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The association of fractional cover, foliage projective cover and biodiversity with birthweight

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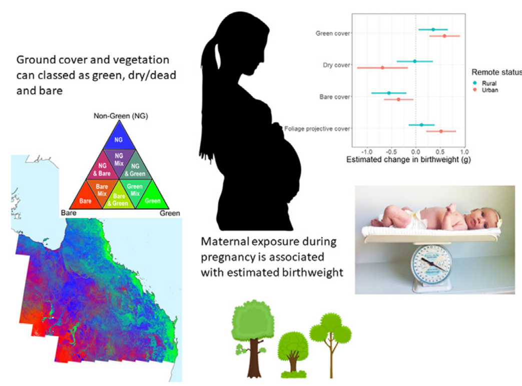
HIGHLIGHTS

- Greenness and tree cover is associated with higher birthweight.
- Dry and dead vegetation is associated with lower birthweights, as is bare ground.
- Biodiversity was not associated with birthweight in this study.
- Green space is associated with birthweight in both rural and urban areas.

GRAPHICAL ABSTRACT



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ABSTRACT

Introduction: Environmental exposures can contribute both benefits and risks to human health. Maternal exposure to green space has been associated with improvements in birthweight, among other birth outcomes. Newer measures of green space have been developed, which allows for an exploration of the effect of different ground covers (green, dry and bare earth), as well as measures of biodiversity. This study explores the association of these novel green space measures with birthweight in a large birth cohort in Queensland, Australia.
Methods: Birthweight was acquired from the routine health records. Records were allocated green space values for fractional cover, biodiversity and foliage projective cover. Directed acyclic graphs were developed to guide variable selection. Mixed-effects linear regression and generalised linear mixed-effects models were developed, with random intercepts for maternal residential locality and year of birth. Results are presented as standardised beta coefficients or odds ratios, with 95% confidence intervals.
Results: An IQR increase of green cover (29.6 g, 95% CI 13.8–45.5) and foliage projective cover (26.0 g, 95% CI 10.8–41.3) are associated with birthweight in urban areas. An IQR increase in dry cover −34.4 g, 95% CI -60.4 to −8.4) and bare earth (−17.7 g, 95% CI -32.8 to −2.6) are associated with lower birthweight. Mothers living in rural areas had similar results, with an IQR increase in green cover (17.8 g, 95% CI 2.9–32.7) associated with higher birthweight, and bare earth (−27.7 g, 95% CI -45.7 to −9.7) was associated with lower birthweight. The biodiversity measure used in this study was not associated with any birthweight outcomes.
Conclusion: This study finds that the types of ground cover within the maternal residential locality are associated with small, but significant, changes in estimated birthweight, and these effects are not limited to urban areas.
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1. Introduction

Urban green space, the area of an urban setting occupied with photosynthetic vegetation such as grass, shrubs and trees, is perhaps the best example of an environmental factor that may act as a public health good. Research has identified health benefits associated with green space, such as improvement in mental wellbeing, reduction in cortisol, an increase in physical activity, improved neighbourhood cohesion, and exposure to beneficial microbiota (Hartig et al., 2014). Living in close proximity to green space is associated with better overall health (Maas et al., 2009; Dadvand et al., 2016; Sugiyama et al., 2008; de Vries et al., 2013; Maas et al., 2006) and better mental health (Sugiyama et al., 2008; de Vries et al., 2013; Richardson et al., 2013; Beyer et al., 2014; Nutsford et al., 2013). Lower mortality rates have been seen for populations with higher levels of green space in their neighbourhoods (Gascon et al., 2016; Villeneuve et al., 2012). Better cardiovascular health (Richardson et al., 2013; Hartig et al., 2003; Tamosiunas et al., 2014) and lower levels of obesity (Lachowycz and Jones, 2011; Ellaway et al., 2005; Dadvand et al., 2014) have also been attributed to green space exposure. Green space may play a role in ameliorating hazardous environmental exposures, such as air pollution and temperature extremes (Feng and Astell-Burt, 2017; Alcock et al., 2017; Miri et al., 2018; Harlan et al., 2006; Nayak et al., 2018; Gill et al., 2007; Middel et al., 2014). Despite these promising results, other studies have found no association between green space and health outcomes (Hillsdon et al., 2006; Schipperijn et al., 2013; Gidlow et al., 2016), and in some studies there has been an association between green space exposure and increased risk of asthma (Dadvand et al., 2014; Andrusaityte et al., 2016).

Weight at birth is a useful indicator of the immediate health of the neonate, as well as a predictor of long-term health outcomes (Barker et al., 2001; Malin et al., 2014). In 2007, it was estimated that nearly 1.5 million deaths globally were attributable to low birthweight, as well as 140 million Disability-adjusted Life Years (Global Burden of Disease Collaborative Network, 2018). Low birthweight is linked to foetal mortality and morbidity (Robert et al., 2015). Babies born large-for-gestational age (LGA) are also at increased risk of mortality and morbidity in the neonatal period, especially if they are both LGA and pre-term (Robert et al., 2015; Weissmann-Brenner et al., 2012). Both small-for-gestational age (SGA) and LGA neonates tend to have longer hospital stays and be more likely to be admitted to intensive care units (Weissmann-Brenner et al., 2012; Australian Institute of Health and Welfare, 2015). The impacts of birthweight can extend across the life span. It has been postulated that the time *in utero* can be an opportunity to build life-course resilience Currey et al., 2013; Lynch and Smith, 2005).

Studies on green space and birth outcomes have been conducted, and have been the subject of six reviews, including 3 recent meta-analyses (Akaraci et al., 2020; Lee et al., 2020; Zhan et al., 2020). The overall finding in the recent meta-analyses was that maternal exposure to greenness in the residential area is associated with higher estimated birthweight and lower odds for SGA births. The pooled estimates, whilst small, are statistically significant and support the results of an earlier meta-analysis conducted in 2014 (Dzhambov et al., 2014). The meta-analysis by Zhan et al., found a dose response for greenness, with each increasing unit of NDVI (0.1) associated with a 2% reduction in risk of low birth weight and a 1% reduction in risk of SGA (Zhan et al., 2020). In a large review of the urban environment and birth outcomes, green space emerged as the factor with the most consistent association with improved birthweight (Nieuwenhuijsen et al., 2019). A systematic review in 2017 found higher estimated birthweight for increasing green space, mixed results for gestational length, and limited studies on head circumference, Apgar score, and mortality (Banay et al., 2017; Cusack et al., 2017). These reviews offer good support for the role of green space in improving pregnancy outcomes, although some studies have found mixed or null associations between green space and birthweight (Lin et al., 2020; Anabitarte et al., 2020; Abelt and McLafferty, 2017; Casey et al., 2016; Cusack et al., 2018).

There remain some methodological limitations within the current body of research. There is a strong reliance on the normalised difference vegetation index (NDVI) for assessing the effects of green space. NDVI is a long established indicator of live green vegetation, and is based on the difference between the measured reflectance in the near infrared and red wavelengths (The Earth Observatory, 2000). While NDVI is a useful indicator, more detailed and novel assessments of ground cover that are relevant to health outcomes of interest in observational epidemiological studies are available from remote sensing products. For example, fractional cover provides a measure of greenness (green cover), dry and dead vegetation (dry cover) and bare earth. To our knowledge, no studies have utilised fractional cover in health research. There is also a need to explore measures of biodiversity, to see if they are associated with birthweight. The maternal microbiome has been linked to adverse pregnancy outcomes (Dunlop et al., 2015), and there is increasing focus on the link between the environmental microbiota and the human microbiome (Mills et al., 2019). There are gaps in our knowledge of how the environmental microbiome interacts with the human microbiome (Flies et al., 2017), however there is evidence that green environments contribute to airborne microbial counts, suggesting a potential inhalation route (Lymperopoulou et al., 2016; Mhuireach et al., 2016). The dermis is likely to play a strong role in the interface between human health and environment too, with evidence of changing skin microbiome depending on the environmental make up (Prescott et al., 2017). While natural environments produce a unique microbiome not seen in the built environment, interacting with nature increases the likelihood of transport of that microbiome into the built environments (Stamper et al., 2016), suggesting that nature contact could improve the diversity of microbes in domestic environments. Little information exists on the effects of green space on birthweight outcomes across the urban-rural spectrum. Two studies were identified that included rural settlements. In a study by Casey et al. (2016) an association between greenness and birthweight was found only in urban centres. A more recent paper by Dzhambov et al. (2019) explored the association of green space with birth outcomes in Alpine areas. The results showed variability across study sites, and the authors highlighted the need to conduct research with larger samples. There is also a need to explore different climate and ecological zones; previous research has almost exclusively used populations residing in the northern hemisphere, with only one study conducted in the southern hemisphere (Nichani et al., 2017). Lastly, some studies have included other environmental exposures as covariates (primarily air pollution and/or noise), however, to our knowledge, none of the previous work included temperature as a model covariate. The objective of this current study was therefore to explore the association between novel measures of green space, such as fractional cover and biodiversity, with birthweight and to test the association in both rural and urban settings, after adjusting for covariates.

2. Methodology

2.1. Study design

We conducted a cross-sectional study to assess the association between novel green space measures and birthweight in Queensland, Australia, over the years 2007 to 2015.

2.2. Study area and population

Queensland is a large state in Australia's east, with a population of ~5 million persons. It is a diverse state in terms of climate and population characteristics, with a climate ranging from tropical, to warm temperate, and hot arid. Queensland has the most de-centralised population of all Australian states, with more than 50% of the population living outside the capital city, and a 39% living in rural or remote areas

(Queensland Government, 2018a). Data on birth outcomes and maternal characteristics for all live births, as well as still births of a minimum of 20 weeks gestation and/or 400 g in weight were obtained from the Perinatal Data Collection (PDC); a Queensland Government-held repository of births data in Queensland. For the purpose of this study, data were obtained of all births registered with the PDC for the period of 1st January 2007 to June 30th 2015. Variables on infant characteristics, maternal demographics, pregnancy complications, smoking status and locality were requested. A total of 529,860 records were acquired.

All live singleton births were eligible for inclusion. Babies were excluded from the analysis if they presented with a congenital anomaly that acts to independently affect birthweight or constitutes a major anomaly ($n = 17{,}163$). Records were excluded if residential postcode was outside QLD ($n = 8178$), birthweight <100 g ($n = 100$), indeterminate sex ($n = 179$), missing birthweight values (n = 100), or could not be matched to a locality code ($n = 42{,}753$). After exclusions, 494,126 records remained. Records with missing data were excluded from the analysis. The final sample size for the main fractional cover analysis was 302,422.

Maternal residential address is collected in the PDC at the time of birth, and due to privacy concerns was supplied as locality and postcode for this study. Each record was allocated an Index of Relative Socio-Economic Advantage and Disadvantage (IRSAD) decile based on maternal residential postcode. The IRSAD is the sum of weighted census variables relating to both advantage and disadvantage (Pink, 2011). Records were allocated a remoteness area from the Australian Bureau of Statistics Remoteness Structure at postcode level to ensure that socioeconomic score and remoteness category were set at the same spatial scale. This structure outlines five levels of remoteness areas, based on the relative access to services in each area (Australian Bureau of Statistics, 2018).

2.3. Outcome data

The outcome measures were raw birthweight (g), SGA and LGA. Each baby was allocated a birthweight percentile using the ChildSDS package (Vogel, 2017) in R. Completed weeks of gestation, birthweight, and gender were used to calculate an age-standardised ranking. Babies below the 10th birthweight percentile were categorised as SGA, and babies above the 90th percentile were classified as LGA age.

2.4. Exposure data

Exposure to green space was estimated using three remote sensing products: fractional cover, foliage projective cover and a biodiversity index. Each record was allocated a pregnancy-specific value for the maternal residential locality; the smallest geographical unit that could be supplied from the PDC (see Supplementary Table 1).

The fractional vegetation cover is a remote sensing product, which uses an unmixing algorithm to give the proportion of different ground covers in each 30 × 30 m pixel. The data were obtained from the Joint Remote Sensing Research Project (JRSRP) within the Queensland Department of Environment and Resource Management. Images were obtained from the Landsat series of satellites (between 8-day and 16-day revisit frequency, depending on study year) and were geometrically and radiometrically corrected by the Statewide Landcover and Tree Survey (Scarth et al., 2006; Geoscience Australia, 2015). The JRSRP then used a constrained spectral mixture analysis based model to extract the percentage of land cover that is comprised of green vegetation (photosynthetic), non-green vegetation (non-photosynthetic vegetation such as leaf litter, branches and dry grass), and bare earth (bare soil or rock). The green vegetation element is highly correlated with NDVI, and results of green cover can be compared with previous studies using NDVI (Scarth et al., 2006; Geoscience Australia, 2015; Queensland Government, 2018b; Scarth et al., 2012). The resulting dataset comprises seasonal medians for the whole of Australia, which is illustrated in Fig. 1 Geoscience Australia, 2015). The data set was calibrated from, and validated against national field studies measuring on-the-ground vegetation composition (Scarth et al., 2006; Scarth et al., 2012; Schmidt et al., 2010; Rickards et al., 2014). To assign each record a monthly value, each month in a season was given the same value. The fractional cover pixels were averaged to provide a median value for each locality (using the Queensland Bounded Locality boundaries), which was then matched to the birth records by maternal residential locality. The resulting dataset gave each record a pregnancy specific value for each component of the fractional cover, and are as follows: green cover values refers to photosynthetic (green) vegetation, dry covers refers to non-photosynthetic vegetation, and bare earth refers to the bare soil and rock.

The Foliage Projective Cover (FPC) is a remote sensing product that estimates the percentage of ground area covered with foliage that vertically projects at least 2 m in height (Queensland Department of Environment and Science, 2018). The foliage projective cover is produced from Landsat images, obtained every 16 days, that have been corrected for topographic and atmospheric conditions, water and cropping. The images come from the dry period of May to October, and foliage projective cover is generated using an automated decision tree classification to give the percentage of each 30 × 30 m pixel covered by foliage. These data were calibrated against 2009 field sites and validated against airborne lidar from 19 field sites (Armston et al., 2009). Data were validated through field studies. Briefly, around 400 field sites were established and a modified discrete point sampling method was employed to record the ground cover, mid-storey and over-story at each metre interval (Scarth et al., 2006). The data were acquired through the Department of Environment and Science, Queensland Government, and are produced as a yearly estimate in raster form. The mean foliage projective cover value for each locality was extracted using the Spatial Analyst extension in ArcMap 10.6. These values were exported as a table, and joined to the PDC in R by locality code and year of birth. The foliage projective cover was only available for the following years: 2001, 2008–2010, and 2012–2014. The year of birth was used to match each record to its nearest foliage projective cover year.

A measure of vegetation biodiversity was obtained for the whole of Australia. The data were provided in raster format, and comprised of 250 m × 250 m pixels with a Shannon's diversity calculation from the National Vegetation Information System major vegetation classes in a 3 km radius of the pixel (Liddicoat et al., 2018). The Shannon's Index measures species richness and species variation within a given area, and gives a composite value (Buckland et al., 2005). As the value of the Shannon's Index increases, it indicates that both richness (number of species present) and evenness (the abundance of each species present) has increased. The higher the value the greater the biodiversity (Magurran, 2013). The mean diversity value for each locality was extracted using the Spatial Analyst extension in ArcMap 10.6.

Given the number of environmental variables, definitions for the purpose of this study are provided. In this manuscript, the term green cover refers to the specific dataset of green fractional cover. The term green space refers to any of the environmental variables representing green space (green cover, foliage projective cover, biodiversity), ground cover (dry cover) or a lack of both (bare earth). A table of these definitions is presented in the Supplementary material.

2.5. Other environmental variables

Data on air pollution and meteorological factors were obtained for use as covariates. Monthly averages of minimum and maximum temperature, dew point temperature, and relative humidity were obtained from The Bureau of Meteorology and allocated to each record based on the nearest temperature monitor measured by straight line distance. Only maximum temperature was associated with birthweight in our study, in a non-linear fashion. A basis spline was used in the final model to account for the non-linear relationship. A modelled air pollution dataset was obtained for the entirety of Queensland. Annual

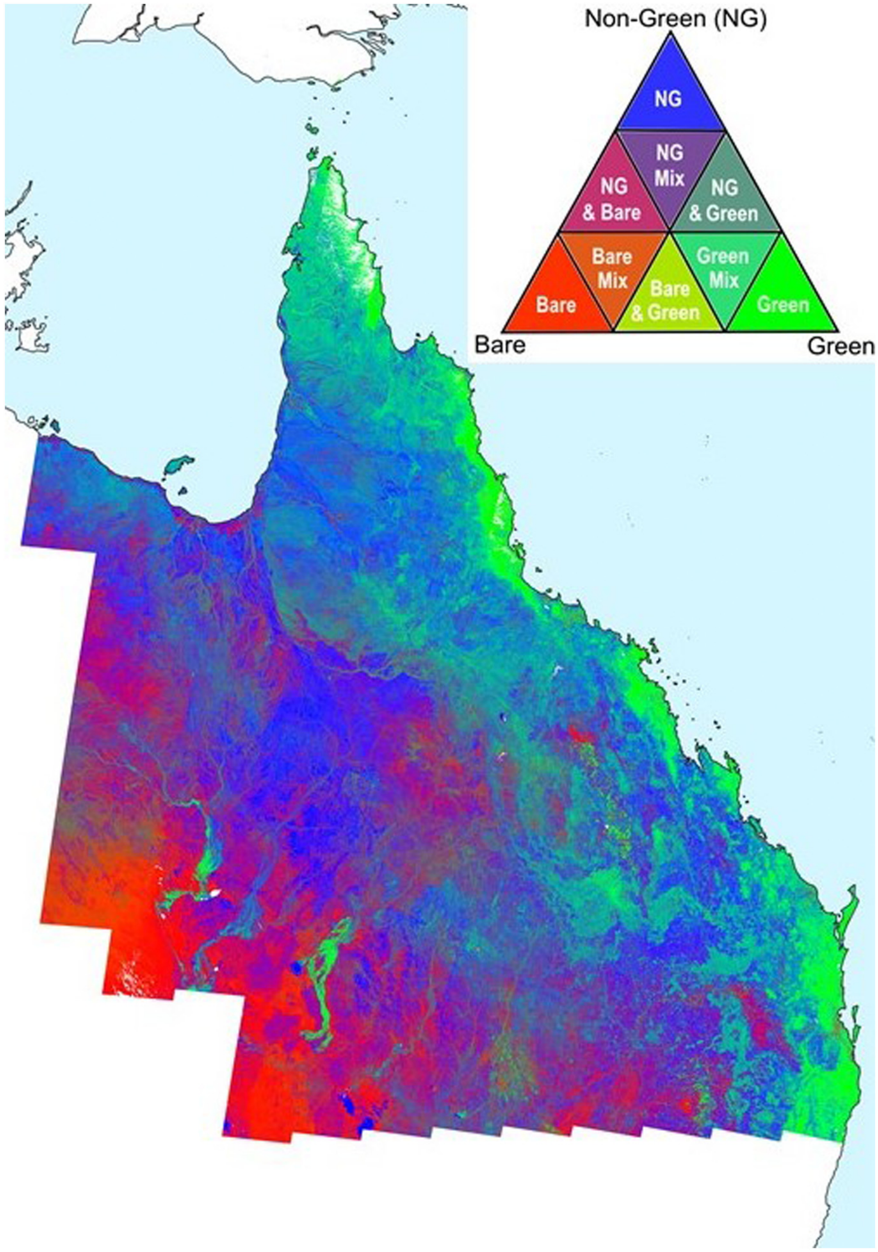

Fig. 1. An example image of seasonal fractional ground cover.

average estimates of two air pollutants (NO_2 and particles <2.5 μm [$PM_{2.5}$]), obtained from two satellite-based land-use regression models, were used as a surrogate for a woman's long-term exposure. These models included time-varying (annual) remote sensing information for each pollutant, and other spatial predictors such as roads, land use, meteorological variables, and point-source emissions; the models are described in detail elsewhere (Knibbs et al., 2014; Knibbs et al., 2018). The NO_2 model explained 81% of spatial variability in annual NO_2 (RMSE: 1.4 ppb), and in external validation explained 66% of annual NO_2 at urban and urban background locations (RMSE: 2 ppb) (Knibbs et al., 2016). The $PM_{2.5}$ model explained 62% of spatial variability in annual PM2.5 (RMSE: 1 μg/m^3), and 52% in external validation (RMSE: 1.2 μg/m^3) (Knibbs et al., 2018).

2.6. Directed acyclic graph (DAG)

A DAG, informed by existing literature, was developed (see online data supplement). The hypothesised pathway tested in the study was green space → birthweight. Major maternal and socio-demographic exposures were added to a DAG with environmental variables to identify a minimum sufficient set of confounders by considering the known or hypothesised pathways.

2.7. Analysis

Descriptive statistics are provided for variables of interest. Testing for differences across groups was performed using a chi-squared test for categorical variables and ANOVA for continuous variables. Correlation tests were performed using Pearson product-moment correlation coefficient.

The final models were run to assess each green space exposure individually against the outcome. Final models have been adjusted for maternal age group, smoking status, maternal Indigenous status, presence of confirmed or suspected congenital anomalies, previous pregnancy, maternal country of origin, season of birth, gestational hypertension and pre-eclampsia, maternal pre-pregnancy BMI, gestational or pre-existing diabetes, gestational age, baby's sex, socioeconomic decile of maternal residential address, maternal remoteness category, year of birth, maternal residential locality, NO_2, $PM_{2.5}$ and maximum temperature. Green space was tested as a non-linear variable using a spline, as some evidence suggests a potential threshold effect of green space (Fong et al., 2018). Models fit with a spline on green space did not perform better than the linear models, based on Akaike information criterion scores (an estimate of the model's ability to predict estimates) and adjusted R square. The linear model was retained due to ease of interpretation and comparison with previous studies. Linear mixed-effect models were developed to obtain restricted maximum likelihood estimates for birthweight, and generalised linear mixed-effects model for age-standardised birthweight (Bates et al., 2014). Random intercepts were applied to year of birth and maternal residential locality. The random effect for maternal residential locality was chosen to minimise uncontrolled confounding for unmeasured effects at the neighbourhood level. The random effect for calendar year is controlling for change across years that may arise from unmeasured effects, such as changing maternal care practices. All estimates for birthweight are presented as standardised beta coefficients with 95% confidence intervals. Odds ratios and 95% confidence intervals are presented for SGA and LGA analysis. Sub-group analysis was performed by re-parameterising models to provide birthweight estimates for different levels of maternal smoking, BMI, socio-economic status, and season. Sensitivity analyses were performed to assess the effect of prematurity and maternal morbidly on the association between green cover and birthweight outcomes. Data were processed and analysed using R version 3.5.1 (R Core Team, 2016) and Esri®ArcMap 10.3.1 (ESRI, 2011).

2.8. Ethics approval and Public Health Act approval

Ethical approval for this study was granted by the Children's Health Queensland Hospital and Health Service Human Research Ethics Committee (HREC/16/QRCH/320) and The University of Queensland's Human Research Ethics Committees A & B. Approval under the Public Health Act was granted by the Health Innovation, Investment and Research Office (RD006923).

3. Results

3.1. Characteristics of study population

The characteristics of this population have been reported previously (Vilcins et al., 2020). Briefly, the majority of babies in the cohort were born at full term (94%) and at an appropriate birthweight for their gestational age and sex (80%). The population characteristics are summarised in Table 1.

Table 1
Characteristics of the study population (live, singleton births between 2007 and 2015, $n = 414{,}478$) from Queensland, Australia.

Predictors	Category	Summary
Birthweight		3427 g (±SD 539.97)
	SGA	4.6%
	LGA	15.6%
Gestational age		38.94 wks (±SD 1.71)
Prematurity	Preterm (<37 wks)	6%
	Full term (≥37 wks)	94%
Sex	Female	48.7%
	Male	51.3%
Maternal age group	<25	21.2%
	25–34	59.1%
	35–44	19.6%
	45+	0.2%
Maternal Indigenous status	Indigenous and/or Torres Strait Islander	5%
Maternal BMI category	Underweight	3.4%
	Normal range	51.2%
	Overweight	20.7%
	Obese	24.7%
Smoking status	Yes	15.3%
Remoteness category	Major cities	66%
	Regional	31%
	Remote	3%
SES category	Most disadvantaged	4.6%
	Most advantaged	13.7%

3.2. Description of environmental variables

The mean fractional cover for each maternal locality was 48% green cover, 27% dry cover and 24% bare earth. The mean foliage projective cover was far lower than green cover at 27%. Diversity scores were very low with a mean Shannon's index of 0.60 (Table 2 and Table 3).

Correlation testing showed a strong correlation between birthweight and gestation ($r = 0.68$, $p < 0.001$), but not between birthweight and the environmental variables. Air pollution was positively correlated with bare ground: only moderately with PM2.5 ($r = 0.38$, $p < 0.001$) but more strongly with NO_2 ($r = 0.59$, $p < 0.001$) (see Supplementary materials Fig. 3).

3.3. Analysis of fractional cover and birthweight

3.3.1. Birthweight in grams

In the fully adjusted model, an IQR increase of green space cover was associated with an estimated increase in birthweight. Stratifying the model to give an estimate at each level of remoteness category showed slightly different, but still significant, estimates for urban and rural women. In the adjusted model of dry cover, an IQR increase of dry cover was associated with an increase in estimated birthweight for urban women only. Bare earth was associated with a small reduction in birthweight estimates, with a slightly stronger effect for rural women. The results of the adjusted analyses are shown in Table 4.

3.3.2. Age-standardised birthweight outcomes

There was no association between any green space variable and SGA in the fully adjusted models, with the exception of foliage projective cover in urban women. An IQR increase in foliage projective cover was associated with a borderline reduction in the odds for SGA. There was a small but significant increase in the odds for LGA babies per IQR of green cover in both urban and rural women, and a small decrease in the odds for dry cover in urban women only. Bare earth was associated with decreased odds for LGA in both urban and rural women, however the confidence interval for urban women included 1. There was also a small increase in the odds for foliage projective cover and LGA (Table 4).

3.4. Foliage projective cover

In the fully adjusted model for birthweight, an IQR increase of foliage projective cover was associated with an estimated increase in birthweight for mothers in major cities only (Table 4). There was no association between foliage projective cover and birthweight in rural women (Fig. 2). There was a small but borderline reduction in the odds for SGA with foliage projective cover for women in urban areas and a corresponding small increase in the odds for LGA.

3.5. Biodiversity

In adjusted models there was no relationship between biodiversity and any birthweight outcomes (Table 4). Sub-setting to areas with low biodiversity values (≤0.686) increased the estimate for green space. In areas with low biodiversity, an IQR increase in green cover was associated with an increase of 36.5 g of birthweight (95% CI

Table 2
Summary of environmental variables.

	Green[a] (%)	Dry[b] (%)	Bare[c] (%)	FPC (%)	Diversity	NO_2 (ppb)
Minimum	2.0	4.2	0.7	0.02	0.0	1.1
Median (IQR)	47.9 (40.8, 55.6)	25.8 (21.9, 30.4)	23.0 (15.0, 31.3)	27.6 (19.6, 33.3)	0.5 (0.4, 0.8)	4.8 (3.5, 6.2)
Mean (sd)	47.8 ± 12.0	27.1 ± 8.2	23.9 ± 12.1	27.0 ± 11.5	0.6 ± 0.3	4.9 ± 1.8
Maximum	90.9	70.4	75.1	85.8	2.1	16.4
Missing %	13	13	13	5	5	5

	PM2.5 (ug/m^3)	Maximum temperature (°C)	Minimum temperature (°C)	Dew point temperature (°C)	Relative humidity (%)
Minimum	0.5	18.0	3.9	0.9	23.3
Median (IQR)	5.9 (5.2, 6.6)	26.3 (25.4, 27.4)	15.9 (14.4, 17.2)	14.7 (13.7, 15.6)	70.6 (68.4, 73.1)
Mean (sd)	5.9 ± 1.4	26.5 ± 1.8	15.8 ± 2.3	14.7 ± 2.1	70.5 ± 4.9
Maximum	12.3	38.0	25.9	24.3	87.0
Missing (%)	6	30	30	26	26

[a] Green cover from fractional cover: the percentage of ground covered by green vegetation.
[b] Dry cover: dry and dead vegetation.
[c] Bare earth: bare ground, rock, dirt.

16–57). The association was not significant for biodiversity, when data were subset to low or high green space values (Fig. 3).

3.6. Subgroup and sensitivity analysis

For women who smoke, the potentially beneficial effect of green space was reduced, and for urban women the association between green cover and birthweight became non-significant. The benefits of green space differed by socio-economic status, with women in the most disadvantaged localities having no association between birthweight and green space, while only urban women in the most advantaged localities showing a significant association between green cover and birthweight. There were small changes in the estimates for green cover across season of birth, especially for winter births, however

Table 3
Mean and standard deviation of environmental variables, summarised for each level of age-standardised birthweight, 2007–2015 Queensland, Australia.

	SGA	Appropriate weight	LGA	p
n	25,822	408,082	77,597	
Green cover (%)	47.55 (12.24)	47.74 (12.01)	48.05 (11.95)	<0.001
Dry cover (%)	26.98 (8.34)	27.05 (8.21)	27.39 (8.25)	<0.001
Bare earth (%)	24.21 (12.32)	23.95 (12.06)	23.29 (11.93)	<0.001
Foliage projective cover (%)	26.76 (11.59)	27.00 (11.46)	26.96 (11.46)	0.004
Diversity (Shannon's Index)	0.59 (0.33)	0.60 (0.33)	0.60 (0.33)	0.001
Nitrogen dioxide (ppb)	4.94 (1.91)	4.91 (1.85)	4.81 (1.79)	<0.001
PM2.5 (μg/m3)	5.88 (1.41)	5.87 (1.36)	5.89 (1.34)	0.004
Maximum temperature (°C)	26.54 (1.81)	26.47 (1.77)	26.44 (1.77)	<0.001
Minimum temperature (°C)	15.90 (2.39)	15.84 (2.28)	15.76 (2.28)	<0.001
Dew point temperature (°C)	14.74 (2.21)	14.66 (2.13)	14.60 (2.12)	<0.001
Relative humidity (%)	70.57 (4.95)	70.45 (4.93)	70.41 (4.92)	<0.001

P values obtained from one-way ANOVA test.

Table 4
Birthweight estimates and odds ratio with 95% confidence intervals for the association between selected green space factors and birthweight outcomes in an adjusted regression analysis of births ($n = 302{,}422$) between 2007 and 2015 in Queensland, Australia.

Predictors	Birthweight (g)			SGA			LGA		
	Estimates	CI	p	OR	CI	p	OR	CI	p
Green cover									
Cities	29.6	13.8–45.5	**<0.001**	0.93	0.80–1.09	0.362	1.19	1.08–1.31	**<0.001**
Rural	17.8	2.9–32.7	**0.019**	1.07	0.92–1.24	0.364	1.10	1.01–1.20	**0.033**
Dry cover									
Cities	−34.4	−60.4 to −8.4	**0.010**	1.12	0.86–1.45	0.362	0.83	0.71–0.97	**0.018**
Rural	−1.1	−19.7–17.6	0.912	0.95	0.78–1.14	0.364	1.0	0.89–1.12	0.992
Bare earth									
Cities	−17.7	−32.8 to −2.6	**0.022**	1.03	0.89–1.19	0.722	0.89	0.82–0.98	**0.016**
Rural	−27.7	−45.7 to −9.7	**0.003**	0.96	0.81–1.15	0.686	0.85	0.76–0.95	**0.004**
Foliage projective cover									
Cities	26.0	10.8–41.3	**0.001**	0.85	0.73–0.98	**0.026**	1.14	1.04–1.25	**0.004**
Rural	5.9	−7.4–19.3	0.382	1.07	0.93–1.22	0.348	1.03	0.95–1.12	0.475
Biodiversity									
Cities	25.3	−480–531.3	0.922	0.04	0.00–4.59	0.186	0.46	0.03–8.46	0.604
Rural	−436.1	−938.3–66.0	0.089	22.12	0.17–2868.59	0.212	0.31	0.01–6.55	0.451

Models adjusted for maternal age, smoking, Indigenous status, congenital anomalies, previous pregnancies, maternal country of birth, season of birth, maternal hypertension, BMI, gestational diabetes, pre-existing diabetes, SES status, temperature, gestational age, sex, nitrogen dioxide, and PM2.5, with random intercepts on year and locality. Estimates are for a IQR increase. The bolded P values are those that are significant at the level set for this study, which is $p < 0.05$.

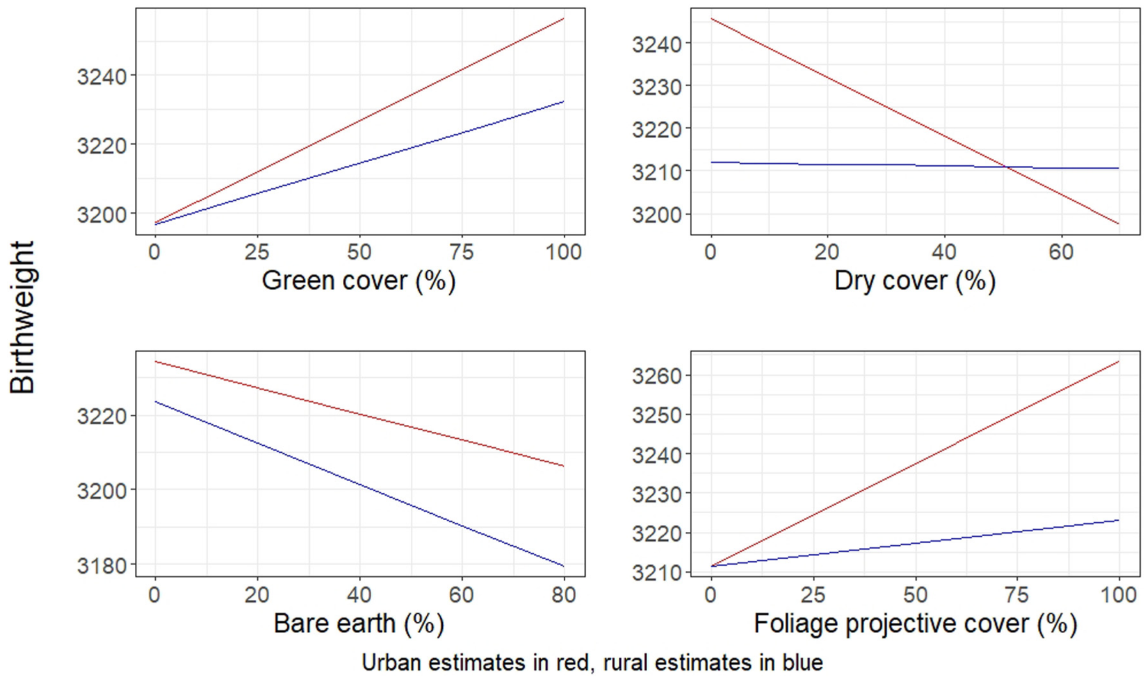

Fig. 2. Effect plots of the association of green space variables and birthweight in a birth cohort in Queensland, Australia 2007–2015 from a fully-adjusted mixed effects models.

this is not statistically significant. The estimated effect of green space tended to be stronger for overweight mothers compared with normal weight mothers, but again this is not statistically significant. There was no association between green cover and birthweight for underweight women, however there are very low numbers in this category (Fig. 4).

Models were built to explore the effects of multiparity. This was used as a proxy for other children in the home, as it has been argued that mothers with children may visit green spaces more. In models fit to give an estimate for both levels of the predictor, there was no association with green cover for women who had not previously given birth (0.25 g, 95% CI -0.06–0.56, $p = 0.120$). Women with previous pregnancies had a small positive association with green cover (0.56 g, 95% CI 0.31–0.80, $p \leq 0.001$). When the subset of women who have not previously been pregnant were examined, there was a significant interaction with remoteness. Women who have not previously been pregnant and live in urban areas had higher estimated birthweight for each increasing percentage of green cover. For nulliparous women living in rural areas, there is a negative association with green cover (see Supplementary materials).

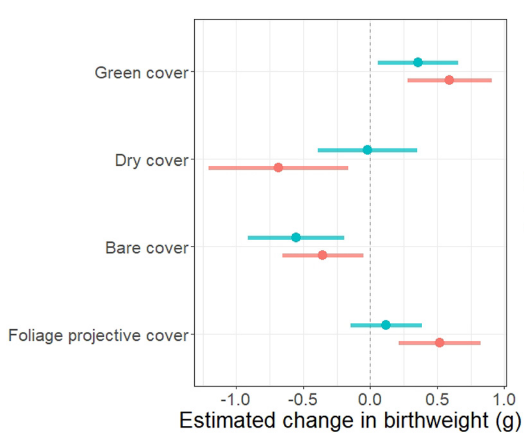

Fig. 3. Birthweight estimates and 95% confidence intervals for green space variables from fully adjusted mixed-effect models of a 2007–2015 birth cohort in Queensland, Australia.

Sensitivity analysis found small changes in the estimates when babies born <37 weeks were excluded from the analysis. The estimated change in birthweight for an IQR increase in green cover was 30.9 g (95% CI 14.9–47.00) for full term babies (see Supplementary material). Small changes were also found in the sensitivity analysis that excluded mothers with diabetes or hypertension (23.1 g, 95% CI 6.9–39.4). Lastly, a model exploring interactions between all variables and remote status found small increases in the estimates for green cover when interactions were included, but the magnitude of these changes is small (see Supplementary materials).

4. Discussion

The current study provides the first evidence for novel green space measures and their association with birthweight, and finds the types of ground cover within the maternal residential locality were associated with small, but significant changes in estimated birthweight. Further, the current study finds that green space is associated with birthweight for women residing in rural areas, as well as urban areas.

4.1. Strengths

This study had a number of strengths. The novel measures of green space in the current study had not previously been employed in birth outcome research. We used several measures such as fractional cover, foliage projective cover and a biodiversity measure (Shannon's index) to explore different aspects of land cover, shading effects, and biodiversity. Two key environmental exposures were included as covariates, air pollution and ambient temperature. The current study allocated each record a value of green cover, dry cover and bare earth for the period covering the pregnancy, which is a limitation in the methodologies of earlier works. The population represents virtually all births in Queensland across a 9-year period, gives a large sample size across a diverse

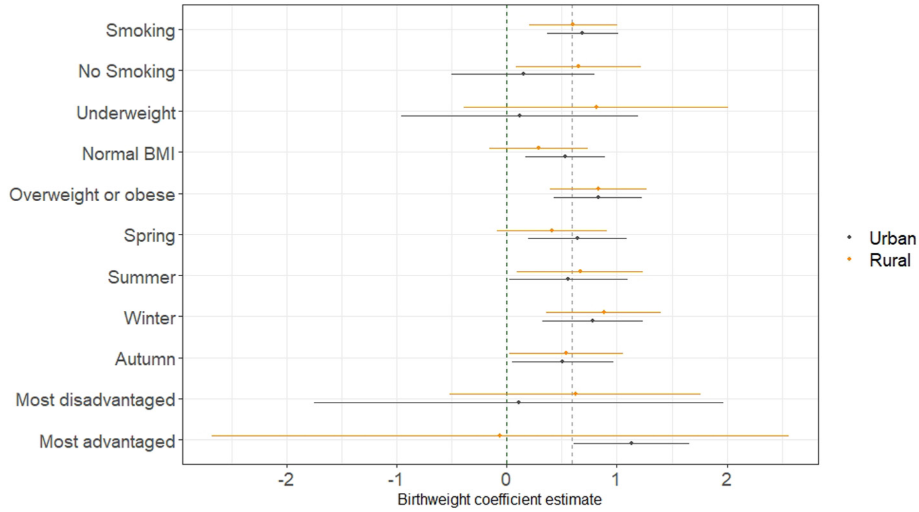

Fig. 4. Birthweight estimates and 95% CI for green cover by selected maternal characteristics from fully adjusted mixed-effect models of a 2007–2015 birth cohort in Queensland, Australia. These estimates are for a percentage increase in exposure.. The dashed line at 0.59 g represents estimated birthweight from the main green cover model in urban areas. Smoking $n = 84{,}137$, underweight $n = 15{,}907$, overweight $n = 215{,}208$, disadvantaged $n = 25{,}143$, advantaged $n = 65{,}480$, spring $n = 117{,}643$, summer $n = 127{,}525$, winter n = 127,059, autumn $n = 140{,}509$.

population and across the rural-urban divide. It also accounts for a large range of important cofounders. The spatial units used in this study (localities) is both a strength and a limitation. The strengths associated with this unit was that it was quite small compared to the more typically used administrative units in Australia, such as postcode or statistical area 2. The use of locality allows for a more localised neighbourhood effect, compared to the larger units.

4.2. Limitations

There are several limitations to the current study. The first is exposure misclassification; exposure is based on maternal locality, and all women in a given area are assumed equally exposed to the environmental risk factors of interest to this study. Previous work has shown that air pollution is often underestimated when using residential address and modelled data, thus the results in our study are likely to be conservative (Zeger et al., 2000; Blanchard et al., 2018). All records were allocated a biodiversity value from one point in time. We were not able to account for maternal mobility. The spatial units (locality) used in the current study are considered small by Australian privacy standards, nonetheless they are significantly coarser than those used in overseas studies. A further limitation on the use of locality as the spatial unit is that locality boundaries may have changed over the duration of the study, and this cannot be accounted for in this study. This should only affect a small number of records, and given the coarseness of our locality measure, we do not expect small changes in boundaries to affect the results. The temporal range of our remote sensing products may miss small changes in ground cover that happen when a period of rainfall causes a small flush of green vegetation (such as grass greening) that dries quickly. While this is a limitation in all remote sensing products, it is not expected to change the outcome given exposure was averaged across the pregnancy. Lastly, research of green space is troubled by the issue of reverse causation: where individuals who are most advantaged may buy into greener neighbourhoods, and the health benefits associated with green space may be a result of an unmeasured element of this advantage. The current study is unable to fully account for the influence of reverse causation. Stratification of results by socioeconomic status shows a trend towards higher estimated birthweight for the most advantaged mothers living in urban areas. However, the confidence intervals of the other groups are very wide with no significant differences between groups. Queensland is a diverse state with high levels of green space across both rural and urban areas. Very few places in Queensland major cities (36/487) have less than 30% green cover during the study period and none of those localities were in the most disadvantaged category (13 were in the most advantaged category).

4.3. Green space, bare earth, biodiversity and birthweight outcomes

The current study finds that the types of ground cover within the maternal residential locality are associated with small, but significant changes in estimated birthweight. Higher levels of green cover were associated with small increases in birthweight for women residing in both urban and rural locations. The results of this study are similar to others in the field, which found effect sizes as ranging from 2.17 g (per IQR increase) (Laurent et al., 2013) to 34.40 g (per IQR increase) (Dadvand et al., 2012). Plausibility for a positive effect of green space on birth weight comes from negative birth outcomes being linked to some of the factors that green space is hypothesised to improve; such as poor social cohesion, increased mental stress levels, poor physical activity, and environmental risk factors (Kondo et al., 2018).

The use of fractional cover allowed this study to find other ground cover elements associated with birthweight, which had effect estimates of a similar magnitude to green cover. The amount of dry cover in the maternal locality had a negative association with birthweight in urban areas. Similarly, bare earth is associated with a small, but significant reduction in birthweight. The effect estimates for bare earth are stronger in rural areas compared with urban areas, although both are statistically significant. We believe this is the first study to explore the effect of dry vegetation and bare earth on birth outcomes, and among the first to explore the effect of these on human health. Literature searching uncovered no papers making a link between potential effects of dry vegetation and health, so it is difficult to assess the potential mechanism by which dry cover is associated with birthweight in this study. Higher levels of dry cover in dryland regions are strongly affected by climatic conditions (Hueso-González et al., 2018). Drought has been linked to mental health issues (Vins et al., 2015), and higher levels of dry cover may occur in periods of low rainfall. Leaf fall has been linked to higher levels of soil-based polyaromatic hydrocarbons (PAH) (De Nicola et al., 2014), an air pollutant which has been associated with foetal growth retardation (Choi et al., 2012; Dejmek et al., 2000; Tang et al., 2006). This may explain the lack of association between dry cover and birthweight in rural areas, as urban areas have significantly higher

PAH levels (Song et al., 2019). In a study of PAH on vegetation, levels in urban areas were 5–20 times higher compared with vegetation in rural areas (Wagrowski and Hites, 1997). Another hypothesis is that decaying dry matter, such as leaf litter, could indicate higher levels of microbes available in the environment due to the fungal and bacterial communities involved in decomposition (Purahong et al., 2016; Voříšková and Baldrian, 2013). However, without further research in this field is it not possible to explore casual mechanisms. There is a growing body of research on the role of soils in human health. Modern research has started to focus on the benefits to the human microbiome from healthy soils (Wall et al., 2015), but traditionally public health has focused on the risks to health from bare earth, especially from infectious disease and contamination (Oliver, 1997). A greater proportion of bare earth also increases the risk of airborne dust, which has been linked to health outcomes both from direct contact with the respiratory system and through the transport of contaminants (Brevik and Sauer, 2015).

Foliage projective cover was associated with small increases in estimated birthweight for women in urban areas only. The effect estimates for foliage projective cover were similar to that of green cover. A previous paper found a reduction in the odds for SGA associated with tree cover of a similar magnitude as the current study (Donovan et al., 2011). Tree cover may reduce the effect of heat or pollution. The addition of temperature into the adjusted models did strengthen the estimate for foliage projective cover (all regions) from 19 g to 26 g. This suggests that foliage projective cover may mediate the effects of temperature to some degree. As foliage projective cover was only significant for urban women it suggests that benefits may be mediated by a different mechanism compared with green cover. The most likely explanation relates to the effect of shading and cooling seen with trees and shrubs, which may be more important in urban areas where building density and impervious space is higher (Edmondson et al., 2016; Tan et al., 2016).

Biodiversity was not associated with any birthweight outcome in this study. In areas with low biodiversity, the estimated effect of green cover on birthweight was increased. This suggests that higher levels of green cover may be beneficial in areas of lower biological diversity, as is commonly found in urban and developed areas. A recent systematic review found that the number of papers exploring the effects of biodiversity on human health is limited (Aerts et al., 2018). Further, the studies in this field tend to focus on self-perceived psychological health or general health. This is an area that could be explored in future research on measured health outcomes.

With the exception of a small reduction in the odds of small for gestational age births with increasing values of foliage projective cover, none of the green space variables were associated with SGA. There were, however, small increases in the odds for LGA for green cover and foliage projective cover, and a reduction in the odds for dry cover and bare earth. This effect is interesting, and is potentially explained by the cohort in the current study. This is a cohort with relatively good access to free maternal health care, in a developed nation, with rates of SGA that are comparatively low on a global scale (Black, 2015). In this cohort, it is likely that the small estimated increase in birthweight from green cover does not reduce the odds of SGA births further. However, the small increases may be enough to push higher rates of LGA in a population where birthweight have been increasing since the early 1990s (Hadfield et al., 2009; Lahmann et al., 2009). This finding cannot be compared with previous research, as it was not a reported outcome in studies identified in the literature review.

4.4. The rural-urban divide

Previous studies of green space and birthweight have been heavily urban based. Only one study was identified that examined the association between green space and birthweight outcomes in rural and urban sites (Casey et al., 2016). They found that green space was associated with SGA (but not birthweight) in cities only. In the current study the positive trend for green cover across both urban and rural areas shows that the benefits of green space are not limited to urban areas. It can difficult to define what is a rural area, and definitions and boundaries vary across regions. One limitation in the current study is that remoteness is based on proximity to services and not the type of environment each locality is located within. Queensland has a diverse mix of vegetation groups and climatic conditions, and future research should look for correlations between birthweight and green cover within these different settings.

Few studies have explored whether health benefits of green space are different across the rural-urban divide. A study in the Netherlands found that perceived health was related to greenness at all levels of urbanity (Maas et al., 2006). A study of mortality risk in urban and rural areas found that increasing green space was associated with lower mortality rates but only when the population remained stable (Hartig et al., 2020). A study of gardens in the United Kingdom found that health deprivation scores had a negative relationship with both green space and garden cover, and this effect was strongest in rural areas (Dennis and James, 2017). An earlier study in the same country found health benefits of green space for both urban and rural areas, although the association only held true for low income rural areas (Mitchell and Popham, 2007). More recent research found that for children living in rural areas from the age of 2 years, increasing greenness was associated with reduced odds for attention-deficit hyperactivity disorder (Donovan et al., 2019).

The current study finds that the beneficial effects of green space, and the potentially negative effects of other ground cover types, is not limited to urban areas. The difference in effect across the rural-urban divide suggests that rural areas should be considered in future research of environmental factors.

5. Conclusion

Healthy birthweight offers babies better health outcomes, both in the early post-natal period and across the life span. The current study provides the first evidence for novel green space measures and their association with birthweight, and finds the types of ground cover within the maternal residential locality were associated with small, but significant changes in estimated birthweight. These beneficial effects of green space, and the negative effects of other ground cover types, is not limited to urban areas. The difference in effect across the rural-urban divide suggests that green space and ground cover should be considered as an important environmental exposure in both rural and urban areas.

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CRediT authorship contribution statement

Dwan Vilcins: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft. **Peter Scarth:** Methodology, Resources, Writing - review & editing. **Peter D. Sly:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Paul Jagals:** Conceptualization, Writing - review & editing. **Luke Knibbs:** Conceptualization, Methodology, Writing - review & editing. **Peter Baker:** Methodology, Formal analysis, Data curation, Writing - review & editing, Supervision.

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 data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.143051.

References

Abelt, K., McLafferty, S., 2017. Green streets: urban green and birth outcomes. Int. J. Environ. Res. Public Health 14 (7).

Aerts, R., Honnay, O., Van Nieuwenhuyse, A., 2018. Biodiversity and human health: mechanisms and evidence of the positive health effects of diversity in nature and green spaces. Br. Med. Bull. 127 (1), 5–22.

Akaraci, S., Feng, X., Suesse, T., Jalaludin, B., Astell-Burt, T., 2020. A systematic review and meta-analysis of associations between green and blue spaces and birth outcomes. Int. J. Environ. Res. Public Health 17 (8).

Alcock, I., White, M., Cherrie, M., Wheeler, B., Taylor, J., McInnes, R., et al., 2017. Land cover and air pollution are associated with asthma hospitalisations: a cross-sectional study. Environ. Int. 109, 29–41.

Anabitarte, A., Subiza-Pérez, M., Ibarluzea, J., Azkona, K., García-Baquero, G., Miralles-Guasch, C., et al., 2020. Testing the multiple pathways of residential greenness to pregnancy outcomes model in a sample of pregnant women in the metropolitan area of Donostia-San Sebastián. Int. J. Environ. Res. Public Health 17 (12).

Andrusaityte, S., Grazuleviciene, R., Kudzyte, J., Bernotiene, A., Dedele, A., Nieuwenhuijsen, M.J., 2016. Associations between neighbourhood greenness and asthma in preschool children in Kaunas, Lithuania: a case–control study. BMJ Open 6 (4), e010341.

Armston, J.D., Denham, R.J., Danaher, T.J., Scarth, P.F., Moffiet, T.N., 2009. Prediction and validation of foliage projective cover from Landsat-5 TM and Landsat-7 ETM+ imagery. J. Appl. Remote. Sens. 3 (1) 033540-033528.

Australian Bureau of Statistics, 2018. Australian statistical geography standard (ASGS). Remoteness Structure. Volume 5 [cited 19/12/2018]; Available from. http://www.abs.gov.au/ausstats/abs@.nsf/mf/1270.0.55.005.

Australian Institute of Health and Welfare, 2015. Australia's Mothers and Babies 2013 - in Brief. Canberra AIHW.

Banay, R.F., Bezold, C.P., James, P., Hart, J.E., Laden, F., 2017. Residential greenness: current perspectives on its impact on maternal health and pregnancy outcomes. Int. J. Women's Health 9, 133–144.

Barker, D.J.P., Forsén, T., Uutela, A., Osmond, C., Eriksson, J.G., 2001. Size at birth and resilience to effects of poor living conditions in adult life: longitudinal study. BMJ 323 (7324), 1273.

Bates, D., Mächler, M., Bolker, B., SJapa, Walker, 2014. Fitting Linear Mixed-Effects Models Using lme4.

Beyer, K.M.M., Kaltenbach, A., Szabo, A., Bogar, S., Nieto, F.J., Malecki, K.M., 2014. Exposure to neighborhood green space and mental health: evidence from the survey of the health of Wisconsin. Int. J. Environ. Res. Public Health 11 (3), 3453–3472.

Black, R., 2015. Global prevalence of small for gestational age births. Nestle Nutr. Inst Workshop Ser. 81, 1–7.

Blanchard, O., Deguen, S., Kihal-Talantikite, W., François, R., Zmirou-Navier, D., 2018. Does residential mobility during pregnancy induce exposure misclassification for air pollution? Environ. Health 17 (1), 72.

Brevik, E.C., Sauer, T.J., 2015. The past, present, and future of soils and human health studies. SOIL 1 (1), 35–46.

Buckland, S., Magurran, A., Green, R., Fewster, R., 2005. Monitoring change in biodiversity through composite indices. Philos. Trans. R. Soc. B: Biol. Sci. 360 (1454), 243–254.

Casey, J.A., James, P., Rudolph, K.E., Wu, C.D., Schwartz, B.S., 2016. Greenness and birth outcomes in a range of Pennsylvania communities. Int. J. Environ. Res. Public Health 13 (3).

Choi, H., Wang, L., Lin, X., Spengler, J.D., Perera, F.P., 2012. Fetal window of vulnerability to airborne polycyclic aromatic hydrocarbons on proportional intrauterine growth restriction. PLoS One 7 (4), e35464.

Currey, B., Stoll, B., Chastonay, P., 2013. Reducing risks to the unborn child. J. R. Soc. Med. 106 (11), 428–430.

Cusack, L., Larkin, A., Carozza, S., Hystad, P., 2017. Associations between residential greenness and birth outcomes across Texas. Environ. Res. 152, 88–95.

Cusack, L., Sbihi, H., Larkin, A., Chow, A., Brook, J.R., Moraes, T., et al., 2018. Residential green space and pathways to term birth weight in the Canadian Healthy Infant Longitudinal Development (CHILD) study. Int. J. Health Geogr. 17 (1), 43.

Dadvand, P., Sunyer, J., Basagaña, X., Ballester, F., Lertxundi, A., Fernández-Somoano, A., et al., 2012. Surrounding greenness and pregnancy outcomes in four Spanish birth cohorts. Environ. Health Perspect. 120 (10), 1481–1487.

Dadvand, P., Villanueva Cristina, M., Font-Ribera, L., Martinez, D., Basagaña, X., Belmonte, J., et al., 2014. Risks and benefits of green spaces for children: a cross-sectional study of associations with sedentary behavior, obesity, asthma, and allergy. Environ. Health Perspect. 122 (12), 1329–1335.

Dadvand, P., Bartoll, X., Basagaña, X., Dalmau-Bueno, A., Martinez, D., Ambros, A., et al., 2016. Green spaces and general health: roles of mental health status, social support, and physical activity. Environ. Int. 91, 161–167.

De Nicola, F., Baldantoni, D., Alfani, A., 2014. PAHs in decaying Quercus ilex leaf litter: mutual effects on litter decomposition and PAH dynamics. Chemosphere 114, 35–39.

de Vries, S., van Dillen, S.M.E., Groenewegen, P.P., Spreeuwenberg, P., 2013. Streetscape greenery and health: stress, social cohesion and physical activity as mediators. Soc. Sci. Med. 94, 26–33.

Dejmek, J., Solansky, I., Benes, I., Lenicek, J., Sram, R.J., 2000. The impact of polycyclic aromatic hydrocarbons and fine particles on pregnancy outcome. Environ. Health Perspect. 108 (12), 1159–1164.

Dennis, M., James, P., 2017. Evaluating the relative influence on population health of domestic gardens and green space along a rural-urban gradient. Landsc. Urban Plan. 157, 343–351.

Donovan, G.H., Michael, Y.L., Butry, D.T., Sullivan, A.D., Chase, J.M., 2011. Urban trees and the risk of poor birth outcomes. Health Place 17 (1), 390–393.

Donovan GH, Michael YL, Gatziolis D, Mannetje A, Douwes J. Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study. Lancet Planet. Health 2019;3(5):e226-e34.

Dunlop, A.L., Mulle, J.G., Ferranti, E.P., Edwards, S., Dunn, A.B., Corwin, E.J., 2015. Maternal microbiome and pregnancy outcomes that impact infant health: a review. Adv. Neonatal Care 15 (6), 377–385.

Dzhambov, A.M., Dimitrova, D.D., Dimitrakova, E.D., 2014. Association between residential greenness and birth weight: systematic review and meta-analysis. Urban For. Urban Green. 13 (4), 621–629.

Dzhambov, A.M., Markevych, I., Lercher, P., 2019. Associations of residential greenness, traffic noise, and air pollution with birth outcomes across Alpine areas. Sci. Total Environ. 678, 399–408.

Edmondson, J.L., Stott, I., Davies, Z.G., Gaston, K.J., Leake, J.R., 2016. Soil surface temperatures reveal moderation of the urban heat island effect by trees and shrubs. Sci. Rep. 6 (1), 33708.

Ellaway, A., Macintyre, S., Bonnefoy, X., 2005. Graffiti, Greenery, and Obesity in Adults: Secondary Analysis of European Cross Sectional Survey. vol. 331 pp. 611–612 (7517).

ESRI, 2011. ArcGIS Desktop: Release 10. Redlands, CA. .

Feng, X., Astell-Burt, T., 2017. Is neighborhood green space protective against associations between child asthma, neighborhood traffic volume and perceived lack of area safety? Multilevel analysis of 4447 Australian children. Int. J. Environ. Res. Public Health 14 (5), 543.

Flies, E.J., Skelly, C., Negi, S.S., Prabhakaran, P., Liu, Q., Liu, K., et al., 2017. Biodiverse green spaces: a prescription for global urban health. Front. Ecol. Environ. 15 (9), 510–516.

Fong, K.C., Kloog, I., Coull, B.A., Koutrakis, P., Laden, F., Schwartz, J.D., et al., 2018. Residential greenness and birthweight in the state of Massachusetts, USA. Int. J. Environ. Res. Public Health 15 (6).

Gascon, M., Triguero-Mas, M., Martínez, D., Dadvand, P., Rojas-Rueda, D., Plasència, A., et al., 2016. Residential green spaces and mortality: a systematic review. Environ. Int. 86, 60–67.

Geoscience Australia, 2015. Fractional Cover (FC25) Product Description. Australian Government, Australia.

Gidlow, C.J., Randall, J., Gillman, J., Smith, G.R., Jones, M.V., 2016. Natural environments and chronic stress measured by hair cortisol. Landsc. Urban Plan. 148, 61–67.

Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., 2007. Adapting cities for climate change: the role of the green infrastructure. Built Environ. 33 (1), 115–133.

Global Burden of Disease Collaborative Network, 2018. Global Burden of Disease Study 2017 (GBD 2017) Results. Institute for Health Metrics and Evaluation (IHME), Seattle, United States.

Hadfield, R., Lain, S., Simpson, J., Ford, J., Raynes-Greenow, C., Morris, J., et al., 2009. Are babies getting bigger? An analysis of birthweight trends in New South Wales, 1990-2005. Med. J. Aust. 190, 312–315.

Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. Soc. Sci. Med. 63 (11), 2847–2863.

Hartig, T., Evans, G.W., Jamner, L.D., Davis, D.S., Gärling, T., 2003. Tracking restoration in natural and urban field settings. J. Environ. Psychol. 23 (2), 109–123.

Hartig, T., Mitchell, R., Vries, Sd, Frumkin, H., 2014. Nat. Health 35 (1), 207–228.

Hartig, T., Astell-Burt, T., Bergsten, Z., Amcoff, J., Mitchell, R., Feng, X., 2020. Associations between greenspace and mortality vary across contexts of community change: a longitudinal ecological study. J. Epidemiol. Community Health 74 (6), 534–540.

Hillsdon, M., Panter, J., Foster, C., Jones, A., 2006. The relationship between access and quality of urban green space with population physical activity. Public Health 120 (12), 1127–1132.

Hueso-González, P., Muñoz-Rojas, M., Martínez-Murillo, J.F., 2018. The role of organic amendments in drylands restoration. Curr. Opin. Environ. Sci. Health 5, 1–6.

Knibbs, L.D., Hewson, M.G., Bechle, M.J., Marshall, J.D., Barnett, A.G., 2014. A national satellite-based land-use regression model for air pollution exposure assessment in Australia. Environ. Res. 135, 204–211.

Knibbs, L.D., Coorey, C.P., Bechle, M.J., Cowie, C.T., Dirgawati, M., Heyworth, J.S., et al., 2016. Independent validation of national satellite-based land-use regression models for nitrogen dioxide using passive samplers. Environ. Sci. Technol. 50 (22), 12331–12338.

Knibbs, L.D., van Donkelaar, A., Martin, R.V., Bechle, M.J., Brauer, M., Cohen, D.D., et al., 2018. Satellite-based land-use regression for continental-scale long-term ambient PM2.5 exposure assessment in Australia. Environ. Sci. Technol. 52 (21), 12445–12455.

Kondo, M.C., Fluehr, J.M., McKeon, T., Branas, C.C., 2018. Urban green space and its impact on human health. Int. J. Environ. Res. Public Health 15 (3), 445.

Lachowycz K, Jones AP. Greenspace and obesity: a systematic review of the evidence. Obes. Rev. 2011;12(5):e183-e9.

Lahmann, P., Wills, R.-A., Coory, M., 2009. Trends in birth size and macrosomia in Queensland, Australia, from 1988 to 2005. Paediatr. Perinat. Epidemiol. 23, 533–541.

Laurent, O., Wu, J., Li, L., Milesi, C., 2013. Green spaces and pregnancy outcomes in Southern California. Health Place 24, 190–195.

Lee, K.J., Moon, H., Yun, H.R., Park, E.L., Park, A.R., Choi, H., et al., 2020. Greenness, civil environment, and pregnancy outcomes: perspectives with a systematic review and meta-analysis. Environ. Health 19 (1), 91.

Liddicoat, C., Bi, P., Waycott, M., Glover, J., Lowe, A.J., Weinstein, P., 2018. Landscape biodiversity correlates with respiratory health in Australia. J. Environ. Manag. 206, 113–122.

Lin, L., Li, Q., Yang, J., Han, N., Chen, G., Jin, C., et al., 2020. The associations of residential greenness with fetal growth in utero and birth weight: a birth cohort study in Beijing, China. Environ. Int. 141, 105793.

Lymperopoulou, D.S., Adams, R.I., Lindow, S.E., 2016. Contribution of vegetation to the microbial composition of nearby outdoor air. Appl. Environ. Microbiol. 82 (13), 3822–3833.

Lynch, J., Smith, G.D., 2005. A life course approach to chronic disease epidemiology. Annu. Rev. Public Health 26, 1–35.

Maas, J., Verheij, R.A., Groenewegen, P.P., de Vries, S., Spreeuwenberg, P., 2006. Green space, urbanity, and health: how strong is the relation? J. Epidemiol. Community Health 60 (7), 587–592.

Maas, J., van Dillen, S.M.E., Verheij, R.A., Groenewegen, P.P., 2009. Social contacts as a possible mechanism behind the relation between green space and health. Health Place 15 (2), 586–595.

Magurran, A.E., 2013. Measuring Biological Diversity. John Wiley & Sons.

Malin, G.L., Morris, R.K., Riley, R., Teune, M.J., Khan, K.S., 2014. When is birthweight at term abnormally low? A systematic review and meta-analysis of the association and predictive ability of current birthweight standards for neonatal outcomes. BJOG 121 (5), 515–526.

Mhuireach, G., Johnson, B.R., Altrichter, A.E., Ladau, J., Meadow, J.F., Pollard, K.S., et al., 2016. Urban greenness influences airborne bacterial community composition. Sci. Total Environ. 571, 680–687.

Middel, A., Häb, K., Brazel, A.J., Martin, C.A., Guhathakurta, S., 2014. Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. Landsc. Urban Plan. 122, 16–28.

Mills, J.G., Brookes, J.D., Gellie, N.J.C., Liddicoat, C., Lowe, A.J., Sydnor, H.R., et al., 2019. Relating Urban Biodiversity to Human Health with the 'Holobiont' Concept. vol. 10 p. 550.

Miri, M., Alahabadi, A., Ehrampoush, M.H., Ghaffari, H.R., Sakhvidi, M.J.Z., Eskandari, M., et al., 2018. Environmental determinants of polycyclic aromatic hydrocarbons exposure at home, at kindergartens and during a commute. Environ. Int. 118, 266–273.

Mitchell, R., Popham, F., 2007. Greenspace, urbanity and health: relationships in England. J. Epidemiol. Community Health 61 (8), 681–683.

Nayak, S.G., Shrestha, S., Kinney, P.L., Ross, Z., Sheridan, S.C., Pantea, C.I., et al., 2018. Development of a heat vulnerability index for New York State. Public Health 161, 127–137.

Nichani, V., Dirks, K., Burns, B., Bird, A., Morton, S., Grant, C., 2017. Green space and pregnancy outcomes: evidence from growing up in New Zealand. Health Place 46, 21–28.

Nieuwenhuijsen, M.J., Agier, L., Basagaña, X., Urquiza, J., Tamayo-Uria, I., Giorgis-Allemand, L., et al., 2019. Influence of the Urban Exposome on Birth Weight. vol. 127 p. 047007 (4).

Nutsford, D., Pearson, A.L., Kingham, S., 2013. An ecological study investigating the association between access to urban green space and mental health. Public Health 127 (11), 1005–1011.

Oliver, M.A., 1997. Soil and human health: a review. Eur. J. Soil Sci. 48 (4), 573–592.

Pink, B., 2011. Socio-Economic Indexes for Areas (SEIFA) 2011 Technical Paper. Australian Bureau of Statistics.

Prescott, S.L., Larcombe, D.-L., Logan, A.C., West, C., Burks, W., Caraballo, L., et al., 2017. The skin microbiome: impact of modern environments on skin ecology, barrier integrity, and systemic immune programming. World Allergy Organ. J. 10 (1), 29.

Purahong, W., Wubet, T., Lentendu, G., Schloter, M., Pecyna, M.J., Kapturska, D., et al., 2016. Life in leaf litter: novel insights into community dynamics of bacteria and fungi during litter decomposition. Mol. Ecol. 25 (16), 4059–4074.

Queensland Department of Environment and Science, 2018. Statewide Landcover and Trees Study (SLATS): Overview of Methods. Brisbane. .

Queensland Government, 2018a. Statistics and facts. Available from:. https://www.qld.gov.au/about/about-queensland/statistics-facts.

Queensland Government, 2018b. Ground Cover Mapping Methodology. Queensland Government, Queensland, Australia Available from https://www.qld.gov.au/environment/land/management/mapping/statewide-monitoring/groundcover/methodology. . (Accessed 26 July 2019). .

R Core Team, 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Richardson, E.A., Pearce, J., Mitchell, R., Kingham, S., 2013. Role of physical activity in the relationship between urban green space and health. Public Health 127 (4), 318–324.

Rickards, J., Stewart, J., McPhee, R., Randall, L., 2014. Australian ground cover reference sites database package 2014. The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).

Robert, M.K., Bonita, M.D.S., Joseph St, G., Nina, F.S., 2015. Nelson Textbook of Pediatrics. Twentieth edition. Elsevier Health Science, United States.

Scarth, P., Byrne, M., Danaher, T., Henry, B., Hassett, R., Carter, J., et al., 2006. State of the paddock: monitoring condition and trend in groundcover across Queensland. Proc. of the 13th Australasian Remote Sensing Conference.

Scarth, P.R.A., Schmidt, M., Denham, R., 2012. Tracking grazing pressure and climate interaction - the role of Landsat fractional cover in time series analysis. Proceedings of the 15th Australasian Remote Sensing and Photogrammetry Conference. Remote Sensing and Photogrammetry Commission of the Spatial Sciences Institute Canberra, Alice Springs, Australia.

Schipperijn, J., Bentsen, P., Troelsen, J., Toftager, M., Stigsdotter, U.K., 2013. Associations between physical activity and characteristics of urban green space. Urban For. Urban Green. 12 (1), 109–116.

Schmidt, M., Denham, R., Scarth, P., 2010. Fractional ground cover monitoring of pastures and agricultural areas in Queensland. 15th Australasian Remote Sensing and Photogrammetry Conference.

Song, S., Lu, Y., Wang, T., Zhang, S., Sweetman, A., Baninla, Y., et al., 2019. Urban-rural gradients of polycyclic aromatic hydrocarbons in soils at a regional scale: quantification and prediction. J. Environ. Manag. 249, 109406.

Stamper, C.E., Hoisington, A.J., Gomez, O.M., Halweg-Edwards, A.L., Smith, D.G., Bates, K.L., et al., 2016. The microbiome of the built environment and human behavior: implications for emotional health and well-being in postmodern Western societies. Int. Rev. Neurobiol. 131, 289–323.

Sugiyama, T., Leslie, E., Giles-Corti, B., Owen, N., 2008. Associations of neighbourhood greenness with physical and mental health: do walking, social coherence and local social interaction explain the relationships? J. Epidemiol. Community Health 62 (5), e9.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., et al., 2014. Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. Environ. Health 13 (1), 20.

Tan, Z., Lau, K.K.-L., Ng, E., 2016. Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. Energy Build. 114, 265–274.

Tang, D., Li, T.Y., Liu, J.J., Chen, Y.H., Qu, L., Perera, F., 2006. PAH-DNA adducts in cord blood and fetal and child development in a Chinese cohort. Environ. Health Perspect. 114 (8), 1297–1300.

The Earth Observatory, 2000. Measuring Vegetation (NDVI & EVI) NASA Goddard Space Flight Center. [27 May 2020]; Available from. https://earthobservatory.nasa.gov/features/MeasuringVegetation.

Vilcins, D., Baker, P., Jagals, P., Sly, P.D., 2020. Association of maternal and social characteristics with age-standardised birthweight. J. Public Health.

Villeneuve, P.J., Jerrett, M., Su, J., Burnett, R.T., Chen, H., Wheeler, A.J., et al., 2012. A cohort study relating urban green space with mortality in Ontario, Canada. Environ. Res. 115, 51–58.

Vins, H., Bell, J., Saha, S., Hess, J.J., 2015. The mental health outcomes of drought: a systematic review and causal process diagram. Int. J. Environ. Res. Public Health 12 (10), 13251–13275.

Vogel, M., 2017. Childsds: Data and Methods Around Reference Values in Pediatrics.

Voříšková, J., Baldrian, P., 2013. Fungal community on decomposing leaf litter undergoes rapid successional changes. ISME J. 7 (3), 477–486.

Wagrowski, D.M., Hites, R.A., 1997. Polycyclic aromatic hydrocarbon accumulation in urban, suburban, and rural vegetation. Environ. Sci. Technol. 31 (1), 279–282.

Wall, D.H., Nielsen, U.N., Six, J., 2015. Soil biodiversity and human health. Nature 528, 69.

Weissmann-Brenner, A., Simchen, M.J., Zilberberg, E., Kalter, A., Weisz, B., Achiron, R., et al., 2012. Maternal and neonatal outcomes of large for gestational age pregnancies. Acta Obstet. Gynecol. Scand. 91 (7), 844–849.

Zeger, S.L., Thomas, D., Dominici, F., Samet, J.M., Schwartz, J., Dockery, D., et al., 2000. Exposure Measurement Error in Time-Series Studies of Air Pollution: Concepts and Consequences. vol. 108 pp. 419–426 (5).

Zhan, Y., Liu, J., Lu, Z., Yue, H., Zhang, J., Jiang, Y., 2020. Influence of residential greenness on adverse pregnancy outcomes: a systematic review and dose-response meta-analysis. Sci. Total Environ. 718, 137420.