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The influence of early-life residential exposure to different vegetation types and paved surfaces on early childhood development: A population-based birth cohort study

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ABSTRACT

Background: Growing evidence suggests that exposure to green space is associated with improved childhood health and development, but the influence of different green space types remains relatively unexplored. In the present study, we investigated the association between early-life residential exposure to vegetation and early childhood development and evaluated whether associations differed according to land cover types, including paved land.

Methods: Early childhood development was assessed via kindergarten teacher-ratings on the Early Development Instrument (EDI) in a large population-based birth cohort (n = 27,539) in Metro Vancouver, Canada. The residential surrounding environment was characterized using a high spatial resolution land cover map that was linked to children by six-digit residential postal codes. Early-life residential exposure (from birth to time of EDI assessment, mean age = 5.6 years) was calculated as the mean of annual percentage values of different land cover classes (i.e., total vegetation, tree cover, grass cover, paved surfaces) within a 250 m buffer zone of postal code centroids. Multilevel models were used to analyze associations between respective land cover classes and early childhood development.

Results: In adjusted models, one interquartile range increase in total vegetation percentage was associated with a 0.33 increase in total EDI score (95% CI: 0.21, 0.45). Similar positive associations were observed for tree cover (β-coefficient: 0.26, 95% CI: 0.15, 0.37) and grass cover (β-coefficient: 0.12, 95% CI: 0.02, 0.22), while negative associations were observed for paved surfaces (β-coefficient: −0.35, 95% CI: −0.47, −0.23).

Conclusions: Our findings indicate that increased early-life residential exposure to vegetation is positively associated with early childhood developmental outcomes, and that associations may be stronger for residential exposure to tree cover relative to grass cover. Our results further indicate that childhood development may be

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negatively associated with residential exposure to paved surfaces. These findings can inform urban planning to support early childhood developmental health.

1. Introduction

Early childhood development is an important predictor for physical, socio-emotional, and cognitive health across the life course (Gluckman et al., 2008). Globally, there is public health concern over the high prevalence of developmental health issues among children, including emotional and behavioral problems (e.g., attention-deficit/hyperactivity disorder) that often impose lasting harmful effects on children's lives and considerable social and economic burdens (Baranne and Falissard, 2018). Previous studies indicate that family risk factors, including socio-economic status, are strong predictors of children's developmental trajectories (Brownell et al., 2016); however, features of the surrounding environment that are associated with child development remain understudied.

Growing evidence demonstrates the potential of urban green spaces – such as forests, street trees, and gardens – to positively influence early childhood health and development (Davis et al., 2021; Mygind et al., 2021, 2019; Tillmann et al., 2018b; Vanaken and Danckaerts, 2018). Green spaces are hypothesized to promote health and development through several pathways, including reducing stress, enhancing attentional functioning, encouraging physical activity and social contact, and mitigating harmful environmental exposures, such as excessive heat, noise, and air pollution (Dzhambov et al., 2020; Markevych et al., 2017; Zhang et al., 2021). Prior research supports these hypothetical pathways and has demonstrated positive associations between green space exposure and multiple childhood health outcomes, such as reduced emotional and behavioral problems (Liao et al., 2020; Madzia et al., 2019; Markevych et al., 2014), improved attention and working memory (Dadvand et al., 2018, 2017, 2015), higher academic achievement (Kuo et al., 2021; Sivarajah et al., 2018), and better overall quality of life (Tillmann et al., 2018a).

While a growing amount of work suggests a positive association between green space exposure and indicators of early childhood health and development, the current evidence base is inconclusive (Davis et al., 2021; Mygind et al., 2021). The heterogeneity in findings may be due, in part, to the unidimensional definitions of green space and relatively crude exposure measures (e.g., normalized difference vegetation index, NDVI) that do not take the specific type or structure of green space into consideration. Though urban green space may take many forms, few studies have investigated the health associations related to distinct vegetation types (Holland et al., 2021; Jarvis et al., 2020a). Different types of vegetation may support different pathways linking green space exposure to health outcomes. For instance, trees provide shade and, thus, likely reduce surrounding air temperatures and heat-related morbidities to a greater extent than do grassy areas, whereas open grass space may encourage group activities and, thus, support social well-being to a greater extent than dense wooded areas. Furthermore, open grass space may be associated with higher presence of play and recreational spaces and, therefore, encourage greater physical activity than forested areas; though, trees may also provide an attractive setting for physical activity due to shading. Equally, the relative influence of non-vegetated land, such as paved surfaces, has rarely been evaluated in this context (Larson et al., 2018). Paved surfaces may be negatively associated with early childhood development through, for example, association with heat exposure and traffic-related air and noise pollution.

In the present study, we investigate the association between early-life residential exposure to vegetation and childhood development in a population-based birth cohort in Metro Vancouver, Canada (van den Bosch et al., 2018). We addressed current gaps in the literature by evaluating residential exposure to distinct land cover types and their association to childhood developmental outcomes. We hypothesized that there would be a positive association between vegetated land cover and childhood development. Given the body of evidence for varying pathways of nature-health associations and potential differing capacities of vegetation types in supporting these pathways, we hypothesized that associations would vary according to vegetation type. We also hypothesized that there would be a negative association between paved land cover and childhood development. Given there is limited available evidence concerning the childhood health associations related to distinct land cover types, our study was exploratory and did not build more specific hypotheses concerning which land cover type would be most strongly associated with early childhood development.

2. Materials and Methods

2.1. Study area and population

We conducted this study in Metro Vancouver – the third largest metropolitan area in Canada, comprising over 2.5 million residents (Statistics Canada, 2017). The region covers 2,883 km^2 of land area in southwestern British Columbia (BC) and has a population density of approximately 855 persons/km^2 (Statistics Canada, 2017). The regional geography is diverse, ranging from high density built-up areas to low density large suburban areas, to agricultural crops, and to undeveloped forests.

Outcome, environmental exposure, and individual- and area-level covariate data were linked using six-digit residential postal codes, recorded at each contact with the healthcare system, that were summarized on an annual basis (i.e., single recorded postal code per year). In circumstances where multiple unique postal codes were reported in a single year, the latest recorded postal code for the year was selected. The six-digit postal code is a common geographic identifier applied in Canadian environmental epidemiological studies and generally corresponds to a block or single multi-unit building in urban areas, with a positional accuracy within approximately 100–160 m (Khan et al., 2018; Supplemental Materials Fig. S1).

The study cohort was identified using administrative data from the BC Ministry of Health (British Columbia Ministry of Health, 2011a, 2011b; Canadian Institute for Health Information, 2011), the BC Vital Statistics Agency (British Columbia Vital Statistics Agency, 2011a, 2011b), Perinatal Services BC (Perinatal Services BC, 2011), and the Human Early Learning Partnership (Human Early Learning Partnership, 2011), through Population Data BC that provided individual-data linkage across data sources. The cohort comprised all live, singleton births to mothers residing in Metro Vancouver from April 2000 to December 2005. To be eligible, children and their mothers had to be registered in the provincial health insurance program, Medical Services Plan (MSP), and have lived in Metro Vancouver for the duration of the exposure period. The MSP is a mandatory universal health insurance program in the province of BC, covering nearly all residents (Chamberlayne et al., 1998). The exposure period was from birth to time of outcome assessment (second half of kindergarten school year). In BC, children can commence full-day kindergarten in the September of the calendar year in which they turn five years old (Government of British Columbia, 2021). Children who moved outside of the study region, had a gap in residential history, or who died during the exposure period were excluded from the cohort.

2.2. Assessment of early childhood development

Early childhood development was assessed via kindergarten teacher ratings on the Early Development Instrument (EDI) completed in the 2005/2006 to 2010/2011 academic years (Janus and Offord, 2007). The EDI is a population-level dataset that consists of demographic information and 103 binary and Likert-scale items, each scored from 0 (low) to 10 (high), assessing a child's ability to meet age-appropriate developmental expectations in five domains: (1) physical health and well-being; (2) social competence; (3) emotional maturity; (4) language and cognitive development; and (5) communication skills and general knowledge. For each item, teachers rate statements about the child's behavior in the past six months. The EDI is administered in early spring to ensure teachers have sufficient experience with each child's behavior. For each of the five domains, a child receives a domain score, calculated as the mean across all domain items, ranging from 0 (lowest) to 10 (highest). Children also receive a total EDI score, calculated by adding up scores from all of the five domain scores, ranging from 0 (lowest) to 50 (highest). Numerous studies have documented the EDI's validity and reliability as a measure of children's developmental outcomes (Forer and Zumbo, 2011; Janus et al., 2011; Janus and Offord, 2007). For the current study, we used the total EDI score as an indicator of individual children's overall childhood development, with higher scores corresponding to better developmental outcomes.

2.3. Early-life residential environmental exposure

We characterized the environment surrounding children's residence using a land cover map of Metro Vancouver (5 m spatial resolution) derived from a combination of RapidEye high spatial resolution imagery from 2014 and airborne laser scanning data (Supplemental Materials Fig. S2). The map includes 12 different land cover classes and has an overall accuracy of 88% (kappa 0.87) (Williams et al., 2018). The land cover classes refer to the surface cover on the ground (e.g., vegetation, water, soil, paved) and differ from land use data that refers to the purpose the land area serves (e.g., recreation, commercial, residential) (Government of Canada, 2015). Further details on the land cover map are described elsewhere (Williams et al., 2018). Out of the 12 different land cover classes, we examined residential exposure to those that represent different vegetation types: grass cover (i.e., combined natural and modified grass-herb land cover) and tree cover (i.e., combined coniferous and deciduous land cover). We also created a composite class to represent total vegetation (i.e., combined coniferous, deciduous, shrub, natural grass-herb, and modified grass-herb land cover). Additionally, we considered residential exposure to paved surfaces. On average, a large proportion (~75%) of tree cover was comprised of deciduous trees. The amount of 'shrub' and 'water' land cover classes was limited near residences and thus excluded as individual exposures from our analyses. We defined residential exposure as the percentage of each land cover class within a 250 m buffer of participants' six-digit residential postal code centroid. We selected a buffer size of 250 m to serve as a proxy for exposure within a walkable distance from home, as we assumed that prior to entering elementary school children would be spending most of their time at or within close proximity of their residence. A time-weighted early-life residential exposure estimate was calculated as the mean of annual land cover percentage values across the exposure period (from birth to time of EDI assessment), while accounting for residential address changes reported in the context of a universal healthcare system.

2.4. Potential confounders

We developed a directed acyclic graph (Textor and Hardt, 2011) to *a priori* identify and select potential confounders of the association between residential exposure and childhood development (Supplemental Materials Fig. S3). Individual-level variables for children included sex (male, female), season of birth (January to March as winter, April to June as spring, July to September as summer, and October to December as fall), and English as a second language status (yes, no). While not hypothesized to be related to residential exposure, child's sex was included in our models as it is routinely controlled for in prior studies (e.g., Amoly et al., 2014; Andrusaityte et al., 2020; Bell et al., 2020; Binter et al., 2022; Dadvand et al., 2015; Liao et al., 2019). English as a second language was used as a proxy for a child's cultural and/or ethnic background, which has been associated with childhood developmental outcomes and may influence selection of residential location (Guhn et al., 2016b; Milbrath and Guhn, 2019). Likewise, an association between season of birth and childhood development has been suggested (Asano et al., 2016; Grootendorst-Van Mil et al., 2017). Information on individual socio-economic status was not available in this study, but data on maternal age (<25, 25–40, >40) and lone parent household (yes, no) at time of birth were included as proxies of household socio-economic status. In addition, health practitioner Premium Subsidy Codes recorded in the MSP, that indicate the rate of provincial health insurance premium subsidy, were used as a proxy of low household income. Following methodology from previous research (Guhn et al., 2020), we created a binary variable (yes, no) to indicate if a child received subsidized MSP for their earliest recorded health practitioner visit. Socio-economic status has been associated with environmental exposure and childhood developmental outcomes (Doiron et al., 2020; Falster et al., 2018; Guhn et al., 2020; Janus and Duku, 2007; Spady et al., 2001).

The material deprivation dimension of the 2006 Canadian Marginalization (CAN-Marg) Index was used to assess neighborhood-level socio-economic status, with higher scores corresponding to areas of greater marginalization (Matheson et al., 2012). CAN-Marg has been widely used in Canadian epidemiological studies and has been associated with health and behavioral outcomes (Matheson et al., 2012; White et al., 2013). The material deprivation dimension indicates education, employment, income, and family structure measures within dissemination areas, which are small geographic units comprised of 400 to 700 individuals (Statistics Canada, 2015). Material deprivation scores were assigned to children using six-digit postal codes (CanMap, 2016). Neighborhood-level urbanicity (urban, rural/*peri*-urban), geocoded to six-digit postal codes, was derived from Statistics Canada (Statistics Canada, 2011). Neighborhoods are classified as urban if they are located in regions in which the surrounding census metropolitan area has a population of at least 50,000 individuals (Statistics Canada, 2011). The degree of urbanicity may influence the amount and type of vegetation in a neighborhood (Jarvis et al., 2020b) and has been reported to modify nature-health associations (Bijnens et al., 2020; Browning et al., 2022).

2.5. Statistical analysis

We used multilevel regression models with total EDI score as the outcome, residential exposure as a fixed effect, and teacher as a random effect to account for teacher-rater bias. We tested for residual independence with Moran's I statistic and found no evidence of spatial autocorrelation, so spatial dependence was not formally included in our statistical analyses. In each model, the outcome was regressed on a single explanatory variable (total vegetation, tree cover, grass cover, paved surfaces) to evaluate the association with each land cover class independently. We estimated the change in outcome score associated with one interquartile range (IQR) increase in lifetime mean percent land cover. The IQR was deemed an appropriate unit, as it closely approximated the standard deviation and is in alignment with previously published environmental health literature (e.g., Bijnens et al., 2020; Binter et al., 2022; Dadvand et al., 2015; Liao et al., 2019). We tested multicollinearity among the covariates with generalized variance-inflation factors. With the largest generalized variance-inflation factor of 1.13, we found little evidence of multicollinearity, and therefore, we controlled for all eight covariates in adjusted models. We tested for potential differences in estimated effects depending on a child's sex and socio-economic status through interaction terms and stratified analyses. Respondents with missing data for any of the outcome ($n = 5,700$;

15.1%), exposure (n = 1,241; 3.3%), or confounder (n = 2,038; 5.4%) variables were excluded from the study sample.

While we were primarily interested in evaluating the influence of environmental exposure on overall childhood development, as measured by total EDI score, we ran complementary analyses evaluating associations between residential exposure and the five EDI domain scores separately (range 0–10) to evaluate the consistency of results across dimensions of early childhood development. We also conducted several sensitivity analyses to test the robustness of the findings to different measures of the outcome and the exposures. First, we analyzed associations between residential exposure and EDI scores with multi-level logistic regression by dichotomizing outcomes to reflect developmental vulnerability (not vulnerable, vulnerable). Using standardized approaches (Janus and Duku, 2007), children were considered 'vulnerable' if any one of their five EDI domain scores were within the bottom 10th percentile. Second, given varying distributions of land cover types, we estimated the change in outcome score associated with a one percent unit increase in early-life mean land cover to evaluate trends across land cover types with a comparable unit increase across exposures. Third, we ran the analyses with early-life residential exposure calculated as the mean of annual land cover percentage values within 100- and 500 m buffer zones. Finally, we tested the association with early-life residential 'total vegetation' exposure estimated as the mean of annual values for two alternative greenness metrics: spectrally unmixed vegetation percentage and NDVI. In addition to testing for robustness of our findings to alterative greenness measures, this sensitivity analysis permits greater comparability of our results with other literature. Vegetation percentage values were derived from linear spectral unmixing of Landsat (30 m spatial resolution) satellite image composites spanning 2000 to 2011 (Czekajlo et al., 2020). NDVI values were provided by the Canadian Urban Environmental Health Research Consortium (CANUE) and were derived from 2000 to 2011 Landsat (30 m spatial resolution) and 2017 Planet Scope (3 m spatial resolution) satellite images (Canadian Urban Environmental Health Research Consortium, 2019; CanMap, 2015; Gorelick et al., 2017; USGS, n.d., n.d., n.d., n.d.).

All analyses were performed in R version 4.0.3 (R Core Team, 2020) using the 'lme4' and 'lmerTest' statistical modeling packages (Bates et al., 2015; Kuznetsova et al., 2017). Ethics approval for this study was granted by the University of British Columbia Behavioral Research Ethics Board (certificate H18-00908). The data that underlie this study were accessed via Population Data BC with the approval of Data Stewards and terms of use were outlined in data sharing agreements that restricted the use of data for research purposes.

3. Results

3.1. Characteristics of the study sample

The final study sample included 27,539 children (Supplemental Materials Fig. S4). Descriptive and correlation analyses demonstrated no significant differences between the full cohort and our analytical sample (Supplemental Materials Table S1). Table 1 presents descriptive statistics for the sample. Children were on average 5.6 years of age at time of EDI assessment and 48.4% were female. About one third of children were in the English as a second language group (33.6%). Most children were born to mothers aged 25 to 40 years (87%) and in multi-parent households (96.4%). Approximately one fifth of children belonged to low-income families receiving subsidized MSP (20.3%). Almost all children resided in urban neighborhoods (97.9%). Total EDI score was negatively skewed, as most children received high scores. On average, children received a total EDI score of 40.2 (range 0–50). The mean early-life total vegetation exposure percentage within a 250 m buffer was 36%. Within the distinct vegetated classes, there was a higher mean early-life percentage of tree cover exposure (23.2%) compared to grass cover exposure (12.2%). The mean early-life percentage of paved surfaces exposure was 32.2%.

Table 1
Characteristics of cohort of children to examine the association between early-life residential exposure to distinct land cover types and early childhood development in Metro Vancouver, Canada. Data presented are means ± standard deviation or number (percentage). EDI, Early Development Instrument; MSP, Medical Services Plan.

	Total sample (n = 27,539)
Demographic variables	
Age at EDI assessment	5.6 ± 0.3
Sex	
Female	13,331 (48.4)
Male	14,208 (51.6)
English as a second language	
Yes	9,241 (33.6)
No	18,298 (66.4)
Season of birth	
Winter	6,505 (23.6)
Spring	6,932 (25.2)
Summer	7,113 (25.8)
Fall	6,989 (25.4)
MSP subsidy	
Yes	5,600 (20.3)
No	21,939 (79.7)
Lone-parent household	
Yes	996 (3.6)
No	26,543 (96.4)
Maternal age	
<25	2,832 (10.3)
25–40	23,948 (87.0)
>40	759 (2.8)
Neighborhood-level material deprivation	−0.3 ± 0.7
Urbanicity	
Urban	26,951 (97.9)
Rural/*peri*-urban	588 (2.1)
Outcome variable	
Overall EDI score	40.2 ± 7.8
Environmental exposure variables	
Total vegetation (%)	36.0 ± 13.6
Tree cover (%)	23.2 ± 12.2
Grass cover (%)	12.2 ± 6.6
Paved surfaces (%)	32.2 ± 8.9

3.2. Child development in association with residential environmental exposure

Results from the unadjusted and adjusted models of the association between early-life residential exposure and total EDI score are presented in Table 2. In the unadjusted model, for every IQR (17%) increase in residential exposure to total vegetation, there was a 0.90 (95% CI: 0.78, 1.02) increase in total EDI score, indicating a weak positive association given the range (0–50) of this score. Positive associations were also observed for residential exposure to tree cover (β-coefficient: 0.75, 95%

Table 2
Unadjusted and adjusted associations between early-life residential exposure to distinct land cover types and early childhood development among Metro Vancouver children (n = 27,539). Data presented are β-coefficients (95% confidence interval) with one interquartile range increase in environmental exposure within a 250 m buffer of participants' six-digit postal code. Adjusted models control for sex, English as a second language, season of birth, lone-parent household, maternal age, MSP subsidy, neighborhood-level material deprivation, and urbanicity. Models include random effect for teacher ID. All estimated effects and 95% confidence intervals are rounded. CI, confidence interval; EDI, Early Development Instrument; IQR, interquartile range; MSP, Medical Services Plan.

Exposure	IQR (%)	Total EDI score β-coefficient (95% CI)	
		Unadjusted	**Adjusted**
Total vegetation	17	0.90 (0.78, 1.02)	0.33 (0.21, 0.45)
Tree cover	14	0.75 (0.64, 0.86)	0.26 (0.15, 0.37)
Grass cover	7.6	0.29 (0.18, 0.40)	0.12 (0.02, 0.22)
Paved surfaces	12	−0.90 (-1.02, −0.78)	−0.35 (-0.47, −0.23)

CI: 0.64, 0.86) and grass cover (β-coefficient: 0.29, 95% CI: 0.18, 0.40). Conversely, for every IQR (12%) increase in residential exposure to paved surfaces, there was a 0.90 (95% CI: −1.02, −0.78) decrease in total EDI score. Attenuated associations were obtained from fully adjusted models (β-coefficient: 0.33, 95% CI: 0.21, 0.45 for total vegetation; β-coefficient: 0.26, 95% CI: 0.15, 0.37 for tree cover; β-coefficient: 0.12, 95% CI: 0.02, 0.22 for grass cover; β-coefficient: −0.35, 95% CI: −0.47, −0.23 for paved surfaces). To test which land cover classes were most strongly associated with total EDI score, we examined the land cover classes using incremental analyses. Post-hoc incremental models were run with vegetated and paved land cover, and then with tree and grass cover. We did not run models with all four land cover types given multicollinearity among exposures (Supplemental Materials Fig. S5). Each model was adjusted for potential confounding factors included in the overall adjusted model. Similar to our main findings, when accounting for paved surfaces, residential exposure to total vegetation was positively associated with total EDI score; though, the strength of association was attenuated and weaker relative to paved surfaces (Supplemental Materials Table S2). In models with tree cover and grass cover, both exposures were positively associated with total EDI score, with a stronger relative association observed for tree cover (Supplemental Materials Table S3). Analysis of interaction terms between residential exposure and modifying variable (i.e., child's sex, MSP subsidy), as well as stratified analyses, indicated that there were no significant differences in estimated associations based on a child's sex or socio-economic status.

3.3. Sensitivity analyses

Consistent with our main findings, complementary analyses indicated that increased residential exposure to vegetated land cover is positively associated with scores across all five EDI domains; a negative association was observed for residential exposure to paved surfaces (Supplemental Materials Table S4). Equally, when we measured EDI as a binary indicator in the sensitivity analyses, we found that residential exposure to vegetated landcover reduced the odds of being vulnerable to poor childhood development, with the strongest association with residential exposure to total vegetation (OR: 0.88, 95% CI: 0.84, 0.92) (Supplemental Materials Table S5). Sensitivity analyses indicated comparable results when modelling changes in outcome with a one percent unit, as opposed to an IQR, increase in land cover exposure (Supplemental Materials Table S6). The findings were also similar for the 100- and 500 m buffer zones (Supplemental Materials Table S7) and when total vegetation exposure was assessed by spectrally unmixed vegetation percentage or NDVI values (Supplemental Materials Table S8).

4. Discussion

In this large population-based birth cohort study, we observed a positive association between early-life residential exposure to vegetation and early childhood development, as measured by the EDI. Furthermore, we were able to demonstrate that associations between early-life residential exposure and EDI varied according to land cover type. Specifically, early-life residential exposure to tree cover and grass cover was positively associated with child development outcomes and an inverse relationship was observed for residential exposure to paved surfaces. Our findings also indicated that early-life residential exposure to various types of vegetated land cover was associated with reduced odds of being vulnerable to poor childhood development, while residential exposure to paved surfaces was associated with increased odds.

4.1. Early-life residential exposure to vegetation may improve childhood development and reduce risk of developmental vulnerability

Our finding of a positive association between total vegetation exposure and childhood development is consistent with previous research. In general, earlier studies have reported that residential access and exposure to green space is associated with better socio-emotional (Andrusaityte et al., 2020; Bell et al., 2020; Putra et al., 2021; Van Aart et al., 2018), behavioral (Bijnens et al., 2020; Lee et al., 2019), cognitive (Bijnens et al., 2020; Binter et al., 2022; Dadvand et al., 2018, 2017, 2015; Lee et al., 2021), and psychomotor development (Kabisch et al., 2019; Liao et al., 2019) among children; though, some studies have reported null (Donovan et al., 2019; Hartley et al., 2021) or inverse associations (Browning et al., 2018; Nordbø et al., 2020) between green space and childhood development. Studies further indicate that school greenness may be associated with improved academic performance in reading, writing, and mathematics (Kuo et al., 2021; Sivarajah et al., 2018). Our results are consistent with previous research that has shown family- and neighborhood-level socio-economic factors to be more important in explaining variation in EDI scores than characteristics of the surrounding environment, but that the surrounding environment also has an impact (Bell et al., 2020; Christian et al., 2017).

Findings from our sensitivity analysis indicated that residential exposure to vegetated land cover was associated with reduced odds of being vulnerable to poor childhood development. Our finding is consistent with those of Bell et al. who reported that the presence of high-quality neighborhood green space is associated with reduced odds of vulnerability in social development among Australian children (Bell et al., 2020). Previous studies have also suggested that residential green space may reduce adverse developmental outcomes among children, including symptoms and incidence of attention-deficit/hyperactivity disorder (Donovan et al., 2019; Markevych et al., 2018; Thygesen et al., 2020), rates of psychiatric disorders (Engemann et al., 2020b, 2020a), and emotional and behavioral problems (Amoly et al., 2014; Flouri et al., 2014; Liao et al., 2020; Madzia et al., 2019; Markevych et al., 2014). Risk reduction of poor childhood health and development from residential exposure to vegetation indicates important public health benefits. This knowledge can inform preventative programs, including urban greening, to be prioritized towards children considered 'vulnerable' to poor development, for whom interventions may be most effective.

4.2. Associations vary depending on vegetation type

We found that associations between early-life residential exposure to vegetation and childhood development varied according to vegetation type. This finding is supported by a limited number of studies that have identified differences in developmental outcomes among children depending on the type of green space. For instance, comparable to our findings, several North American studies have reported positive associations between schoolyard tree cover and academic achievement (Browning and Locke, 2020; Donovan et al., 2020; Kuo et al., 2021, 2018; Kweon et al., 2017; Leung et al., 2019; Sivarajah et al., 2018; Tallis et al., 2018). Studies have further demonstrated that higher exposure levels to trees is associated with lower autism prevalence (Wu and Jackson, 2017) and conduct problems (Barger et al., 2020), but also to higher quality of life (Kim et al., 2016) and emotional and behavioral regulatory skills (Scott et al., 2018). While we found a positive association between residential exposure to grass cover and childhood development, evidence concerning the health effects of grass cover are relatively limited and inconsistent; some studies have reported positive associations (Taylor and Kuo, 2011; Wu and Jackson, 2017), while others have found null (Donovan et al., 2020; Kuo et al., 2018; Kweon et al., 2017; Sivarajah et al., 2018) or inverse associations (Browning and Locke, 2020; Tillmann et al., 2018a). Inconsistencies in findings across studies may stem from differences in terms of natural environment assessment, outcome assessment, and study population. For instance, studies may estimate exposure using data sets that define and aggregate land cover classes differently (e.g., grass, meadow, agricultural crops).

Our findings indicate that residential exposure to tree cover had a stronger positive association with early childhood development than residential exposure to grass cover. This trend has been observed in prior studies of academic achievement among children (Donovan et al., 2020; Kuo et al., 2018; Sivarajah et al., 2018); though, for other developmental outcomes, few studies have compared the effects of multiple vegetation types (Wu and Jackson, 2017). Limited existing evidence highlights the need for further research to confirm the relative importance of different vegetation types on health associations. We speculate that differences in estimated health effects of vegetation types may, in part, be due to their differing capacities to support pathways of nature-health relations, including regulating and cultural ecosystem services. For instance, areas with more tree cover may provide greater mitigation of air pollution, noise, and heat (Vieira et al., 2017) relative to more open green space, such as grassy fields. Vegetation-related reductions in air pollution, noise, and heat might support improved childhood health and development through subsequent reductions in the adverse health effects associated with these harmful environmental exposures including, for example, central nervous system damage via inflammation and oxidative stress (Lopuszanska and Samardakiewicz, 2020; Zare Sakhvidi et al., 2018). Moreover, as described by the Attention Restoration Theory (Kaplan, 1995), it has been hypothesized that environments with more trees may promote health and development as they possess perceptual attributes (e.g., 'fascination', 'being away', 'extent', 'compatibility') that support restoration from mental fatigue and the capacity for directed attention. Likewise, compared to other vegetation type, trees may encourage greater reduction of stress (Egorov et al., 2020), which could otherwise have an adverse effect on childhood health and developmental trajectories (Lupien et al., 2009). Overall, empirical testing of pathways underlying associations between vegetation exposure and childhood health outcomes is limited (Dzhambov et al., 2020), and more studies in this area may be important for understanding the influence of different vegetation types on childhood health and development.

4.3. *Early-life residential exposure to paved surfaces may impair childhood development and increase risk of developmental vulnerability*

We found that higher early-life residential exposure to paved surfaces was negatively associated with early childhood development. Furthermore, when both total vegetation and paved surfaces were accounted for in the same model, we found that residential exposure to paved surfaces was more strongly associated with total EDI score than residential exposure to total vegetation. Very few studies have reported on the association between human health and exposure to non-natural, impervious surfaces. Our findings are consistent with those of Larson et al. (2018) who reported that the percentage of impervious surface (e.g., buildings and paved surfaces) within neighborhood areas was associated with increased risk of severe anxiety among youth with autism. Previous studies have also suggested that exposure to impervious surface cover surrounding a child's residence or school may be associated with poor self-regulation (Scott et al., 2018), increased autism diagnosis prevalence (Wu and Jackson, 2017), and decreased academic test scores (Donovan et al., 2020). This may be due to the fact that landscapes with greater impervious surface coverage may adversely affect childhood developmental outcomes through association with increased traffic noise, air pollution, and excessive heat exposure.

4.4. *Strengths and limitations*

Our study has several strengths. First, we used a large population-based birth cohort to examine the association between early-life residential exposure to vegetation (from birth to kindergarten) and early childhood development, while accounting for residential address changes of children. The population-based study design reduces the potential for bias in our sample, including accurate representation of demographic groups in our study sample. Most previous research has adopted cross-sectional research designs with much smaller study sample sizes (Amoly et al., 2014; Andrusaityte et al., 2020; Bell et al., 2020; Kim et al., 2016; Lee et al., 2021, 2019; Liao et al., 2020, 2019; Markevych et al., 2014; Scott et al., 2018; Taylor and Kuo, 2011). Second, we addressed important gaps in the literature by using a high spatial resolution land cover map to estimate and compare health associations for various vegetated (i.e., total vegetation, tree cover, grass cover) and non-vegetated (i.e., paved surfaces) land cover classes. Furthermore, we tested the robustness of our findings by running sensitivity analyses with residential vegetation estimated through both a novel metric of vegetation percentage and the commonly employed NDVI; each reflecting different aspects of greenness.

Despite these strengths, we recognize several limitations of the current study. First, as administrative data are not generally collected for research purposes, the lack of individual-level variables may have led to residual confounding. To address this, we used all available variables to operationalize constructs for which we did not have direct measures (e.g., MSP subsidy as proxy for household income). Due to high percentage of missing values, we were unable to account for other potentially important risk factors (e.g., maternal education, smoking, alcohol consumption, substance use). Second, due to the lack of follow-up data on the EDI outcome, some portion of the observed effects could be the result of self-selection, whereby, for example, neighborhoods with abundant surrounding vegetation attract families of higher socio-economic status who already have healthy lifestyles and greater social support for healthy childhood development. On the other hand, we were able to demonstrate a temporal sequence in the association because we had access to exposure data preceding the outcome. Third, since data on participant's residential address were unavailable, we assigned environmental exposures to six-digit postal codes. This may have resulted in some exposure misclassification associated with spatial discrepancy between participants' postal code centroid and true residential location; however, error is likely minimal given the small size of urban postal codes (Khan et al., 2018). We also acknowledge that referencing exposures to children's residential postal codes may not accurately reflect the activity spaces of children and the environments in which health effects are most likely to accrue and recommend that future research additionally consider exposure outside of the home, such as daycare and school location. Additional exposure misclassification may have arisen from the temporal misalignment between the regional land cover map 2014 and our study period (2000 to 2011); however, sensitivity analyses with temporally aligned greenness estimates (i.e., vegetation percentage and NDVI) showed comparable trends. Similarly, we could not account for potential seasonal variation in health associations since the regional land cover map only reflected exposure for the summer growing period. Fourth, given their limited and highly skewed distribution near residences, some distinct land cover classes (i.e., shrubs, water) were excluded from our analyses. Moreover, our exposure estimates did not account for the qualitative attributes (e.g., walkability, safety) or actual use of the surrounding environment. These factors may be important to nature-health relations and, thus, should be taken into consideration in future study designs. Fifth, while the validity and reliability of the teacher-rated EDI has been demonstrated in prior studies, we recognize that it will be important to replicate this study with other measures of children's early development. Furthermore, more longitudinal studies using EDI scores are required to aid in understanding the real-life implications of our findings; though, prior research indicates that teacher-ratings on the EDI are associated with self-reported well-being (Gregory et al., 2021; Guhn et al., 2016a), physician-assessed mental health conditions (Thomson et al., 2021, 2019), and academic achievement in later childhood (Brinkman et al., 2013; Davies et al., 2016; Duncan et al., 2020). Finally, our study cohort was largely comprised of children born into multi-parent households, who spoke English as their first language, and who resided in urbanized neighborhoods. Given prior research has reported that associations between green space and early childhood development may be modified by population characteristics (McEachan et al., 2018) and degree of urbanicity (Bijnens et al., 2020), our findings may not be generalizable to other sociodemographic groups and rural populations. Moreover, since Metro Vancouver is a region with relatively high levels of vegetation cover, our results may not be generalizable to other geographic contexts with less available green space. Though, preliminary research indicates that even within arid regions with desert landscapes, low levels of vegetation may offer health benefits to a degree that is similar to regions with higher baseline levels of vegetation (Olvera-Alvarez et al., 2021).

5. Conclusions

In this population-based birth cohort, we found a positive association between early-life residential exposure to vegetated land cover (i.e., total vegetation, tree cover, grass cover) and early childhood development; a negative association was observed for residential exposure to paved surfaces. Our findings contribute to an improved understanding of associations between green space exposure and early childhood development, particularly because we were able to assess associations for different vegetation types, suggesting that tree cover may be of more importance than grass cover. Our results also indicate that even when accounting for the negative effects of paved surfaces, residential exposure to vegetation can still have a positive influence on early childhood development. Together, our results suggest that converting paved surfaces to vegetated environments may have important effects on early childhood health and development, as not only will they offer added beneficial services provided by green spaces, but perhaps more so reduce the adverse effects associated with impervious environments. While the strength of observed associations between residential exposure and childhood development was relatively weak, even small individual gains can shift the population distribution of early childhood development to higher levels, resulting in important public health benefits. Our findings indicate that urban planning and policy frameworks aimed at increasing the availability of vegetation in neighborhoods may be beneficial for early childhood developmental outcomes. If confirmed by other studies, our findings can inform urban planners of the types of green space that support optimal early childhood health and development, with potential positive health benefits across the life course.

CRediT authorship contribution statement

Ingrid Jarvis: Data curation, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing. **Hind Sbihi:** Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Zoë Davis:** Data curation, Writing – original draft, Writing – review & editing. **Michael Brauer:** Methodology, Writing – review & editing. **Agatha Czekajlo:** Resources, Writing – review & editing. **Hugh W. Davies:** Methodology, Writing – review & editing. **Sarah E. Gergel:** Supervision, Writing – review & editing. **Martin Guhn:** Methodology, Writing – review & editing. **Michael Jerrett:** Methodology, Writing – review & editing. **Mieke Koehoorn:** Supervision, Writing – review & editing. **Lorien Nesbitt:** Methodology, Writing – original draft, Writing – review & editing. **Tim F. Oberlander:** Methodology, Writing – review & editing. **Jason Su:** Methodology, Writing – review & editing. **Matilda van den Bosch:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107196.

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