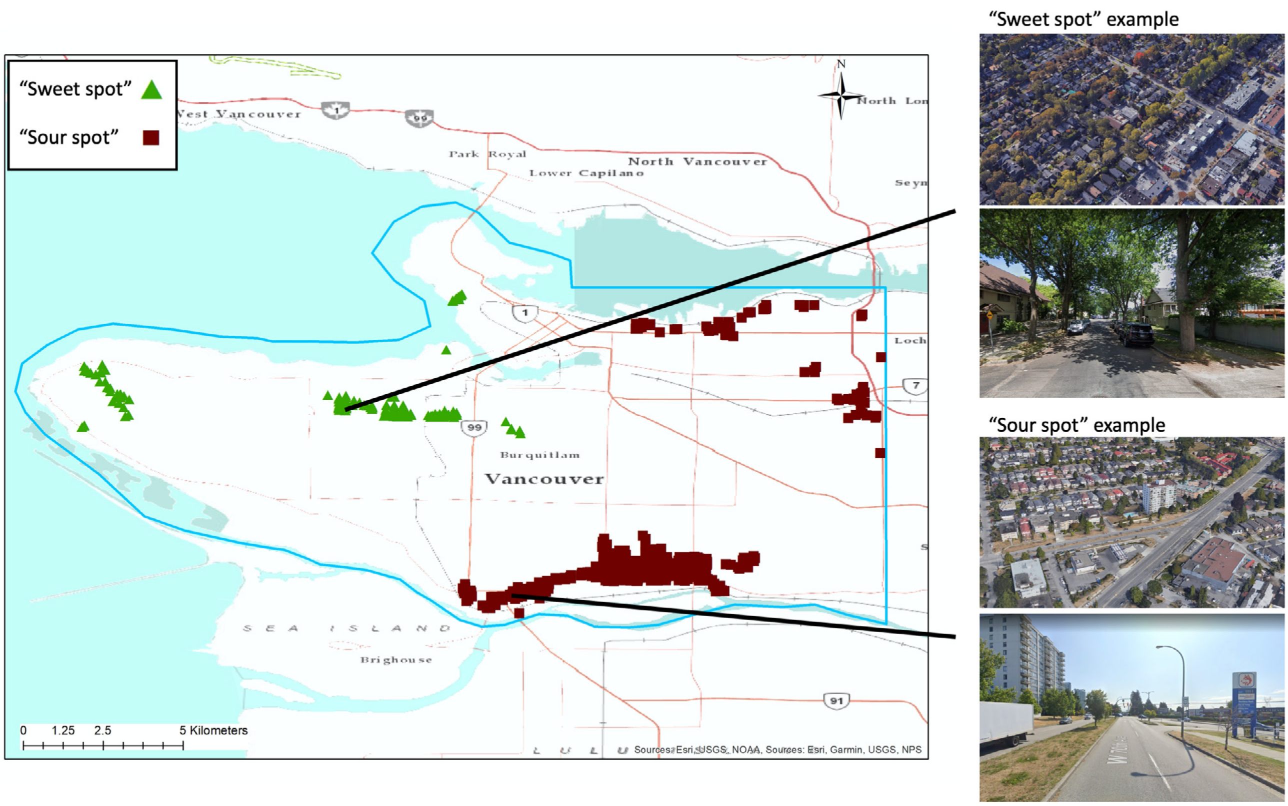

Fig. 3. "Sweet" and "sour spots" postal codes in the city of Vancouver.

Table 4
Prevalence of favorable and unfavorable environment postal codes*.

	City total	"*Sweet spot*" n (%)	"*Sour spot*" n (%)	High walk., low NO_2	Low walk., High NO_2	High walk., high green.	Low walk., low green.
Toronto	41 200 (100%)	782 (1.9)	1 653 (4.0)	3 552 (8.6)	3 685 (8.9)	2 537 (6.2)	2 576 (6.3)
Montreal	28 558 (100%)	182 (0.6)	558 (2.0)	514 (1.8)	1 260 (4.4)	1 345 (4.7)	680 (2.4)
Vancouver	14 181 (100%)	127 (0.9)	557 (3.9)	1054 (7.4)	1 125 (7.9)	445 (3.1)	837 (5.9)

* A "sweet spot" is defined as a postal code characterized by the highest tertiles of walkability and greenness *and* lowest tertile of NO_2. A "sour spot" is a postal code characterized by low walkability, low greenness *and* high NO_2.

made up 6.2% of postal codes in Toronto, 4.7% of postal codes in Montreal, and 3.1% of postal codes in Vancouver. The proportion of low walkability/low greenness postal codes was 2.4% in Montreal, 5.9% in Vancouver and 6.3% in Toronto.

Table 5 shows the population distribution across walkability, NO_2, and greenness exposure tertiles, as well as "*sweet*" and "*sour spots*". When comparing low vs. high tertiles of each exposure, a larger proportion of individuals within each city lived in areas of relatively high walkability, high NO_2 or low greenness. Between 37.6% (Montreal) to 47% (Vancouver) of individuals lived in areas of relatively high walkability, whereas 24.9% (Vancouver) to 27.5% (Montreal) lived in neighbourhoods characterized by a low active living index. Between 37.2% (Montreal) to 39.3% (Vancouver) of the population of each city lived in high NO_2 postal codes, compared to 25.4% (Vancouver) to 29.1% (Toronto) in relatively low NO_2 areas. Finally, almost half (48.2%) of the city of Vancouver lived in postal codes characterised by relatively low greenness compared to about 1 in 4 (22.4%) in areas of relatively high greenness. In Toronto and Montreal, 43% and 38.2% of individuals lived in low greenness postal codes, respectively, and 24.5% and 24.9% lived in neighbourhoods of relatively high greenness, respectively. Finally, between 0.6% (Montreal) and 1.8% (Toronto) of the population lived in postal codes characterised by a cluster of favorable factors (i.e. "*sweet spot*"), and between 2.1% (Montreal) and 4.3% (Toronto) lived in postal codes characterised by three undesirable environmental factors.

4. Discussion

This study made use of nationally consistent metrics to show the distribution and co-location of urban environmental attributes within

Table 5
Population distribution by walkability, NO_2, and greenness exposure tertiles and by "*sweet*" and "*sour spots*".

	City total	*Low walk.*	*Low NO_2*	*Low green*	*High walk.*	*High NO_2*	*High green*	*"Sweet spot"*	*"Sour spot"*
Population, n (%)									
Toronto	2 698 574 (100%)	738 476 (27.4)	786 144 (29.1)	1 159 786 (43.0)	1 055 981 (39.1)	1 040 782 (38.6)	662 256 (24.5)	49 496 (1.8)	117 019 (4.3)
Montreal	1 687 560 (100%)	463 608 (27.5)	470 587 (27.9)	645 132 (38.2)	634 211 (37.6)	627 548 (37.2)	419 882 (24.9)	10 511 (0.6)	34 883 (2.1)
Vancouver	639 702 (100%)	159 470 (24.9)	162 209 (25.4)	308 210 (48.2)	300 413 (47.0)	251 373 (39.3)	142 993 (22.4)	6178 (1.0)	24 864 (3.9)

three large Canadian cities. We showed how greenness, air pollution, and walkability are distributed across levels of socio-economic deprivation, which allowed us to identify patterns of environmental inequity in each city. We were also able to identify clusters of favourable or unfavourable environmental characteristics by overlaying urban environmental factors. Finally, population counts from Canadian Census were used to estimate the proportion of each city's total population experiencing high vs. low levels of each exposure.

In all three cities, high walkability was more common in least deprived areas and less prevalent in highly deprived areas. We also generally saw a greater prevalence of postal codes with relatively high greenness indices and low NO_2 in areas with low deprivation, and a lower greenness prevalence and higher NO_2 concentrations in highly deprived areas, suggesting environmental inequity is occurring.

The most materially deprived areas of Toronto, Montreal and Vancouver were around half as likely to be highly walkable, whereas high walkability was between 68% and 114% more prevalent in the least deprived postal codes. Past studies have suggested SES can modify the relationship between walkability and health. A study of Toronto residents showed the incidence rate of diabetes was two times higher in low- vs. high-income areas at all levels of walkability but that amongst recent immigrants, coexisting low-income and low-walkability led to threefold higher diabetes incidence relative to individuals living in high-income, high walkability areas(Booth et al. 2013).

Persons living in Toronto, Montreal and Vancouver neighbourhoods of high deprivation were also about half as likely to be surrounded by high greenness, relative to city-wide high greenness prevalence. Studies of Canadian populations have shown that exposure to vegetation, or "greenness", is associated with a number of health benefits including increased levels of physical activity(McMorris et al. 2015), beneficial birth outcomes(Hystad et al. 2014), and a lower risk of non-accidental mortality from different causes(Crouse et al. 2017; Villeneuve et al. 2012). Results from our analyses suggest that such co-benefits of greenness exposure might be disproportionately experienced across different socio-economic status (SES) levels. Our results should also be considered with regard to the role of vegetation in alleviating the impacts of climate change in large cities. Overall, current climate scenarios show that Canadian urban centres will experience at least four times as many +30 °C days per year and longer extreme heat events by 2051–2080(Prairie Climate Centre 2019). Given that urban vegetation has been shown to mitigate urban heat(Ziter et al. 2019), the greenness inequity observed in our study could amplify the impact of an increasing number and length of extreme heat events in materially deprived populations.

The most deprived areas of Toronto and Vancouver had a 38% and 23% higher prevalence of high NO_2, respectively, compared to city-wide prevalence, while prevalence of high NO_2 in materially deprived postal codes of Montreal were similar to city-wide prevalence. Positive associations between indicators of neighbourhood-level social and material deprivation and NO_2 air pollution concentrations have been reported for adults and children in similar studies of Toronto, Montreal and Vancouver(Pinault et al. 2016a; Pinault et al. 2016b).

The relationship between deprivation and environmental exposures was not always monotonic. For example, low deprivation areas had an 82% higher prevalence of low greenness in Vancouver, and a 26% higher prevalence of high NO_2 concentrations in Montreal, compared to city-wide prevalence. This suggests that while some environmental justice patterns seen in our study may be generalizable to similar cities in Canada and internationally (e.g. high deprivation and greenness), deprivation-exposure relationships require careful consideration of local context(Crouse et al. 2009).

The "*sweet*" and "*sour spot*" analyses conducted in our study showed that relatively few postal codes were simultaneously characterized by desirable or undesirable walkability, NO_2 and greenness tertiles. Only 127 (0.9%), 182 (0.6%) and 782 (1.9%) postal codes had a cluster of desirable urban environmental factors (i.e. "*sweet spots*") in Vancouver, Montreal, and Toronto, respectively. A slightly higher number of postal codes were considered "*sour spots*" in each city; 557 (3.9%) in Vancouver, 558 (1.8%) in Montreal, and 1 653 (4.0%) in Toronto. When compared to findings from Marshall et al.(Marshall et al. 2009) in Vancouver, Canada, we found slightly larger proportions of postal codes with clusters of desirable or undesirable tertiles of walkability and traffic-related air pollution (i.e. NO_2). In the previous study of the Vancouver Census Metropolitan Area, 3.6% of postal codes were characterized by high walkability yet low traffic-related air pollution (Marshall et al. 2009). In our study, such desirable locations made up 7.4% of postal codes of the Vancouver municipality. The frequency of postal codes in Vancouver with a cluster of undesirable environmental factors (i.e. low walkability and high traffic-related air pollution) were also slightly higher for our study (7.9% vs 6.8%). Cowie and colleagues also found smaller percentages of Census Collection Districts (CCDs) in the city of Sydney, Australia characterized by desirable (4.2%) and undesirable (4.5%) walkability and traffic air pollution tertiles (Cowie et al. 2016), relative to our results for the cities of Vancouver and Toronto. The discrepancy between the present study and past investigations could be due to a number of factors, notably their different geographical coverage (CMA vs. municipality) and the different exposure estimation methods used in each study. Finally, linking exposures to Canadian Census data allowed estimating the number of individuals living in postal codes at either ends of exposure distributions. Results show that a larger proportion of individuals in Canada's 3 largest cities live in areas of high- vs. low walkability and NO_2, and low- compared to high greenness exposure. We also saw that between two and four times more individuals live in "*sour spot*" compared to "*sweet spot*" postal codes in each city.

Spatial analyses of multiple standardized urban environmental factors such as the ones presented in this study can help refine municipal investments and policy priorities. For example, identification of postal codes characterized as "*sour spots*" provides an opportunity for targeted urban interventions. Accordingly, "*sour spots*" postal codes could be given priority for initiatives such as urban tree planting, expanding natural areas, traffic calming measures, and enhancing street connectivity and land use mix in order to help reduce air pollution, increase greenness and/or provide opportunities for active living. That said, the small proportion of postal codes characterized by a confluence of health-promoting environmental characteristics found in our study highlights the need for additional efforts to implement holistic urban planning measures that reduce air pollution and increase walkability and greenness exposure throughout each city. Our results also highlight the importance of considering environmental inequity in city planning and urban public health decision-making. The potential for unequal health impacts of environmental exposures is the result of at least two pathways: differential levels of, and/or susceptibilities to, exposures (Lipfert 2004). While we generally observed higher levels of air pollution and lower exposure to vegetation in more deprived neighbourhoods, past studies have also shown that low-SES individuals are also more susceptible to the health effects of air pollutant exposure(Doiron et al. 2017; Sacks et al. 2011), low walkability(Booth et al. 2013) or greenness exposure(de Keijzer et al. 2017; James et al. 2015). Resources to improve health-relevant built environment factors could therefore also be prioritized in urban areas affected by the "double-burden" of socioeconomic deprivation and unfavorable levels of environmental exposures. Figs. 4, 5 and 6 illustrate the intersections of SES, air pollution and greenness and show the usefulness of mapping tools to guide targeted interventions that improve urban environmental conditions of vulnerable populations.

A few limitations and recommendations for future research should be noted. First, the metrics employed in this study are but one way of quantifying urban environmental exposures. For example, different models have been used to estimate air pollution concentrations, each with their respective advantages, drawbacks and varying levels of accuracy(Jerrett et al. 2004). Moreover, the satellite-derived greenness

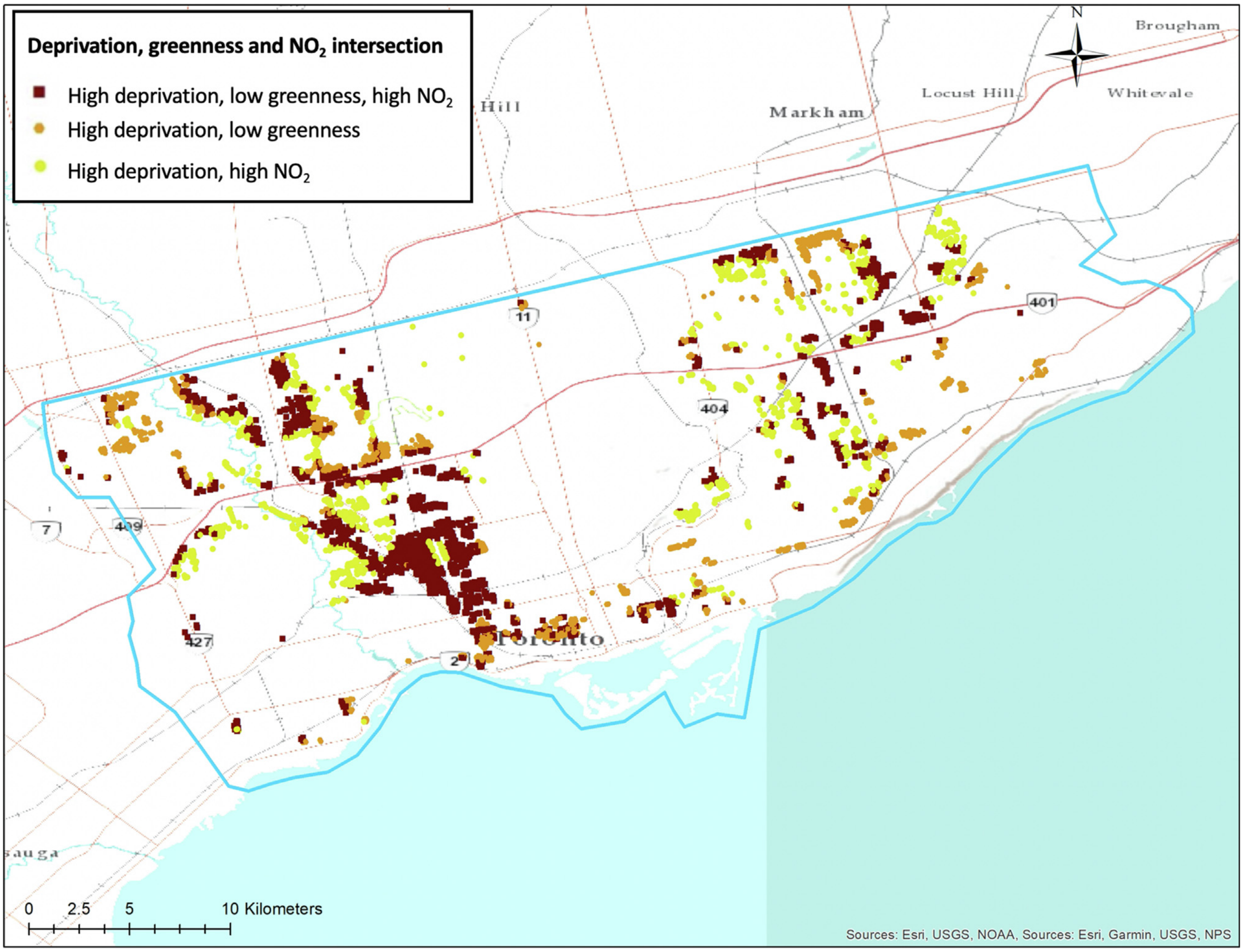

Fig. 4. Intersection between material deprivation, greenness and NO_2 in the city of Toronto.

metrics used in this study do not allow assessing the type or quality of green spaces, which might be more useful to assess health benefits of greenness exposure and to provide more actionable evidence for urban planning interventions(Nieuwenhuijsen et al. 2017). Although satellite-based greenness metrics used in our study have been related to the health and health behaviours of Canadian(Hystad et al. 2014; McMorris et al. 2015), additional work is needed to derive national greenness datasets that may better discriminate between different types of green spaces relevant to specific health relationships. Second, we gave greenness, walkability and NO_2 air pollution exposures equal weight in calculating "*sweet*" and "*sour spots*", which is not necessarily desirable. Additional research is needed to determine appropriate weightings to attribute to different built environment factors based on a range of health outcomes when developing environmental indices or risk scores. This work should also carefully consider how interactions and relationships between exposures may differ for different health outcomes (e.g. cardiovascular disease vs. dementia) and populations (e.g. children vs adults). Third, inclusion of other urban environmental factors beyond those used in our analyses could have provided a more comprehensive picture of the health-relevant built environment characteristics in each city. Additional exposures to consider in future studies include noise pollution, weather and climate variables, food environments, and other air pollutants (e.g. diesel exhaust, ozone, ultra-fine particles). Fourth, our study areas excluded suburban zones under the governance of different municipal administrations, which would typically have higher greenness indices, lower walkability scores and lower NO_2 concentrations. While this reduces the "range" of urban exposures and attributes, limiting analyses to areas managed by a single municipal government can facilitate the implementation of targeted interventions by local policy makers. Fifth, environmental attributes and deprivation metrics were originally developed at different geographic scales. As with other environmental and public health research making use of administrative boundaries, the modifiable area unit problem may be a limitation. However, the use of alternative administrative boundaries in health inequalities research have not shown substantive effects on study results(Stafford et al. 2008). Lastly, results in our study were relative to conditions within each city so absolute levels of each exposure were not compared. This being said, the mean and distribution of each exposure was comparable across cities. Furthermore, using local exposure gradients (i.e. within-city comparisons) provides valuable information for municipal decision-making.

Replicating analyses such as the ones presented in this study across multiple cities would provide a means to reliably benchmark municipalities and track patterns in urban environmental risks. While many urban health indicator tools exist, standardization of methodology and metrics is lacking, leading to substantial duplication of efforts and limited comparability(Pineo et al. 2018). Standardizing data across larger areas and over time would also facilitate comparisons of urban environmental risks across populations, leverage cross-jurisdictional and natural experiment studies, and allow time trend analyses to be conducted. This being said, data standardization is indeed a difficult endeavour. The advent of highly resolved satellite, aerial and street level imagery, and the applications of machine learning techniques to large environmental datasets are, however, opening new avenues for

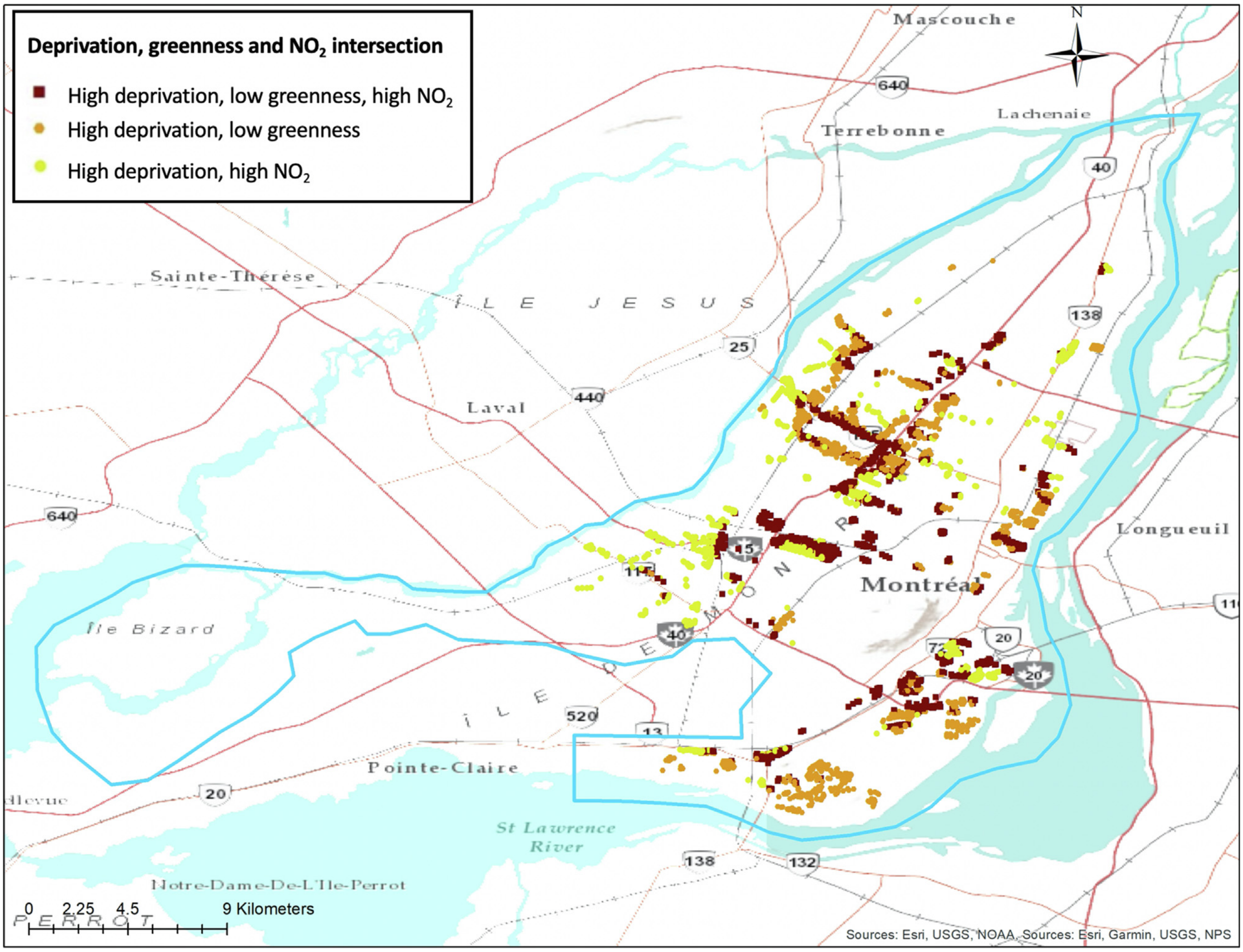

Fig. 5. Intersection between material deprivation, greenness and NO_2 in the city of Montreal.

environmental health research(Apte et al. 2017; European Space Agency 2018; Larkin and Hystad 2019; Weichenthal et al. 2019). Such technologies have the potential to generate health-relevant datasets of small-scale variations in environmental exposures over large areas and over time. Finally, epidemiological analyses that include multiple urban factors are needed to tease out the health impacts of interacting exposures (Brauer and Hystad, 2014; Rugel and Brauer, 2020). Standardized metrics with broader spatial and temporal coverage would help answer this research gap.

5. Conclusion

There is a need to move towards a systematic approach to understanding the health impacts of co-occurring urban environmental factors for healthy urban planning(Vardoulakis et al. 2016). The standardized exposure data and methods employed in this manuscript illustrate the value of new tools that can help meet this need. Environmental exposures presented herein as well as other urban factors are freely available for research purposes via the CANUE data portal (*www.canuedata.ca*). Urban planners, policy makers and public health professionals should leverage such datasets when developing new policies and interventions. As we have shown, they allow exploring how multiple urban factors intersect with each other and with neighbourhood SES and provide an effective way to identify areas in most need of improvements. Employing a consistent analytical approach with standardized data could ultimately help shape appropriate planning and policy decisions that address urban environmental health risks.

CRediT authorship contribution statement

Dany Doiron: Conceptualization, Writing - original draft, Formal analysis. **Eleanor M. Setton:** Conceptualization, Writing - review & editing, Supervision, Project administration, Data curation. **Kerolyn Shairsingh:** Writing - review & editing, Visualization. **Michael Brauer:** Conceptualization, Writing - review & editing. **Perry Hystad:** Writing - review & editing, Data curation. **Nancy A. Ross:** Writing - review & editing, Data curation. **Jeffrey R. Brook:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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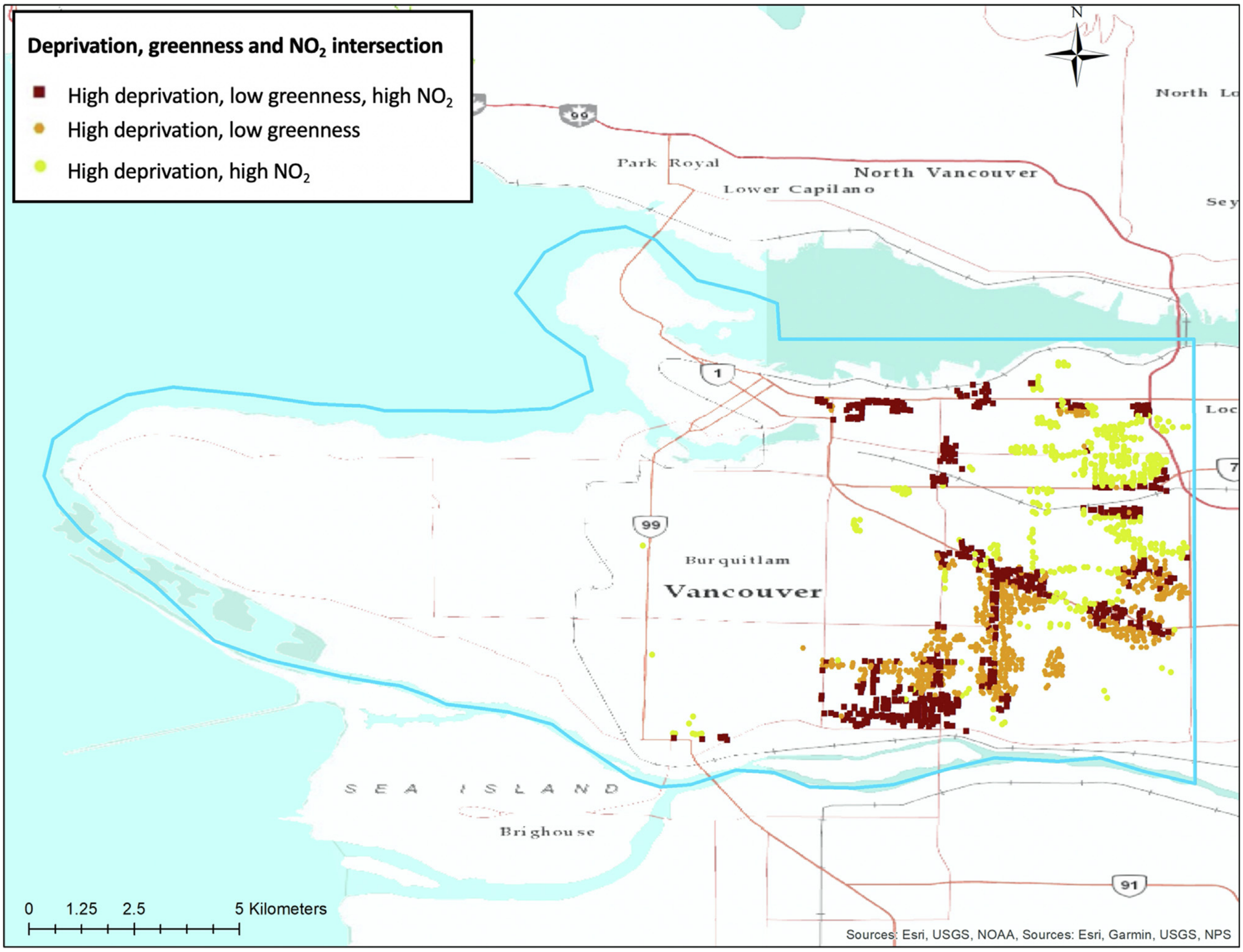

Fig. 6. Intersection between material deprivation, greenness and NO_2 in the city of Vancouver.

deprivation-index].

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.106003.

References

Anderson, J., Thundiyil, J., Stolbach, A., 2012. Clearing the air: A review of the effects of particulate matter air pollution on human health. J. Med. Toxicol. 8, 166–175.
Apte, J.S., Messier, K.P., Gani, S., Brauer, M., Kirchstetter, T.W., Lunden, M.M., Marshall, J.D., Portier, C.J., Vermeulen, R.C.H., Hamburg, S.P., 2017. High-resolution air pollution mapping with google street view cars: Exploiting big data. Environ. Sci. Technol. 51, 6999–7008.
Booth, G.L., Creatore, M.I., Moineddin, R., Gozdyra, P., Weyman, J.T., Matheson, F.I., Glazier, R.H., 2013. Unwalkable neighborhoods, poverty, and the risk of diabetes among recent immigrants to Canada compared with long-term residents. Diabetes Care 36, 302.
Brauer, M., Hystad, P., 2014. Commentary: Cities and health…Let me count the ways. Epidemiology 25, 526–527.
Brook, J.R., Setton, E.M., Seed, E., Shooshtari, M., Doiron, D., Awadalla, P., Brauer, M., Hu, H., McGrail, K., Stieb, D., Subarrao, P., Demers, P., Manuel, D., McLaughlin, J., Carlsten, C., Azad, M., Atkinson, S., Burnett, R., Lou, W., Rainham, D., Evans, G., Copes, R., Pantelimon, O., Smargiassi, A., Davies, H., Villeneuve, P., van den Bosch, M., Chaumont, D., Feddema, J., Takaro, T., Hakami, A., Johnson, M., Hatzopoulou, M., Habib, A., Fuller, D., Widener, M., 2018. The Canadian Urban Environmental Health Research Consortium – a protocol for building a national environmental exposure data platform for integrated analyses of urban form and health. BMC Public Health 18, 114.
Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. The Lancet 360, 1233–1242.
Cowie, C.T., Ding, D., Rolfe, M.I., Mayne, D.J., Jalaludin, B., Bauman, A., Morgan, G.G., 2016. Neighbourhood walkability, road density and socio-economic status in Sydney, Australia. Environ. Health 15.
Crouse, D.L., Goldberg, M.S., Ross, N.A., 2009. A prediction-based approach to modelling temporal and spatial variability of traffic-related air pollution in Montreal, Canada. Atmos. Environ. 43, 5075–5084.
Crouse, D.L., Pinault, L., Balram, A., Brauer, M., Burnett, R.T., Martin, R.V., van Donkelaar, A., Villeneuve, P.J., Weichenthal, S., 2019. Complex relationships between greenness, air pollution, and mortality in a population-based Canadian cohort. Environ. Int. 128, 292–300.
Crouse, D.L., Pinault, L., Balram, A., Hystad, P., Peters, P.A., Chen, H., van Donkelaar, A., Martin, R.V., Ménard, R., Robichaud, A., Villeneuve, P.J., 2017. Urban greenness and mortality in Canada's largest cities: a national cohort study. The Lancet Planetary Health 1, e289–e297.
Dadvand, P., Nieuwenhuijsen, M.J., Esnaola, M., Forns, J., Basagaña, X., Alvarez-Pedrerol, M., Rivas, I., López-Vicente, M., De Castro Pascual, M., Su, J., Jerrett, M., Querol, X., Sunyer, J., 2015. Green spaces and cognitive development in primary schoolchildren. Proc. Natl. Acad. Sci. 112, 7937–7942.
de Keijzer, C., Agis, D., Ambrós, A., Arévalo, G., Baldasano, J.M., Bande, S., Barrera-Gómez, J., Benach, J., Cirach, M., Dadvand, P., Ghigo, S., Martinez-Solanas, È., Nieuwenhuijsen, M., Cadum, E., Basagaña, X., 2017. The association of air pollution and greenness with mortality and life expectancy in Spain: A small-area study. Environ. Int. 99, 170–176.
DMTI Spatial Inc. CanMap Postal Code Suite v2015.3. Markham, Ontario: DMTI Spatial Inc.; 2015.
Doiron, D., de Hoogh, K., Probst-Hensch, N., Mbatchou, S., Eeftens, M., Cai, Y., Schindler, C., Fortier, I., Hodgson, S., Gaye, A., Stolk, R., Hansell, A., 2017. Residential air pollution and associations with wheeze and shortness of breath in adults: A combined analysis of cross-sectional data from two large European cohorts. Environ. Health Perspect. 125, 097025.
Doiron, D., Setton, E., Seed, E., Shooshtari, M., Brook, J., 2018.. The Canadian Urban Environmental Health Research Consortium (CANUE): a national data linkage

initiative. Int. J. Populat. Data Sci. 3.
Dummer, T.J.B., Awadalla, P., Boileau, C., Craig, C., Fortier, I., Goel, V., Hicks, J.M.T., Jacquemont, S., Knoppers, B.M., Le, N., McDonald, T., McLaughlin, J., Mes-Masson, A.-M., Nuyt, A.-M., Palmer, L.J., Parker, L., Purdue, M., Robson, P.J., Spinelli, J.J., Thompson, D., Vena, J., Zawati, M.N., 2018. The Canadian Partnership for Tomorrow Project: a pan-Canadian platform for research on chronic disease prevention. Can. Med. Assoc. J. 190, E710–E717.
European Space Agency. Copernicus Sentinel-5P releases first data, 2018.
Evans, G.W., Kantrowitz, E., 2002. Socioeconomic status and health: The potential role of environmental risk exposure. Annu. Rev. Public Health 23, 303–331.
Fong, K.C., Hart, J.E., James, P., 2018. A review of epidemiologic studies on greenness and health: Updated literature through 2017. Current Environ. Health Reports 5, 77–87.
Giles-Corti, B., Vernez-Moudon, A., Reis, R., Turrell, G., Dannenberg, A.L., Badland, H., Foster, S., Lowe, M., Sallis, J.F., Stevenson, M., Owen, N., 2016. City planning and population health: a global challenge. The Lancet 388, 2912–2924.
Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27.
Hajna, S., Dasgupta, K., Ross, A.N., 2018. Laboratory-assessed markers of cardiometabolic health and associations with GIS-based measures of active-living environments. Int. J. Environ. Res. Public Health 15.
Hankey, S., Marshall, J.D., 2017. Urban form, air pollution, and health. Current Environ. Health Reports 4, 491–503.
Herrmann, T., Gleckner, W., Wasfi, R.A., Thierry, B., Kestens, Y., Ross, N.A., 2019. A pan-Canadian measure of active living environments using open data. Health Rep. 30, 16–25.
Hystad, P., Davies, H.W., Frank, L., Van Loon, J., Gehring, U., Tamburic, L., Brauer, M., 2014. Residential greenness and birth outcomes: evaluating the influence of spatially correlated built-environment factors. Environ. Health Perspect. 122, 1095–1102.
Hystad, P., Setton, E., Cervantes, A., Poplawski, K., Deschenes, S., Brauer, M., van Donkelaar, A., Lamsal, L., Martin, R., Jerrett, M., Demers, P., 2011. Creating national air pollution models for population exposure assessment in Canada. Environ. Health Perspect. 119, 1123–1129.
James, P., Banay, R.F., Hart, J.E., Laden, F., 2015. A review of the health benefits of greenness. Current Epidemiol. Reports 2, 131–142.
Jerrett, M., Arain, A., Kanaroglou, P., Beckerman, B., Potoglou, D., Sahsuvaroglu, T., Morrison, J., Giovis, C., 2004. A review and evaluation of intraurban air pollution exposure models. J. Exposure Analy. Environ. Epidemiol. 15, 185.
Larkin, A., Hystad, P., 2019. Evaluating street view exposure measures of visible green space for health research. J. Eposure Sci. Environ. Epidemiol. 29, 447–456.
Levy, I., Mihele, C., Lu, G., Narayan, J., Brook Jeffrey, R., 2014. Evaluating multipollutant exposure and urban air quality: Pollutant interrelationships, neighborhood variability, and nitrogen dioxide as a proxy pollutant. Environ. Health Perspect. 122, 65–72.
Lipfert, F.W., 2004. Air pollution and poverty: Does the sword cut both ways? J. Epidemiol. Community Health 58, 2–3.
Marshall, J.D., Brauer, M., Frank, L.D., 2009. Healthy neighborhoods: Walkability and air pollution. Environ. Health Perspect. 117, 1752–1759.
McCormack, G.R., Shiell, A., 2011. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. Int. J. Behav. Nutrit. Phys. Activity 8, 125.
McMorris, O., Villeneuve, P.J., Su, J., Jerrett, M., 2015. Urban greenness and physical activity in a national survey of Canadians. Environ. Res. 137, 94–100.
Nieuwenhuijsen, M.J., 2016. Urban and transport planning, environmental exposures and health-new concepts, methods and tools to improve health in cities. Environ. Health 15, S38.
Nieuwenhuijsen, M.J., Khreis, H., Triguero-Mas, M., Gascon, M., Dadvand, P., 2017. Fifty shades of green: Pathway to healthy urban living. Epidemiology 28, 63–71.
Northridge, M.E., Sclar, E.D., Biswas, P., 2003. Sorting out the connections between the built environment and health: A conceptual framework for navigating pathways and planning healthy cities. J. Urban Health 80, 556–568.
Pampalon, R., Hamel, D., Gamache, P., Philibert, M.D., Raymond, G., Simpson, A., 2012. An area-based material and social deprivation index for public health in Québec and Canada. Can. J. Public Health / Revue Canadienne de Santé Publique 103, S17–S22.
Pinault, L., Crouse, D., Jerrett, M., Brauer, M., Tjepkema, M., 2016a. Socioeconomic differences in nitrogen dioxide ambient air pollution exposure among children in the three largest Canadian cities. Health Rep. 27, 3–9.
Pinault, L., Crouse, D., Jerrett, M., Brauer, M., Tjepkema, M., 2016b. Spatial associations between socioeconomic groups and NO2 air pollution exposure within three large Canadian cities. Environ. Res. 147, 373–382.
Pineo, H., Glonti, K., Rutter, H., Zimmermann, N., Wilkinson, P., Davies, M., 2018. Urban health indicator tools of the physical environment: A systematic review. J. Urban Health 95, 613–646.
Prairie Climate Centre. The Climate Atlas of Canada, version 2 (July 10, 2019). University of Winnipeg, 2019.
R Core Team. R: A language and environment for statistical computing. in: Computing R. F.F.S., ed. Vienna, Austria, 2019.
Raina, P.S., Wolfson, C., Kirkland, S.A., Griffith, L.E., Oremus, M., Patterson, C., Tuokko, H., Penning, M., Balion, C.M., Hogan, D., Wister, A., Payette, H., Shannon, H., Brazil, K., 2009. The Canadian Longitudinal Study on Aging (CLSA). Can. J. Aging / La Revue canadienne du vieillissement 28, 221–229.
Ross, N., Wasfi, R., Herrmann, T., Gleckner, W., 2018. Canadian Active Living Environments Database (Can-ALE) User Manual & Technical Document. In: Group G.-S.D.O.H.R., ed: Department of Geography, McGill University.
Rugel, E.J., Brauer, M., 2020. Quiet, clean, green, and active: A Navigation Guide systematic review of the impacts of spatially correlated urban exposures on a range of physical health outcomes. Environ. Res. 185, 109388.
Sacks, J.D., Stanek, L.W., Luben, T.J., Johns, D.O., Buckley, B.J., Brown, J.S., Ross, M., 2011. Particulate matter–induced health effects: Who is susceptible? Environ. Health Perspect. 119, 446–454.
Stafford, M., Duke-Williams, O., Shelton, N., 2008. Small area inequalities in health: Are we underestimating them? Soc. Sci. Med. 67, 891–899.
Statistics Canada, 2017. Population size and growth in Canada: Key results from the 2016 Census. The Daily.
Statistics Canada, 2019. Focus on Geography Series, 2016 Census. In: Canada S., ed.
Subbarao, P., Anand, S.S., Becker, A.B., Befus, A.D., Brauer, M., Brook, J.R., Denburg, J.A., HayGlass, K.T., Kobor, M.S., Kollmann, T.R., Kozyrskyj, A.L., Lou, W.Y.W., Mandhane, P.J., Miller, G.E., Moraes, T.J., Pare, P.D., Scott, J.A., Takaro, T.K., Turvey, S.E., Duncan, J.M., Lefebvre, D.L., Sears, M.R., 2015. The Canadian Healthy Infant Longitudinal Development (CHILD) Study: Examining developmental origins of allergy and asthma. Thorax 70, 998.
Tzivian, L., Jokisch, M., Winkler, A., Weimar, C., Hennig, F., Sugiri, D., Soppa, V.J., Dragano, N., Erbel, R., Jöckel, K.-H., Moebus, S., Hoffmann, B., 2017. Associations of long-term exposure to air pollution and road traffic noise with cognitive function—An analysis of effect measure modification. Environ. Int. 103, 30–38.
United Nations, 2018. World Urbanization Prospects 2018: Country Profiles. In: United Nations Department of Economic and Social Affairs P.D., ed.
United Nations, 2019. World Urbanization Prospects: The 2018 Revision. In: Department of Economic and Social Affairs P.D., ed. New York.
Vardoulakis, S., Dear, K., Wilkinson, P., 2016. Challenges and opportunities for urban environmental health and sustainability: The HEALTHY-POLIS initiative. Environ Health 15, S30.
Villeneuve, P.J., Jerrett, M., Su, G.J., Burnett, R.T., Chen, H., Wheeler, A.J., Goldberg, M.S., 2012. A cohort study relating urban green space with mortality in Ontario, Canada. Environ. Res. 115, 51–58.
Wang, R., Henderson, S.B., Sbihi, H., Allen, R.W., Brauer, M., 2013. Temporal stability of land use regression models for traffic-related air pollution. Atmos. Environ. 64, 312–319.
Wasfi, R.A., Dasgupta, K., Orpana, H., Ross, N.A., 2016. Neighborhood walkability and body mass index trajectories: Longitudinal study of Canadians. Am. J. Public Health 106, 934–940.
Weichenthal, S., Hatzopoulou, M., Brauer, M., 2019. A picture tells a thousand…exposures: Opportunities and challenges of deep learning image analyses in exposure science and environmental epidemiology. Environ. Int. 122, 3–10.
Weichenthal, S., Pinault, L.L., Burnett, R.T., 2017. Impact of oxidant gases on the relationship between outdoor fine particulate air pollution and nonaccidental, cardiovascular, and respiratory mortality. Sci. Rep. 7, 16401.
Ziter, C.D., Pedersen, E.J., Kucharik, C.J., Turner, M.G., 2019. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. Proc. Natl. Acad. Sci. 116, 7575.