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Residential Greenness and Birth Outcomes: Evaluating the Influence of Spatially Correlated Built-Environment Factors

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Abstract

Background: Half the world's population lives in urban areas. It is therefore important to identify characteristics of the built environment that are beneficial to human health. Urban greenness has been associated with improvements in a diverse range of health conditions, including birth outcomes; however, few studies have attempted to distinguish potential effects of greenness from those of other spatially correlated exposures related to the built environment.

Methods: We examined associations between residential greenness (measured using satellite-derived normalized difference vegetation index (NDVI) within 100 meters of study participants' homes) and birth outcomes in a cohort of 64,705 singleton births (from 1999–2002) in Vancouver, British Columbia, Canada. We also evaluated associations after adjusting for spatially correlated built environmental factors that may influence birth outcomes, including exposure to air pollution and noise, neighborhood walkability, and distance to the nearest park.

Results: An interquartile increase in greenness [0.1 in residential NDVI] was associated with higher term birth weight (20.6 grams; 95% CI: 16.5, 24.7) and decreases in the likelihood of small for gestational age, very preterm (<30 weeks), and moderately preterm (30-36 weeks) birth. Associations were robust to adjustment for air pollution and noise exposures, neighborhood walkability, and park proximity.

Conclusions: Increased residential greenness was associated with beneficial birth outcomes in this population-based cohort. These associations did not change after adjusting for other spatially correlated built environment factors, suggesting that alternative pathways (e.g. psychosocial and psychological mechanisms) may underlie associations between residential greenness and birth outcomes.

Introduction

More than half of the world's population now live in urban environments and it is estimated that by 2050 this number will grow to 60% (approximately 6.4 billion people) (WHO 2013). A diverse range of characteristics associated with living in urban environments – ranging from environmental hazards to social support to healthcare services – are important to health (Vlahov et al. 2007). Recently, a growing body of evidence has linked exposure to urban greenness (also referred to as natural environments) with measures of health, including mortality (Donovan et al. 2013; Mitchell and Popham 2008; Takano et al. 2002; Villeneuve et al. 2012), respiratory illness (Villeneuve et al. 2012), well-being (Groenewegen et al. 2006; Laforzezza et al. 2009; Maas et al. 2006) and mental health (Sugiyama et al. 2008; van den Berg et al. 2010; Ward Thompson et al. 2012).

Only a few studies have examined associations between exposure to residential greenness during pregnancy and birth outcomes. Adverse birth outcomes, such as preterm birth and low birth weight, are important not only because of their immediate impacts on infant health but also because of the subsequent health and developmental consequences through the individual's life course (Blumenshine et al. 2010). In Portland, Oregon a study of 5,295 births observed that a 10% increase in tree-canopy cover within 50 meters of a residence was associated with a significant decrease in small for gestational age (SGA) births (odds ratio (OR) = 0.85; 95% CI: 0.76, 0.94), with no association observed with preterm births (Donovan et al. 2011). A study of 2,393 births from four Spanish cohorts observed similar relationships (Dadvand et al. 2012a). An interquartile range (IQR) increase in average greenness (assessed using satellite-based Normalized Difference Vegetation index (NDVI)) within 500 meters of residences was associated with an increase in birth weight of 44.2 (95% CI: 20.2, 68.2) grams and an increase in

head circumference of 1.7 (95% CI: 0.5, 2.9) mm. No associations were observed with measures of gestational age. In another cohort of 8,246 births in Barcelona, Spain, NDVI within 100 meters of residences was not associated with birth weight or gestational age in the entire cohort, but in the group with the lowest educational attainment, increasing greenness was associated with higher birth weight (Dadvand et al. 2012b). Finally, for 3,203 births in Munich between 1996 and 1999, and IQR increase in greenness within 500 meters of residences was associated with a 17.6 (95% CI: 0.5, 34.6) gram higher mean birth weight (Markevych et al. 2014).

Given this suggestive evidence and the large potential burden accompanying adverse birth outcomes, it is important to evaluate the robustness of the association between greenness and pregnancy outcomes and the specific pathways through which potential effects may operate. In particular, there is a need to distinguish the effect of residential greenness from other spatially correlated built environment factors. Here we define built environment as urban design, land use, and the transportation system, encompassing patterns of human activity within the physical environment (Handy et al. 2002). There are four general pathways by which we hypothesize greenness may influence birth outcomes: 1) through the reduction of harmful environmental exposures such as air and noise pollution (e.g. Dadvand et al. 2012c); 2) by providing space for increased utilitarian and recreational physical activity (e.g. Sugiyama et al. 2008); 3) by providing a setting for psychosocial influences, such as increased social contacts and community belonging (e.g. Fan et al. 2011); and 4) through directly reducing psychological stress and depression (e.g. Ward Thompson et al. 2012). Here we focused on evaluating the pathways related to reductions of environmental exposures and increases in physical activity levels (pathways 1 and 2 above).

Reduction of air pollution and noise exposures may be a pathway by which residential greenness influences pregnancy outcomes, due in part to the potential spatial clustering of these exposures. Ambient air pollution can vary dramatically within urban areas (Jerrett et al. 2005) and higher exposure during pregnancy has been associated with low birth weight, preterm birth, small for gestational age, and intrauterine growth retardation (Brauer et al. 2008; Padula et al. 2012; Shah and Balkhair 2011; Sram et al. 2005). Increased exposure to air pollution among pregnant women has been associated with decreased residential greenness (Dadvand et al. 2012c). The only study to evaluate the effects of greenness after controlling for air pollution exposures was based on four Spanish birth cohorts study, which found that the effect size for greenness on birth weight was slightly attenuated (from 36.1 to 28.5 grams per IQR increase in NDVI) after the inclusion of nitrogen dioxide (NO₂) exposures (Dadvand et al. 2012a). No study has included noise exposure, which we (Gehring et al. 2013) and others (Knipschild et al. 1981; Schell 1981) have shown may be associated with preterm birth and birth weight. Whether noise and residential greenness levels are spatially correlated is unknown.

Physical activity is another important pathway through which residential greenness may influence birth outcomes (Hegaard et al. 2007). While proximity to green space as an indicator of physical activity resources and activity levels has been widely used in the literature (e.g. Kaczynski and Henderson 2007), more generalized measures of the built environment (referred to as walkability here) are increasingly found to predict levels of physical activity and are suggested to be an important upstream determinant of behavior (e.g. Durand et al. 2011). Walkability is a composite index of the built environment that is associated with physical activity (Frank et al. 2010) and may also be associated with residential greenness levels.

Here we use a large population based birth-cohort of 64,705 singleton births (from 1999–2002) in Vancouver, British Columbia, Canada, to examine associations between residential greenness and birth outcomes. We also evaluate the extent to which these associations may be mediated by additional spatially correlated factors related to the built environment (air pollution, noise, walkability of residential neighborhoods and access to parks) to help elucidate potential pathways of influence.

Methods

Description of cohort

Linked administrative data were used to establish a birth cohort that comprised all births from 1999–2002 in metropolitan area of Vancouver, British Columbia, Canada (Brauer et al. 2008). Medical services and hospitalization data were provided by the British Columbia (BC) Ministry of Health (2009a,b); vital statistics data (BC Vital Statistics 2009) by the British Columbia Vital Statistics Agency (2009); and perinatal data by the British Columbia Reproductive Care Program (2009). A total of 82,347 births were identified over the four years (1999–2002) and 73,387 had mothers with verified complete residential history information within the study area during the nine months of pregnancy. We excluded 988 multiple births, seven children without recorded birth weight or parity status, 2,014 births to women with missing maternal age, 1,593 children with missing first nations status (ethnicity), and 1,197 who were missing specific census covariates. The cohort was therefore reduced to 68,249 births that had complete covariate information, of which we were able to assign measures of greenness, air pollution, noise pollution and neighborhood walkability for 64,705 births. The study protocol was approved by the Institutional Review Board (Behavioural Research Ethics Board) of the University of British Columbia (#H04-80161). The British Columbia Ministry of Health, Vital Statistics and Perinatal

Services BC approved access to and use of the data facilitate by Population Data BC for this study.

Birth outcomes

All birth outcomes were obtained through vital statistics birth records. We evaluated multiple measures of gestational age: very preterm birth (< 30 weeks of gestation) and moderately preterm birth (30–36 weeks of gestation) versus term birth (\geq 37 weeks of gestation). We examine both very and moderate preterm birth separately to allow focus on the very preterm component which is of greater clinical relevance. We also evaluated term (\geq 37 weeks of gestation) birth weight and fetal growth (SGA, defined as birth weights below the 10th percentile within the study cohort, stratified by sex, for each week of gestation).

Covariates

Individual-level covariates obtained through administrative records included the month and year of birth, sex of the baby, First Nations status, as well as parity, maternal age and maternal smoking during pregnancy. No individual-level data were available for income or maternal level of education. We assigned subjects to neighborhood-level income quintiles and maternal education quartiles using Census data based on their residence at time of birth. Census dissemination area (DA) level data were used, which are the smallest geographic areas for which all Canadian Census data are provided and correspond to one or more neighboring blocks with target populations of 400–700 persons.

Exposure assessments

Exposure to residential greenness, air pollution, noise, neighborhood walkability and distance to parks were estimated for all residences where mothers lived during the nine month pregnancy

period, geocoded to 6-digit postal codes. Due to the high correlations ($r>0.95$) between greenness exposure during specific trimesters/months of pregnancy, we calculated an average exposure across the full period of pregnancy that incorporated time-weighted exposures from each residential address.

Residential greenness

We used satellite-derived NDVI to derive a continuous measure of greenness across the study region. NDVI ranges from -1 to 1 (with higher numbers indicating more greenness) based on land surface reflectance of visible (red) and near infrared parts of spectrum (Weier and Herring 2011). To assign greenness measures to study postal codes, all cloud-free images from Landsat Enhanced Thematic Mapper Plus (ETM+) of the Vancouver region were downloaded from 1999–2002. Average greenness values were extracted for 100 and 250 meter areas around residential postal code centroids and both yearly and seasonal (summer [June to August], fall [September to November], winter [December to February] and spring [March to May] greenness values were calculated. We did not assign the 30 meter NDVI values to each residential postal code as postal codes typically reflect one side of a city block and this area is better captured with a 100 meter buffer distance. The 30 meter NDVI was highly correlated with the 100 ($r=0.80$) and 250 ($r=0.69$) meter NDVI measures. The seasonal measures were also highly correlated ($r>0.94$) with the annual measures and we therefore present only the annual average NDVI results. While there were slight differences in the actual NDVI mean values by season [0.17 (winter) to 0.29 (summer)], the spatial pattern of NDVI did not change, which therefore resulted in a high correlation with seasonal values. The 100 and 250 meter buffer areas were used to assign residential greenness exposure as these distances have been used in prior studies (Dadvand et al. 2012a, 2012b), are at a similar spatial scale to within-city air pollution and noise

variation, and have been shown to correspond to expert assessments of residential greenness from detailed visual audits (Rhew et al. 2011).

Air pollution exposure

Residential air pollution exposure was assessed using high resolution land use regression (LUR) air pollution models developed for the Vancouver metropolitan area for nitric oxide (NO), nitrogen dioxide (NO₂), fine particulate matter (PM_{2.5}), and black carbon (BC). The creation and evaluation of the models has been described previously (Brauer et al. 2008; Henderson et al. 2007; Larson et al. 2009) and such models have been used to examine associations with pregnancy outcomes (Brauer et al. 2008). For the present analysis we estimated air pollution exposures based on LUR models to capture fine-scale spatial variation in air pollution throughout the study region (which may be spatially correlated with greenness levels), rather than interpolation of fixed-site air pollution monitoring data.

Noise exposure

Residential noise exposure was estimated using CadnaA software, a physical model with a focus on transportation-related sources. The creation and evaluation of this model has been described previously (Gan et al. 2012) and used in our previous assessment of noise, air pollution and pregnancy outcomes (Gehring et al., 2013). Briefly, noise exposure was based on transportation-related information, including road traffic data (e.g., speed limits, traffic volume, fleet composition, and road width), railway data (e.g., type of train, velocity, and frequency) and building heights and footprints. Aircraft noise data were obtained from aircraft noise exposure forecasts produced by Vancouver International Airport Authority. Noise level estimates were created from these data that integrated noise levels during the day, evening, and nights using

average A-weighted equivalent continuous noise levels (24 hour averages) with evening and night exposures penalized by 5 and 10 dBA, respectively (“L_{DEN}” described previously by Gan et al. (2012)). Here we examined road traffic noise exposures (motor vehicle noise) as well as all transportation noise (including motor vehicle, railway and aircraft sources).

Neighborhood walkability

A walkability index was used to assess built environment characteristics around residential postal codes that may influence opportunities for physical activity. A detailed description of the methods used to develop the walkability index has been described previously (Frank et al. 2010) as well as associations between walkability and objectively-measured physical activity levels (Frank et al. 2005). Briefly, the walkability index captured four measures of neighborhood walkability (residential density, retail floor space-to-land area ratio, land use mix, and street connectivity or intersection density) within a one kilometer road network distance around a postal code centroid. High levels of the walkability index represent urban form that encourages walking while low levels represent built environment features that inhibit walking. In addition to the walkability index, straight line distance to the border of the nearest park was calculated to capture additional potential influences on leisure physical activity opportunities.

Statistical analysis

Logistic and linear regression analyses were used to estimate associations between residential greenness and birth outcomes. Adjusted analyses included the individual covariates (month and year of birth, sex of the baby, First Nations status (yes/no), parity (yes/no), maternal age (≤ 19 , 20-29, 30-34, 35-40, ≥ 40 years) and maternal smoking during pregnancy (yes/no)) as well as census covariates (maternal education quartiles and income quintiles) described previously. For

the term birth weight analyses, a categorical variable for the completed weeks of gestation (range: 22–43) was also included. Associations between greenness exposures and birth outcomes are presented corresponding to both an approximate IQR increase in exposure measures and by quartiles, since cubic regression splines (gam-function, The R Project for Statistical Computing 2.15.0) identified slightly non-linear relationships. Incremental models are presented to evaluate how association between residential greenness and birth outcomes change when air pollution and noise exposures, neighborhood walkability, and park distance are added. A number of sensitivity analyses were also conducted to determine how associations between residential greenness and birth outcomes changed based on residential mobility during pregnancy, when area contextual factors at the DA level (i.e. low income status, unemployment rate, marital status, family composition variables, building characteristic variables, and visible minority status) were entered into the models, and when models were stratified by area income, education and visible minority status. Visible minority status is defined as persons, other than Aboriginal peoples, who are non-Caucasian in race or non-white in color.

Results

Descriptive statistics of the overall cohort with complete covariate and exposure information (n=64,705), as well as participants stratified by NDVI quartiles, are summarized in Table 1. A total of 230 births (0.4%) were very preterm (<30 weeks of gestation), 3,189 births (5.0%) were moderately preterm (30–36 weeks), 6,817 births (10.5%) were classified as SGA, and the mean birth weight at full term was 3,483 grams. Small differences in birth outcomes as well as individual covariate information can be seen by residential greenness quartiles.

Table 2 summarizes the distribution of residential greenness exposures as well as other built environment exposure variables. The mean annual residential greenness value (using the NDVI)

was 0.24. The spatial distributions of NDVI values for the study area are shown in Figure 1. The correlations between residential greenness exposure and other spatially derived exposure variables are presented in the Supplemental Material, Table S1. Low to moderately negative correlations were observed between average NDVI levels within 100 meters of residences and NO (-0.43), NO₂ (-0.42), PM_{2.5} (-0.36) and BC (-0.31) exposures, traffic (-0.05) and all noise (-0.20) exposures, and neighborhood walkability (-0.58) and distance to the nearest park (-0.05). Figure 2 illustrates the spatial distributions of the study population as well as NO₂ air pollution concentrations, all noise levels, and neighborhood walkability and parks. For reference, the PM_{2.5} exposure map is shown in the Supplemental Material, Figure S1. The spatial autocorrelation of these exposure variables within the study area were measured by the Global Moran's I spatial statistic (ESRI ArcGIS 10.1; inverse distance spatial weights matrix and 1 km threshold distance). The resulting spatial autocorrelation for exposure variables were: NDVI (I=2.81), NO (I=0.06), NO₂ (I=0.04), PM_{2.5} (I=0.03) and BC (I=0.03), neighborhood walkability (I=0.92), park proximity (I=0.38), road traffic noise (I=0.47) and all transportation noise (I=0.48). These spatial autocorrelation measures were sensitive to the spatial weights and distance thresholds used, with increasing autocorrelation generally seen for larger distances (data not shown).

The associations between residential greenness and other built environment exposure measures and birth outcomes are shown in Table 3. These estimates represent each variable entered into separate models (i.e. not mutually adjusted exposure models). For an IQR increase (0.1) in NDVI, the OR for very preterm birth was 0.91 (95% CI: 0.77, 1.07), for moderately preterm birth was 0.95 (95% CI: 0.91, 0.99) and for SGA was 0.97 (95% CI: 0.94, 1.00). Term birth weight was 20.6 grams (95% CI: 16.5, 24.7 grams) higher on average with each 0.1 increase in NDVI. When comparing individuals with the highest quartile of NDVI values (>0.29) compared

with the lowest (<0.18) the ORs for very and moderately preterm birth and small for gestational age were 0.80 (95% CI: 0.55, 1.18), 0.87 (95% CI: 0.79, 0.96) and 0.95 (95% CI: 0.88, 1.03), respectively. Term birth weight was also 44.6 (95% CI: 34.8, 54.4) grams higher for the highest NDVI quartile compared with the lowest. As previously reported, air pollution was associated with very preterm birth and noise and air pollution with SGA and term birth weight (Brauer et al. 2008; Gehring et al. 2014). Higher levels of neighborhood walkability were associated with adverse birth outcomes, a finding that may reflect the positive correlation between walkability and air pollution exposures previously reported for the metropolitan Vancouver area (Marshall et al. 2009).

Incremental models were used to examine how the associations between residential greenness and birth outcomes changed with the inclusion of the other built environment exposure variables. Figure 3 illustrates that the inclusion of individual and area SES indicators attenuated the associations of residential greenness with moderately preterm birth, SGA and term birth weight, while the inclusion of air pollution, noise, walkability and park distance had relatively little influence. Individual and area SES indicators were entered first to control for potential confounding factors. The order that environmental variables were entered into the model did not change observed associations. In the fully adjusted model that included all built environment exposure variables, an IQR increase (0.1) in NDVI was associated with ORs for very preterm birth, moderate preterm birth, and small for gestational age of 0.91 (95% CI: 0.74, 1.13), 0.95 (95% CI: 0.90, 1.00), and 0.95 (95% CI: 0.91, 0.99), respectively, and term birth weight was 19.5 (95% CI: 14.1, 24.9) grams higher on average. An illustration of how individual coefficients for environmental variables and birth weight changed during adjustments is shown in Supplemental Material, Table S2. In general, the associations between air pollution,

neighborhood walkability and park distance with birth weight largely disappeared with the inclusion of greenness exposures, while the effects of noise exposures were reduced by approximately 50%. In a fully adjusted model including all built environment exposure variables, associations with birth weight other than greenness were highly variable. This may be due to multicollinearity. In particular, the two noise exposure variables are highly correlated ($r=0.92$) and the individual variable coefficients are therefore difficult to interpret. Similar patterns were seen for preterm birth, moderate preterm birth, and small for gestational age (data not shown).

Smooth exposure-response curves for residential greenness and birth outcomes from the unadjusted, adjusted and fully adjusted models (including other built environment variables) are shown in Supplemental Material, Figure S2. For all outcomes there is a statistically significant non-linear relationship ($p<0.01$ for linear versus non-linear spline function) with an inflection point occurring around the NDVI value of 0.15, after which the influence of residential greenness on birth outcomes becomes positive and linear. A map of NDVI values above and below this threshold is shown in Supplemental Material, Figure S3.

Sensitivity analyses

In this birth cohort, 36.9% of women moved during their pregnancy. We found little difference in residential mobility between women currently living in the lowest area income quintile who moved (36.9% of women) compared to women currently living in the highest income quintile who moved (37.3%). When the fully adjusted models were stratified by moving status, only slight differences were observed between movers and non-movers (data not shown). For example, in movers a 0.1 increase in NDVI was associated with an increase in term birth weight of 20.1 grams (95% CI: 12.3, 28.0), compared to 21.9 grams (95% CI: 17.0, 26.7) for non-movers.

In place of detailed individual characteristics, we also explored a number of additional area-level variables (e.g. low income status, unemployment rate, marital status, family composition variables, building characteristic variables, and visible minority status) to determine their influence on associations between greenness and birth outcomes. Associations were robust to inclusion of all area-level variables except for those related to the proportion of visible minorities, which attenuated results, primarily for term birth weight (data not shown). For example, including percent Chinese or percent South Asian ethnicity by DA areas (the two most prominent visible minority groups in the study area, who also have lower birth weight (Janssen et al. 2007)) reduced the association between NDVI and term birth weight from 20.6 grams (95% CI: 16.5, 24.7) to 14.0 grams (95% CI: 9.4, 18.6) per 0.1 increase in NDVI. These results need to be interpreted with caution however since visible minority groups were clustered within the study region, and these variables may act as a proxy for geographic area. This may therefore underestimate the true effects of residential greenness due to reductions in the spatial contrast and variation of exposures. In addition, while Chinese and South Asian babies have similarly lower normal birth weights compared to the general population in this study area (Janssen et al. 2007), we found that the above attenuation was driven by the Chinese classification and inclusion of only the South Asian classification increased the strength of associations between NDVI and birth weight (data not shown).

Models stratified by area income, education and percent Chinese or percent South Asian were explored to further examine potential spatial and residual confounding (Supplemental Material, Table S4). Associations were slightly stronger in the highest income quintile, especially for term birth weight where a 0.1 increase in NDVI was associated with a 32.4 gram (95% CI: 20.3, 44.5)

higher average birth weight. However when stratified by area-level education and visible minority status no clear gradients for any birth outcome were observed.

Discussion

We found that increased greenness within 100 meters of residences measured using satellite-derived NDVI was associated with higher term birth weight and with reduced likelihood of very (<30 weeks) and moderately (30–36 weeks) preterm births and SGA. These associations were robust to adjustment for air pollution and noise exposures, the walkability of residential neighborhoods, and distance to the nearest park. This suggests that the association between greenness and birth outcomes is independent of these spatially varying exposures related to the built environment and that alternative pathways may link residential greenness to birth outcomes.

Our results are consistent with those of the small number of studies that have examined residential greenness and birth outcomes. Re-calculated for the NDVI increment of 0.1 used in our study, the study of four Spanish cohorts estimated that birth weight was 22.3 grams higher in association with a 0.1 unit increase in average NDVI within 100 meters (Dadvand et al. 2012a), which is very similar to the estimated effect for our study population. Adjusting for NO₂ air pollution exposures in the Spanish study reduced the magnitude of the association with NDVI within 100 meters by 21 percent to 17.7 grams. In the cohort study of 3,203 births in Munich, the strongest association was observed for NDVI within 500 meters. For NDVI within 100 meters (the metric used in our study), adjusting for NO₂ exposure increased the estimated difference in birth weight from 12.2 grams to 16.2 grams (Markevych et al. 2014). Adjustment for PM_{2.5} and proximity to major roads also increased the magnitude of effect estimates for NDVI, while adjusting for noise attenuated the NDVI and birth weight association by 56 percent. There were differences in associations estimated for NDVI within 100, 250, 500 and 800 meter buffer areas

in the Munich study, especially once adjusted for air pollution and noise exposures. In our study, we observed no appreciable attenuation of NDVI with adjustment for air pollution, noise, neighborhood walkability, and the distance to the nearest park. In the cohort study of 8,246 births in Barcelona, Spain, NDVI within 100 meters of homes was only associated with birth weight among the lowest education group (Dadvand et al. 2012c). We did not observe differences between greenness levels within area-level income or education categories (Supplemental Material, Table S3). The study of 5,295 births in Portland, Oregon used a different metric of greenness exposure (measured using tree-canopy cover within 50 meters of homes), and estimated an OR for SGA of 0.85 (95% CI: 0.76, 0.94) in association with a 10% increase in tree-canopy cover within 50 meters (Donovan et al. 2011). While not directly comparable to our NDVI greenness exposure assessment, our results support these findings. In our study we also observed inflection points for all birth outcomes at an approximate NDVI value of 0.15 in smoothed exposure-response plots, above which most of the associations between greenness and all birth outcomes were observed. If this relationship can be replicated, it suggests that a certain amount of greenness is required before benefits to birth outcomes (and potentially other health outcomes) are observed. No studies are available to compare with this finding.

The fact that residential greenness exposure remained associated with birth outcomes after adjusting for a number of hypothesized environmental exposures suggests that alternative pathways may link greenness exposure to birth outcomes. Two well hypothesized pathways that were not examined in this study include psychosocial and psychological influences. Greenness may facilitate positive psychosocial influences by providing shared spaces for interactions. For example, exposure to greenness has been associated with social support (Maas et al. 2009) and increased social ties and community belonging (Kweon et al. 1998; Sugiyama et al. 2008). The

psycho-evolutionary model proposed by Ulrich (1983) also suggests a direct biological impact of perceiving the natural environment. For example, exposure to greenness has been associated with reduced blood pressure (Hartig et al. 2003) and heart rate (Ulrich et al. 1991) and with changes in salivary cortisol patterns (Ward Thompson et al. 2012). While we were unable to examine these pathways, our findings of a persistent greenness association with birth outcomes that was independent of previously observed associations with noise and air pollution suggests more research is required that includes all potential pathways potentially linking greenness to birth outcomes.

A major strength of our analysis is that, unlike previous studies, we were able to estimate associations between residential greenness and birth outcomes after adjusting for a number of spatially correlated built environment variables. However, our ability to utilize a large population-based cohort derived from administrative data also incorporates inherent limitations related to the lack of individual covariates. While a number of individual-variables were available in these databases, no information was available for individual-level SES (although smoking during pregnancy and maternal age are useful surrogate measures, especially for the lower portion of the SES gradient (BC Ministry of Health, 2011) and other determinants of birth outcomes (e.g. maternal diabetes)). We used the smallest scale of census data available to account for area-level maternal education and income, which attenuated the association between greenness and birth outcomes. Further spatial confounding may be present within the census DA (i.e. correlation between greenness and individual income or education); however, given the fine-scale resolution of the DA census boundary (mean size=0.4 km²) this is unlikely. There was a correlation of -0.30 between residential greenness and percentage of visible minorities, suggesting that spatial confounding may be an issue; although stratified analyses by visible

minority quartiles showed no obvious trend and the largest associations were generally seen for the lowest visible minority quartile. While the NDVI measure enabled us to quantify small-scale variations in greenness in a standardized and objective measure, NDVI does not distinguish between different types of vegetation (e.g. trees or grass fields), quality of greenness, or actual exposure to greenness, which may be important depending on the theorized pathways linking greenness to birth outcomes. In addition, the other built environment exposure variables were modeled at different spatial resolutions, which may incorporate differential exposure misclassification. Only residential history during pregnancy was available to assess NDVI, and nine months represents a relatively short exposure-period unless women had lived at their current residential address for longer periods of time. We did not have information on prior residential duration but we examined residential mobility during pregnancy and found no change in our results. Long-term residential mobility remains a concern if individuals choose to live in neighborhoods based on characteristics that may influence birth outcomes and that are also related to residential greenness.

Conclusions

Residential greenness represents a unique (and potentially modifiable) exposure construct that may be important to health. We determined that increased residential greenness is associated with positive birth outcomes in a population birth cohort in Vancouver, British Columbia Canada and that this association persists after adjusting for exposures to air pollution, noise, residential neighborhood walkability and park proximity. Further research is needed to evaluate the specific pathways that may link residential greenness exposure to birth outcomes, including other built environment features as well as psychosocial and psychological pathways.

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Table 1. Characteristics of the Vancouver metropolitan area birth-cohort [n (%) or mean \pm SD] with complete data for greenness and built environment exposures, overall (N=64,705) and according to NDVI quartiles.

Variable	Entire cohort	NDVI Q1 (<0.18)	NDVI Q2 (0.18-0.23)	NDVI Q3 (0.23-0.29)	NDVI Q4 (\geq 0.29)
Study population (n)	64,705	15,316	13,773	18,120	17,466
Birth outcomes					
Very preterm birth (< 30 weeks), n (%)	230 (0.4%)	61 (0.4%)	57 (0.4%)	63 (0.4%)	53 (0.3%)
Moderately preterm birth (30-36 weeks), n (%)	3,189 (5.0%)	824 (5.4%)	715 (5.2%)	892 (4.9%)	758 (4.4%)
Small for gestational age ^a , n (%)	6,817 (10.5%)	1,719 (11.2%)	1,572 (11.4%)	1,885 (10.4%)	1,641 (9.4%)
Birth weight (g) at full term ^b , mean (sd)	3,483 (472)	3,440 (464)	3,456 (468)	3,491 (473)	3,532 (476)
Covariates					
Female sex, n (%)	31,341 (48.4%)	7,494 (48.9%)	6,657 (48.3%)	8,707 (48.0%)	8,483 (48.6%)
Nulliparous, n (%)	29,339 (45.3%)	8,006 (52.3%)	6,499 (47.2%)	7,926 (43.7%)	6,878 (39.4%)
Maternal age, n (%)					
≤ 19 years	957 (1.5%)	235 (1.5%)	189 (1.4%)	289 (1.6%)	244 (1.4%)
20-29 years	23,760 (36.7%)	5,623 (36.7%)	5,213 (37.9%)	6,910 (38.1%)	6,014 (34.4%)
30-34 years	23,981 (37.1%)	5,698 (37.2%)	5,013 (36.4%)	6,734 (37.1%)	6,536 (37.4%)
35-40 years	13,383 (20.7%)	3,111 (20.3%)	2,815 (20.4%)	3,540 (19.5%)	3,917 (22.4%)
≥ 40 years	2,624 (4.1%)	649 (4.2%)	543 (3.9%)	677 (3.7%)	755 (4.3%)
Maternal smoking during pregnancy, n (%)	4,184 (6.5%)	909 (5.9%)	742 (5.4%)	1,213 (6.7%)	1,320 (7.6%)
First Nations status, n (%)	395 (0.6%)	146 (1.0%)	82 (0.5%)	85 (0.4%)	95 (0.5%)
Maternal education (quartile-census), n (%)					
1 st quartile (lowest education)	14,412 (22.3%)	3,568 (23.3%)	3,298 (24.0%)	4,332 (23.9%)	2,809 (18.2%)
2 nd quartile	14,654 (22.7%)	3,149 (20.6%)	3,336 (24.2%)	4,208 (23.2%)	3,402 (22.0%)
3 rd quartile	17,669 (27.3%)	3,690 (24.1%)	3,815 (27.7%)	5,152 (28.4%)	4,450 (28.8%)
4 th quartile (highest education)	17,970 (27.8%)	4,909 (32.1%)	3,324 (24.1%)	4,458 (24.6%)	4,772 (30.9%)
Income (quintile-census), n (%)					
1 st quintile (lowest income)	13,815 (21.4%)	5,823 (38.0%)	3,603 (26.2%)	2,929 (16.2%)	1,450 (8.3%)
2 nd quintile	14,377 (22.2%)	3,791 (24.8%)	3,597 (26.1%)	4,092 (22.6%)	2,897 (16.6%)
3 rd quintile	13,666 (21.2%)	2,413 (15.8%)	3,012 (21.9%)	4,326 (23.8%)	3,915 (22.4%)
4 th quintile	12,524 (19.4%)	1,753 (11.5%)	2,095 (15.2%)	4,086 (22.5%)	4,590 (26.3%)
5 th quintile (highest income)	10,323 (16.0%)	1,536 (10.0%)	1,466 (10.6%)	2,707 (14.9%)	4,614 (26.4%)
Change of address during pregnancy, n (%)	21,990 (34.0%)	5,129 (33.5%)	5,649 (41.0%)	6,685 (36.8%)	4,389 (28.4%)

^aBirth weight below the 10th percentile of the cohort, stratified by sex, for each week of gestation. ^b \geq 37 weeks of gestation, N = 61,286.

Table 2. Summary of residential greenness and other spatially derived environmental exposure variables for the birth cohort (N=64,705).

Exposure	Mean ± SD	Min	P25	P50	P75	Max
Greenness						
NDVI Index	0.24 ± 0.08	-0.08	0.18	0.24	0.28	0.59
Air pollution						
NO – LUR [$\mu\text{g}/\text{m}^3$]	31.5 ± 3.8	1.4	22.5	28.3	37.2	149.6
NO ₂ – LUR [$\mu\text{g}/\text{m}^3$]	33.7 ± 9.1	0.0	27.4	31.9	36.9	64.5
PM _{2.5} – LUR [$\mu\text{g}/\text{m}^3$]	4.1 ± 1.7	0.0	3.2	4.0	4.7	11.3
BC ^a – LUR [10^{-5} m^{-1}]	1.6 ± 1.2	0.0	0.9	1.0	2.0	5.4
Noise						
Traffic noise [dB(A)]	60.2 ± 5.3	6.2	57.0	59.9	63.1	89.0
All noise [dB(A)]	61.6 ± 5.2	6.2	58.5	61.1	64.5	94.7
Neighborhood walkability						
Walkability index	0.37 ± 3.07	-7.80	-1.80	-0.40	2.55	13.20
Park distance [m]	422 ± 383	1	200	325	525	5850

^aBlack carbon, based on the particle light absorption coefficient. Highly correlated with the concentrations of elemental carbon measured by traditional thermal/optical reflectance. ($R^2 = 0.7\text{--}0.8$); $10^{-5}/\text{m}$ black carbon is approximately equivalent to $0.8 \mu\text{g}/\text{m}^3$ elemental carbon (Rich 2002).

Table 3. Odds ratios for preterm birth and small for gestational age, and average difference in birth weight (with 95% CI) based on separate models of associations with greenness and other spatially derived built environment exposure variables.

Exposure	Very preterm birth (< 30 weeks) OR (95% CI)	Moderately preterm birth (30-36 weeks) OR (95% CI)	Small for gestational age OR (95% CI)	Term birth weight β (95% CI)
Greenness, NDVI 100 m				
Per 0.1 unit	0.91 (0.77, 1.07)	0.95 (0.91, 0.99)	0.97 (0.94, 1.00)	20.6 (16.5, 24.7)
Q1 (< 0.18)	1	1	1	0
Q2 (0.18-0.23)	0.94 (0.66, 1.33)	0.95 (0.86, 1.05)	1.06 (0.99, 1.13)	3.2 (-6.2, 12.7)
Q3 (0.24-0.28)	0.85 (0.59, 1.24)	0.95 (0.86, 1.06)	1.01 (0.94, 1.08)	19.2 (9.4, 29.0)
Q4 (≥ 0.29)	0.80 (0.55, 1.18)	0.87 (0.78, 0.96)	0.95 (0.88, 1.03)	44.6 (34.8, 54.4)
Air pollution				
NO – LUR, per 10 $\mu\text{g}/\text{m}^3$	1.00 (0.91, 1.11)	1.01 (0.99, 1.04)	1.02 (1.00, 1.04)	-6.5 (-9.1, -3.9)
NO ₂ – LUR, per 10 $\mu\text{g}/\text{m}^3$	1.05 (0.91, 1.22)	1.02 (0.98, 1.06)	0.98 (0.96, 1.01)	-5.2 (-9.1, -1.4)
PM _{2.5} – LUR, per 1 $\mu\text{g}/\text{m}^3$	1.07 (1.00, 1.15)	1.01 (0.99, 1.03)	1.01 (0.99, 1.02)	-3.1 (-5.1, -1.1)
BC – LUR, per 10 ⁻⁵ part./m	0.97 (0.87, 1.08)	1.00 (0.98, 1.03)	1.02 (1.00, 1.04)	-3.4 (-6.2, -0.6)
Noise				
All noise, per 6 dB(A)	1.00 (0.86, 1.16)	1.03 (0.99, 1.07)	1.10 (1.06, 1.13)	-19.1 (-22.9, -15.3)
Traffic noise, per 6 dB(A)	0.97 (0.84, 1.12)	1.02 (0.98, 1.06)	1.09 (1.06, 1.12)	-16.8 (-20.5, -13.1)
Neighborhood walkability				
Walkability index, per 4 units	1.06 (0.89, 1.27)	1.04 (1.00, 1.09)	1.00 (0.96, 1.03)	-12.6 (-17.2, -8.0)
Distance to park, per 300 m	1.01 (0.91, 1.12)	0.97 (0.94, 1.00)	0.97 (0.95, 0.99)	5.3 (2.7, 7.9)

Adjusted for sex, parity, First Nations status, maternal age, maternal smoking during pregnancy, maternal education, income, year and month of birth; term birth weight was additionally adjusted for completed weeks of gestation.

Figure legends

Figure 1. Spatial distribution of greenness for the study cohort measured with satellite-derived normalized difference vegetation index (NDVI).

Figure 2. Spatial distribution of study population and annual NO₂ air pollution concentrations, all noise levels and neighborhood walkability and park locations.

Figure 3. Incremental models of exposure to residential greenness and birth outcomes (note changing scale of y-axis). Models including individual and area SES (3rd bar) are those shown in Table 3. Models at the far right are fully adjusted models including individual covariates, area SES measures and all built environment exposures.

Figure 1.

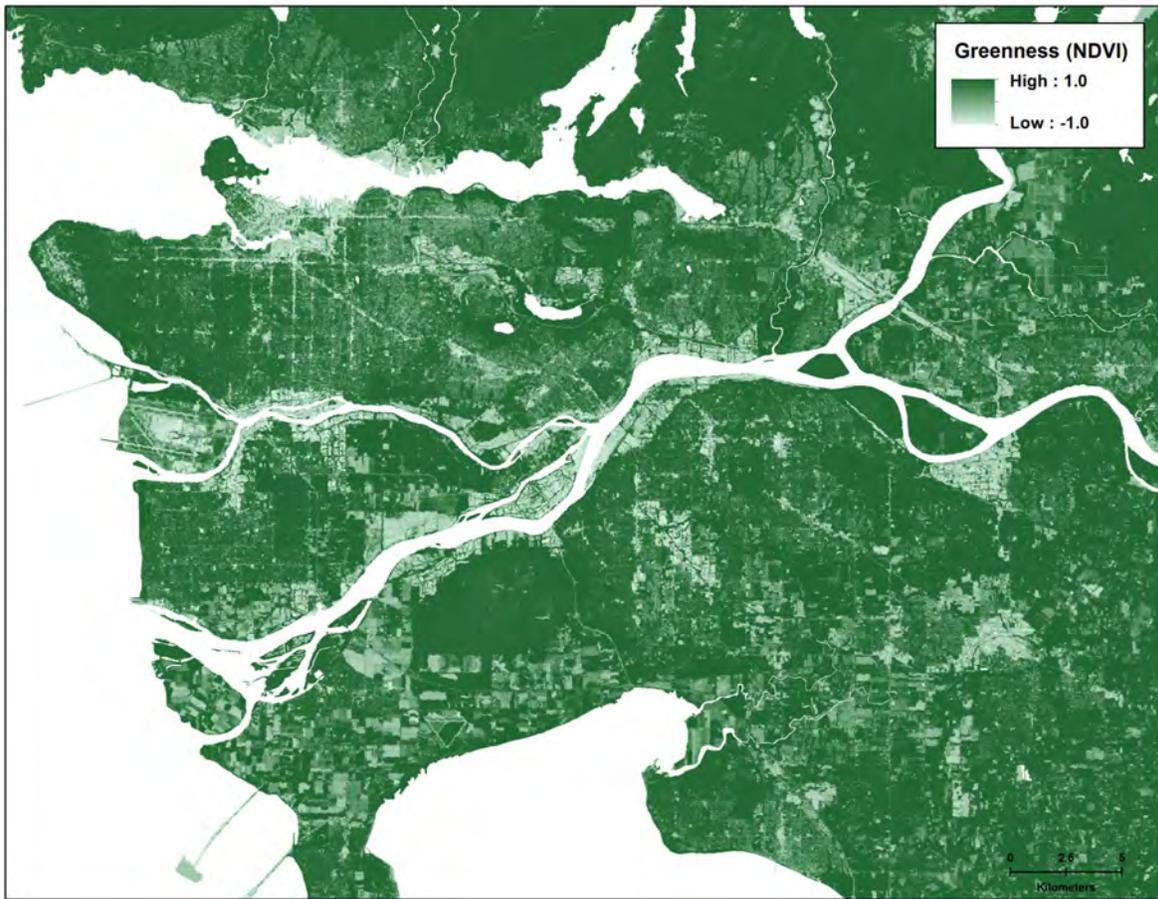


Figure 2.

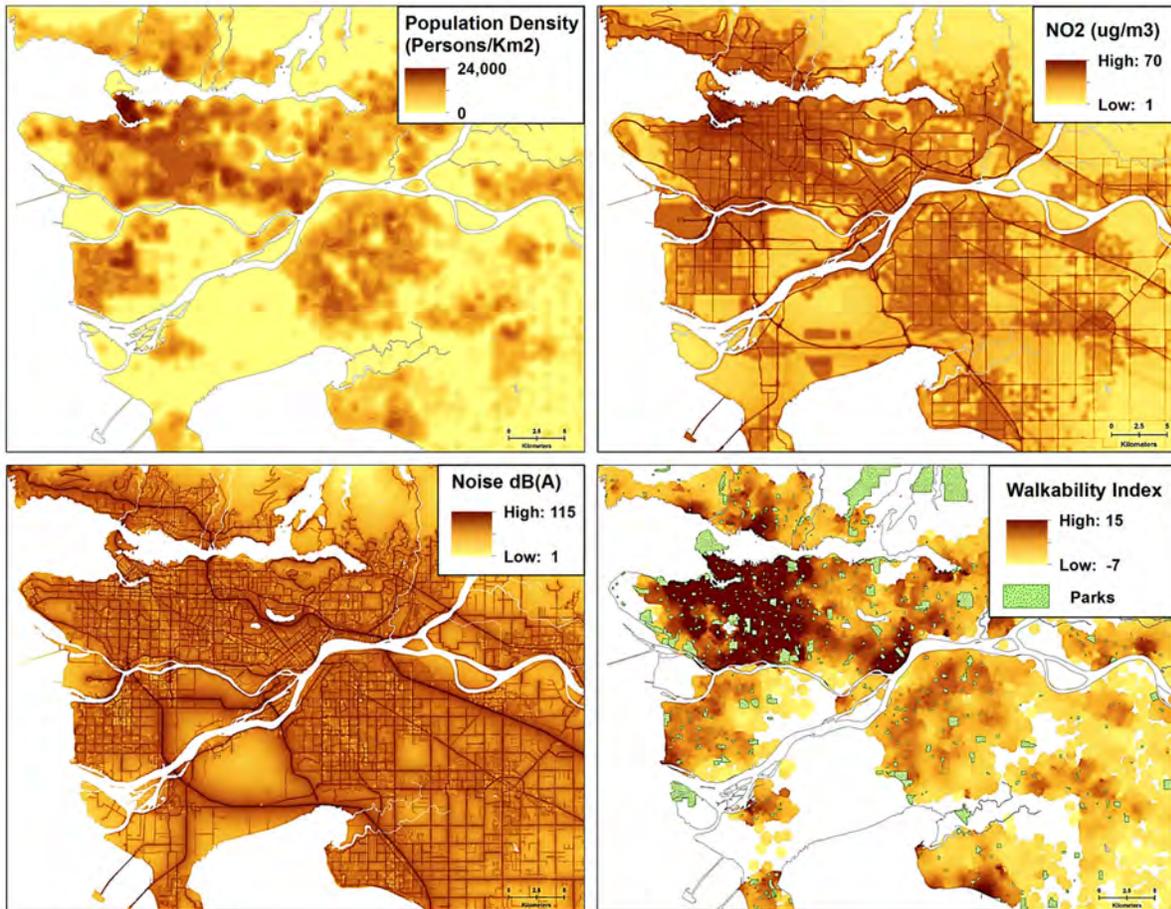


Figure 3.

